Exploration of passive cooling potential to improve indoor environment quality (thermal comfort, relative humidity and air movement) in thermally free-running multi-residential dwellings in Thailand urban areas

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Abstract

Multi-residential buildings in Thailand's urban areas have significant issues regarding indoor environmental quality (IEQ). These buildings, typically designed with single-sided ventilation, tend to suffer from inadequate ventilation, particularly in thermally free-running buildings. This leads to poor IEQ, especially for low-socioeconomic groups. Natural ventilation, as a passive cooling strategy, offers benefits in enhancing thermal comfort, sustainability, and cost-effectiveness.

Three phases of the study were established for investigating the potential of passive design options by focussing on natural ventilation to improve IEQ. Phase 1 involved physical measurements to assess current indoor environmental conditions and occupant perception surveys to characterise typology and typical buildings. These measurements provided base case data for Phase 2, where Computational Fluid Dynamics (CFD) and building simulation models were developed to explore factors affecting natural ventilation and thermal behaviour, both outdoors and indoors. In Phase 3, potential design options for improving IEQ were evaluated, involving consultations with Thai building professionals. The study revealed that the optimal design scenario could improve thermal comfort by up to 21.9% compared to the original room configuration. This optimal case also maintained healthier relative humidity levels 5% longer. During the rainy season, these benefits were even more obvious, with a 42.3% increase in thermal comfort and a 56% increase in periods of healthy humidity levels. Additionally, the optimal design consistently achieved natural ventilation rates exceeding 0.2 $m.s^{-1}$, occasionally reaching up to 0.4 $m.s^{-1}$ at the occupant level, signifying a substantial improvement. The research proposes design options, focusing on passive cooling through natural ventilation for new multi-residential buildings in urban areas.

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Publications

The following papers and posters were published during the research time.

Journal Paper:

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Poster presentation:

Doctoral Academy Exhibition: Image of the Research. 13th December 2022. Bute Building, Cardiff University

PGR Poster Event 2023. 15th March 2023. Bute Building, Cardiff University, awarded the second prize for Best Research Poster

WSA Exhibition Event 2023. 23rd March 2023. Bute Building, Cardiff University

Abbreviation

BES	Building Energy Simulation
CFD	Computational Fluid Dynamics
EPW	EnergyPlus Weather
IAQ	Indoor Air Quality
IEQ	Indoor Environmental Quality
OEQ	Outdoor Environmental Quality
POE	Post-Occupant Evaluation
RMSE	Root Mean Square Error
FDM	Finite Difference Method
FEM	Finite Element Method
FVM	Finite Volume Method
HVAC	Heating Ventilation and Air Conditioning
BEP	Built Environment Professional

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1 Introduction

1.1 Research Context and Contribution

The rapid growth of complex residential buildings in urban areas has caused an obstruction of wind flow and solar radiation in recent decades. (Arnfield 2003; Garcia-Nevado et al. 2016) (see Figure 1- 1). The obstruction exacerbates both outdoor and indoor thermal comfort, especially in tropical climates. (Lau et al. 2019; Rodriguez and D'Alessandro 2019). Additionally, ineffective design of those buildings, such as the limited openable area of window on one façade causes poor ventilation. In turn, poor ventilation impacts the ability to remove internally generated moisture, which exacerbates the development of mould (Nitmetawong et al. 2019). This impacts living comfort and increases the risk of respiratory diseases and, later on mental illness for occupants (Heseltine and Rosen 2009). Numerous studies around the world show that the most vulnerable or disadvantaged populations are frequently located in areas with poorer environmental quality(Evans and Kantrowitz 2002; Jun et al. 2011; Sharifi and Khavarian-Garmsir 2020). Low socioeconomic groups tend to suffer worse health due to inadequate indoor environmental quality, which requires economic solutions to tackle the issue. Therefore, this research focuses on multi-dwelling residences that are thermally free-running (no air conditioning or thermal services) and generally populated by low-socioeconomic groups.

Thailand's population in 2019 was 66,558,935 people (NationalStatisticalOffice 2021) and the UN estimates the population projecting to be 71,801,279 people in 2023 (UnitedNations 2022). In 2021, 52.16% of the population lived in urban areas (WorldBank 2021). Many urban cities in Thailand have a population of more than 1,000 people per square kilometre and are defined as dense cities. For example, 3,625 people per square kilometre, 1,540 people per square kilometre and 1,413 people per square kilometre in Bangkok, Chiang Mai and Khon Kaen urban areas, respectively. Additionally, the population density has increased by approximately 8% in the last decade. This causes an increasing number of multi-storey buildings in the urban area and vicinity by over 20% in the last five years (Center 2020) and over 1.2 million people live in Bangkok's high-density residential zones (AdministrativeStrategyDivision 2018).

High residential density can evoke low indoor air quality and unsatisfactory living conditions, causing health risks to residents (Li et al. 2011). These high-rise blocks could lead to severe sky obstructions and inadequate air ventilation, especially on the lower floor. Such lower-floor rooms generally suffer from being overshaded by nearby buildings, which further affects indoor ventilation, obstructs daylight, and results in mould growth on furniture and interior surfaces (Juangjandee 2017). Additionally, ineffective design of those buildings, such as the limited window of free-running buildings cause poor ventilation, which in turn causes high moisture load, which commonly results in the presence of mould (Nitmetawong et al. 2019) In other words, restricted indoor air circulation can bring about high moisture accumulation and enhance mould growth, particularly in tropical climates (ASHRAE 2009). (see Figure 1- 2). This significantly impacts living comfort and increases the risks of respiratory diseases, such as Allergic Rhinitis, Hypersensitivity Pneumonitis, or Bronchitis, moisture-associated skin damage and later on mental illness for occupants (ASHRAE 2009; Heseltine and Rosen 2009; Valtonen 2017; LeBlanc 2019). Symptoms caused by living in moisture buildings commonly begin with mild, then increase harmfulness to the respiratory tract; eventually, these symptoms may turn into chronic (Valtonen 2017).

Figure 1- 1 High-residential area in Thailand
(Source: Author)

According to previous research on the complex residential buildings in tropical areas indicated that indoor relative humidity values were commonly greater than 80 %RH, which is above a critical standard value of thermal comfort condition for almost the whole day. On the lower floor rooms, there is the additional issue of overshading by nearby buildings, which further affects indoor ventilation and results in mould on furniture and interior surface (Juangjandee 2017; Silveira et al. 2019). Although, Thailand has launched urban regulations, including building coverage ground ratio, open space ratio, and setback regulation to relieve and overcome those buildings' environmental problems. Such regulations are failing to prevent dampness and mould (Chowdhury et al. 2009). These indoor conditions have emerged as an environmental hazard indicator of health risk that raises an urgent need for some concerns.

In the absence of mechanical services, the main strategy available is to reduce the build-up of internal thermal gains and humidity generated from occupant activities through natural (Cook 1989; Sreshthaputra 2003). Increasing the ventilation rate can reduce the condensation rate, which is a significant factor in mould proliferation in buildings (Silveira et al. 2019).

Although the benefits of natural ventilation are widely acknowledged, there is a lack of practical design guides for the modern architectural context (Mumovic and Santamouris 2013; Wang and Malkawi 2019). Most previous research associated with strategies for improving natural ventilation or thermal comfort has focused on traditional residential building or detached house (Prajongsan and Sharples 2012). However, the strategies are less practised in complex residential buildings (Rajagopalan et al. 2014). The complex residential buildings tend to be designed with free-running building planning, which assumes all windows are open to obtain maximum natural ventilation all day and night (Sreshthaputra 2003), however, it does not account for the limited external air movement due to the proximity of the buildings and single-sided window.

This research is to investigate the potential of passive design options focussing on natural ventilation to improve the indoor environment in thermally free-running apartment dwellings in Thailand's climate conditions.

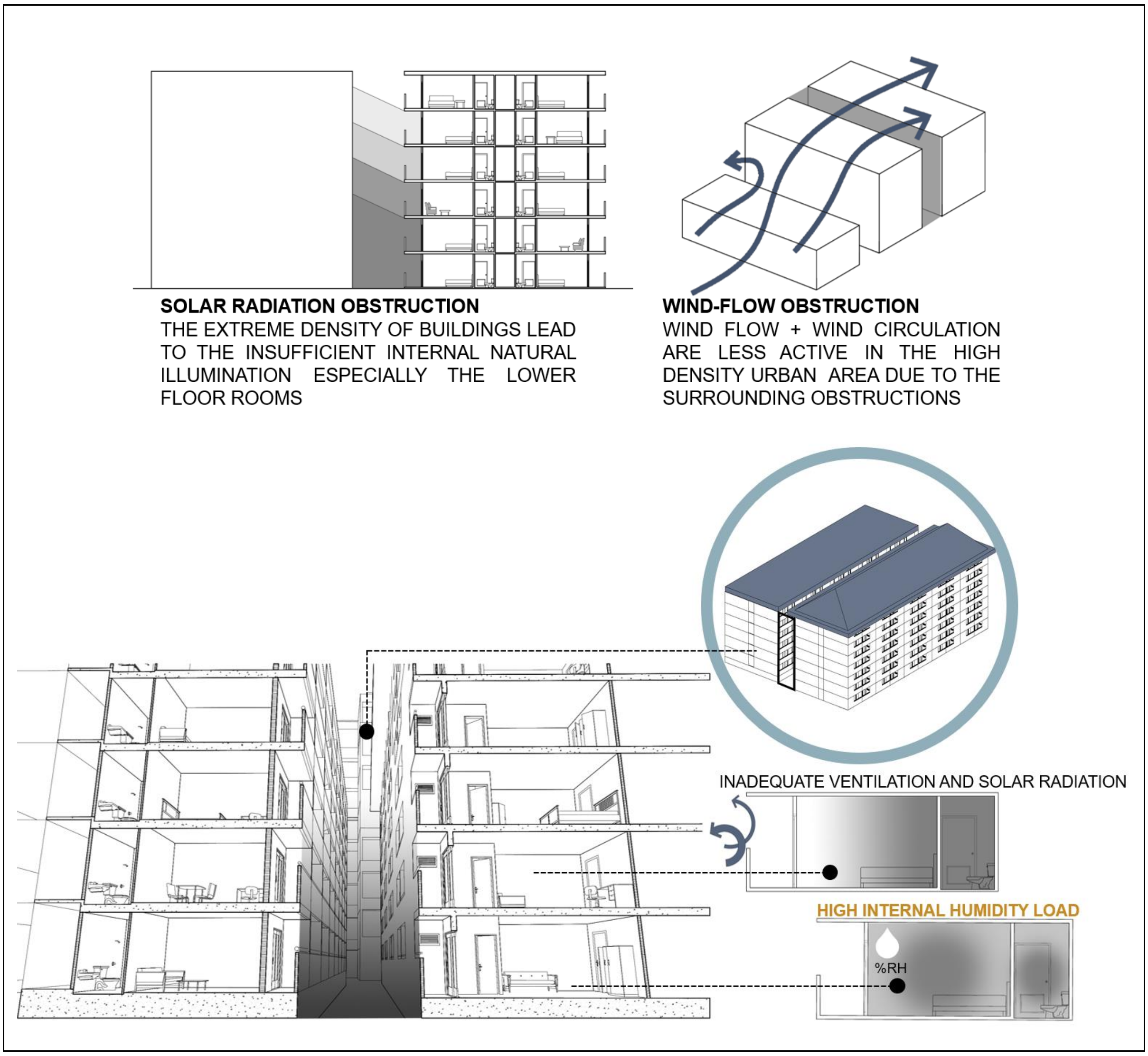


Figure 1- 2 Illustration of problems caused by solar and wind flow obstructed by nearby building
(Source: Author)

1.2 Aims

The aim of this research is to investigate the potential of passive design options (focussing on natural ventilation) to improve indoor environment quality—specifically relative humidity, thermal comfort, and natural ventilation in thermally free-running apartment dwellings in Thailand's climate conditions.

1.3 Research Objectives

1. Evaluate the current situation regarding indoor environmental quality in apartment blocks in Thailand, particularly air temperature, relative humidity, and air speed.

2. Characterise typology and key features of typical apartments in Thailand

3. Establish the relationship between key features of typical buildings in Thailand and current occupants' perceptions with regard to their indoor environmental quality

4. Investigate the influence of external factors on natural ventilation in apartment blocks in Thailand. External factors include wind speed, apartment position within the building, building height, proximity/ direction and density of nearby buildings

5. Investigate the influence of internal factors on natural ventilation in apartment blocks in Thailand. Internal factors include room planning, room orientation, room inlet and outlet size, room outlet location, etc.

6. Create and validate design options to improve the indoor environmental conditions in residential apartment block in Thailand. The effectiveness of the designs will be evaluated using CFD and validated with built environment professionals in Thailand

1.4 Scope and Focus

Scope—Mechanical services for indoor environment quality impact carbon emissions (resulting in climate impacts) and affordability. They are not usually provided in multi-residential dwellings for low socio-economic groups in Thailand. The potential of passive design strategies to improve indoor environmental quality is being investigated for multi-residential dwellings in Thailand.

- The potential of passive design options is proposed based on Thailand weather data, current building standards and regulations.

- This study applies a combination of methods. Quantitative strategies include: physical measurement and monitoring to explore typical apartment features, statistical analysis of survey results on occupant perceptions, computational fluid dynamic analysis of airflow in the vicinity of the building and within the apartments, culminating in analysis of design options. Qualitative analysis is applied to the results of semi-structured interviews exploring the perceptions of the design options with built environment professionals in Thailand.

Focus - evidence indicates that key occupant concerns are:

- limited internal ventilation because of the single-sided ventilation window
- High relative humidity – in some cases resulting in mould formation

- Uncomfortably high temperatures in summer

This investigation proposes to explore the potential of passive design strategies to address these issues. Primarily aim will be to improve natural ventilation in typical multi-residential dwellings, for the climatic conditions in Chiang Mai, Thailand.

1.5 Thesis Structure

The thesis is structured in the following way:

Chapter 2 contains the literature review. The review covers the Thailand Climate and thermal comfort conditions. The effects of high relative humidity are considered. Practical passive cooling solutions in tropical climates are discussed. Previous solar chimney research and methods, which have been utilised in each research, are also examined and analysed.

Chapter 3 contains the Methodology. This chapter begins with research methods and selected methods in relation to research objectives. Then, each method is explained, including physical measurements, questionnaire, selection of criteria to be analysed, Computational Fluid Dynamics (CFD) analysis, and interview.

Chapter 4 analyses the results of physical measurements and considers how internal parameters affect occupants' room perception in Thailand. The result is employed to validate CFD in relation to site data.

Chapter 5 covers the results of occupant perception survey. This chapter starts with the reliability of the survey, then the analysis of demographics, physical environment factors and perception and satisfaction of occupants. The typical apartment block characteristics are discussed.

Chapter 6 contains discussion of external CFD sensitivity analysis. The external factors influencing on natural ventilation of apartment blocks in Thailand are discussed.

Chapter 7 contains CFD sensitivity analysis of internal apartment blocks. Typical apartment block characteristics derived from the resident questionnaire (Chapter 5) are used as a base case for investigating the internal factors of the apartment room's natural ventilation. CFD is used to investigate each scenario. The analysis of the natural ventilation influencing factors is developed to be framework of passive design strategy for apartment dwellings in Thailand.

Chapter 8 analyses the consultation on the design options with Thai built environment professionals.

Chapter 9 discusses the thesis. This chapter compares the research results to those in a related field and discusses the significance of the study.

Chapter 10 concludes the thesis and provides suggestions for future research.

Chapter 11 includes references

2 Literature Review

2.1 Introduction

According to the research issue presented in Chapter 1, multi-residential buildings in Thailand's urban areas typically have low indoor environmental quality (IEQ). This issue adversely affects vulnerable or economically disadvantaged populations, which tend to reside in places with poor environmental conditions. Low socioeconomic groups, in particular, have worse health conditions as a result of inadequate IEQ, emphasising the need for cost-effective solutions to the problem. Given this demographic's socioeconomic limits, deploying typical HVAC systems may be prohibitively costly. As a result, passive design emerges as a potential and practical solution.

Passive design strategies play a crucial role in leveraging natural elements and climatic conditions to effectively regulate temperature, humidity, and airflow within buildings (Bhamare et al. 2019). This approach, when properly implemented, can significantly improve the indoor environmental quality (IEQ) of multi-residential buildings in Thailand. The effectiveness of passive design strategies is significantly influenced by the region's climate conditions. Therefore, to provide a comprehensive framework for this research, the literature review commences by delving into Thailand's climate, thermal comfort, and prevalent building challenges. This in-depth understanding of the context serves as the foundation for investigating applicable passive cooling strategies and exploring suitable materials within the Thai context. The subsequent review of methodology then delves into relevant studies.

This chapter presents a review of previous research and theories relevant to the research aim, focusing on the following topics:

- Thailand's climate and thermal comfort (Section 2.2): This section explores Thailand's climate and thermal comfort conditions. It involves a detailed analysis of temperature, relative humidity, wind speed, and wind direction and their implications for thermal comfort.
- Dehumidification (Section 2.3): This section includes a review of strategies for mitigating humidity in buildings and a recommended thermal comfort range for health benefits.

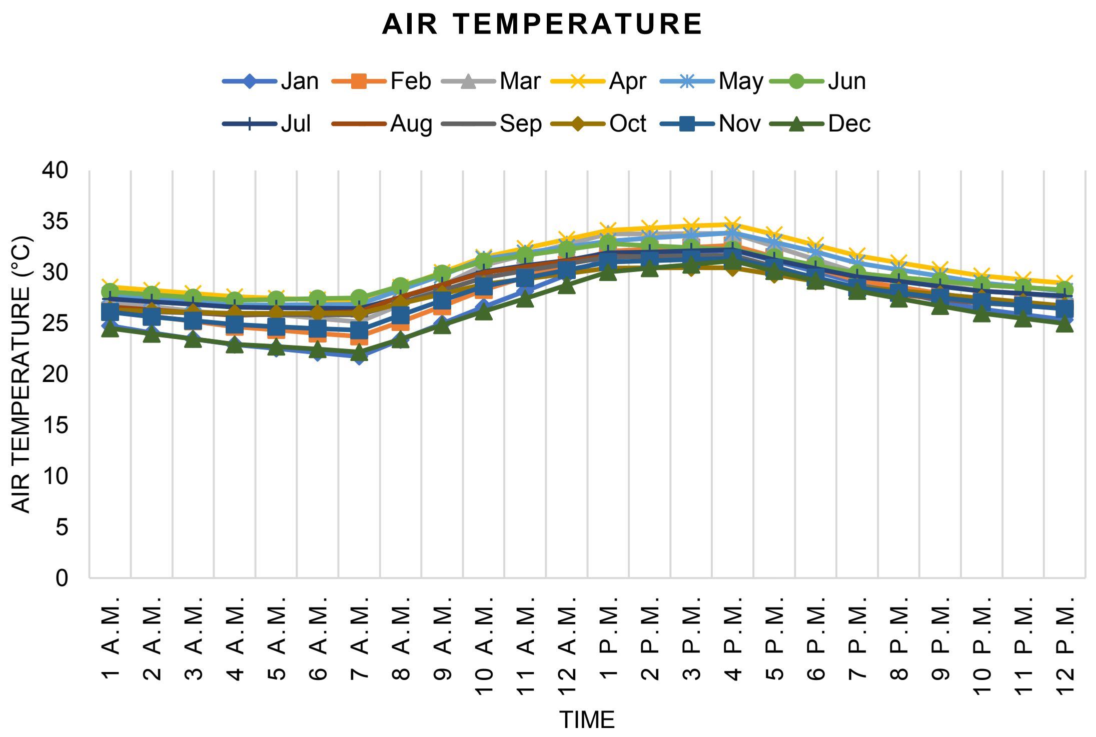
- Passive cooling theory (Section 2.4): This part of the literature review describes principles and relevant research on passive cooling. This includes analysing stack ventilation work, design principles and practices, and their effectiveness in various building contexts, emphasising solar chimney.
- Recycled materials (Section 2.5): Recycled materials can provide properties comparable to those of raw materials, while simultaneously contributing to environmental, and economical sustainability. This section provides material comparisons regarding thermal properties, embodied carbon, water vapour resistance, and reaction to fire.
- Summary and research gap (Section 2.6): This section provides an overview of the key findings from the literature review and addresses the research gap.
- Exploring research methods (Section 2.7): A review of methodologies employed in previous research is analysed and described in this section. This includes insights into both quantitative and qualitative methods. Three main phases of research method exploring includes 1) methods for investigating current situation about multi-residential building context 2) methods for exploring the potential design solutions by evaluating factors affecting natural ventilation performance and 3) methods for investigating design options.

2.2 Thailand Climate and Thermal Comfort

Thailand is a country in Southeast Asia classified as equatorial winter dry (Aw) inland and equatorial monsoon (Am) on the coast by the Köppen-Geiger climate classification. Most of Thailand has a tropical savanna habitat type while the majority of the south and eastern tip of the east have a tropical monsoon climate; besides, parts of the south have a tropical habitat (Beck et al. 2018). According to the Thai Meteorological Department, it is characterised by:

- high rainfall
- high humidity ranging average relative humidity around 68-76%RH (ThaiMeteorologicalDepartment), with more than 80%RH emerging almost 50% of the days in June, August, September and October (see Figure 2- 1)
- mean temperature range is relatively high, around 25.5-28.6°C throughout the year (ThaiMeteorologicalDepartment), with a maximum temperature of 34.69ºC in April (see Figure 2- 1)
- mean average daily global solar radiation is between 93.97-717.45 $Wh.m^{-2}$ (see Figure 2- 2)

Due to minimal temperature differences, the wind speed tends to be low (less than 4 $m.s^{-1)}$ (ThaiMeteorologicalDepartment 2014) (see Figure 2- 3, Figure 2- 4), resulting in poor air circulation in certain areas. The pattern of surface wind directions is featured by the monsoon system. The pattern of wind flow, stream flows and reducing wind acceleration at the ground level are changed by urban configuration; mainly, the velocity of wind around the area obstructed from other buildings or negative pressure areas is around 0.3-1.2 $m.s^{-1}$, which would cause discomfort of living from low natural ventilation rates (Stathopoulos 2009).



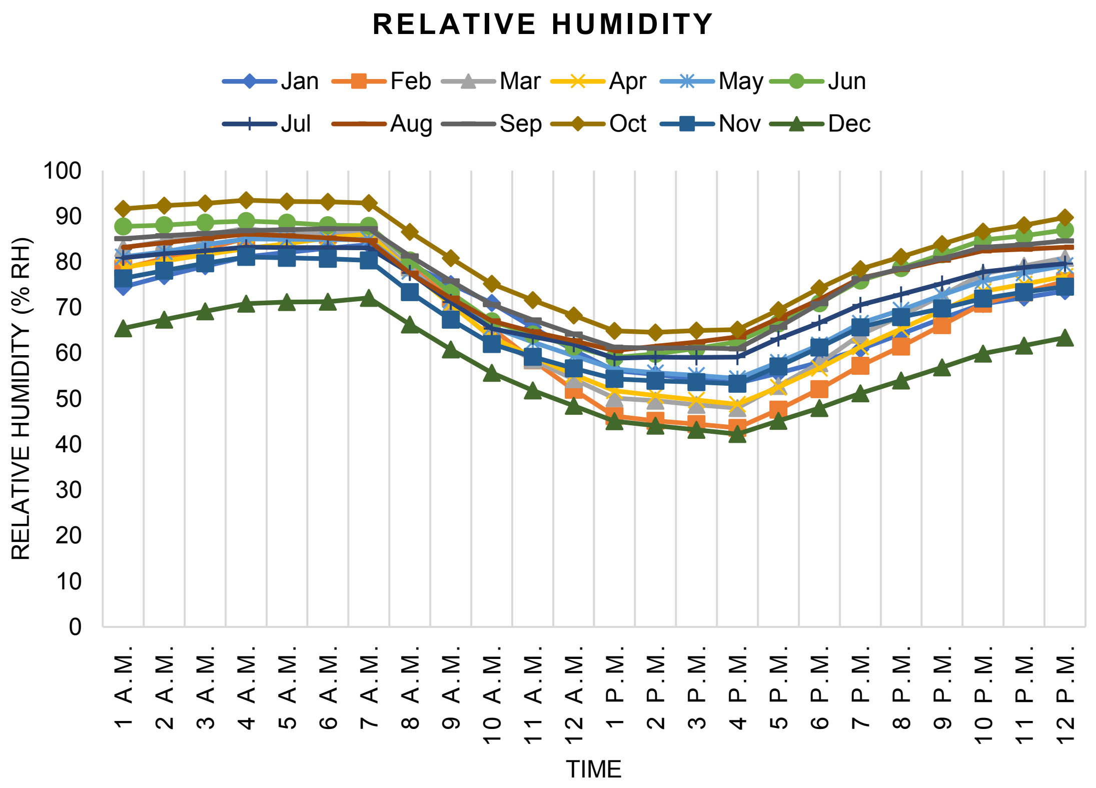


Figure 2- 1 shows the monthly average temperature and relative humidity of Thailand.
(Source: Author adapted data from Climate Consultant 6.0)

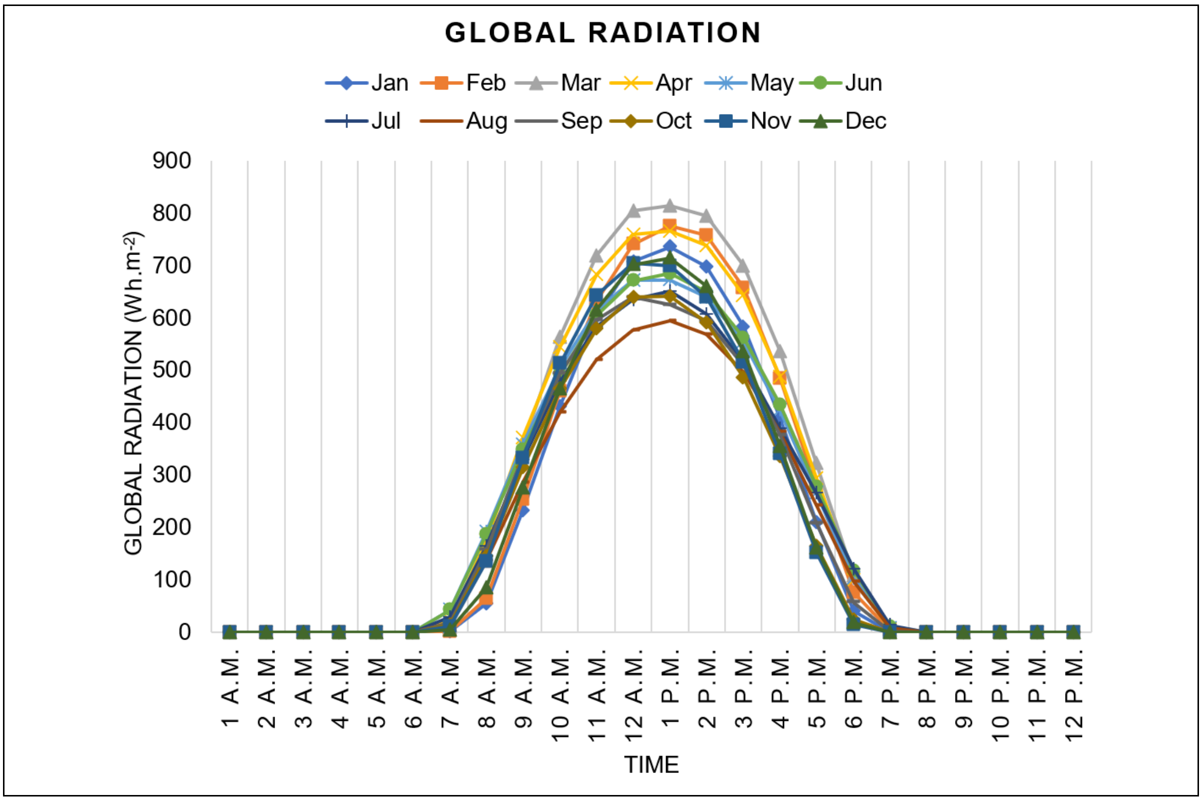


Figure 2- 2 shows the monthly average global radiation of Thailand.
(Source: Author adapted data from Climate Consultant 6.0)

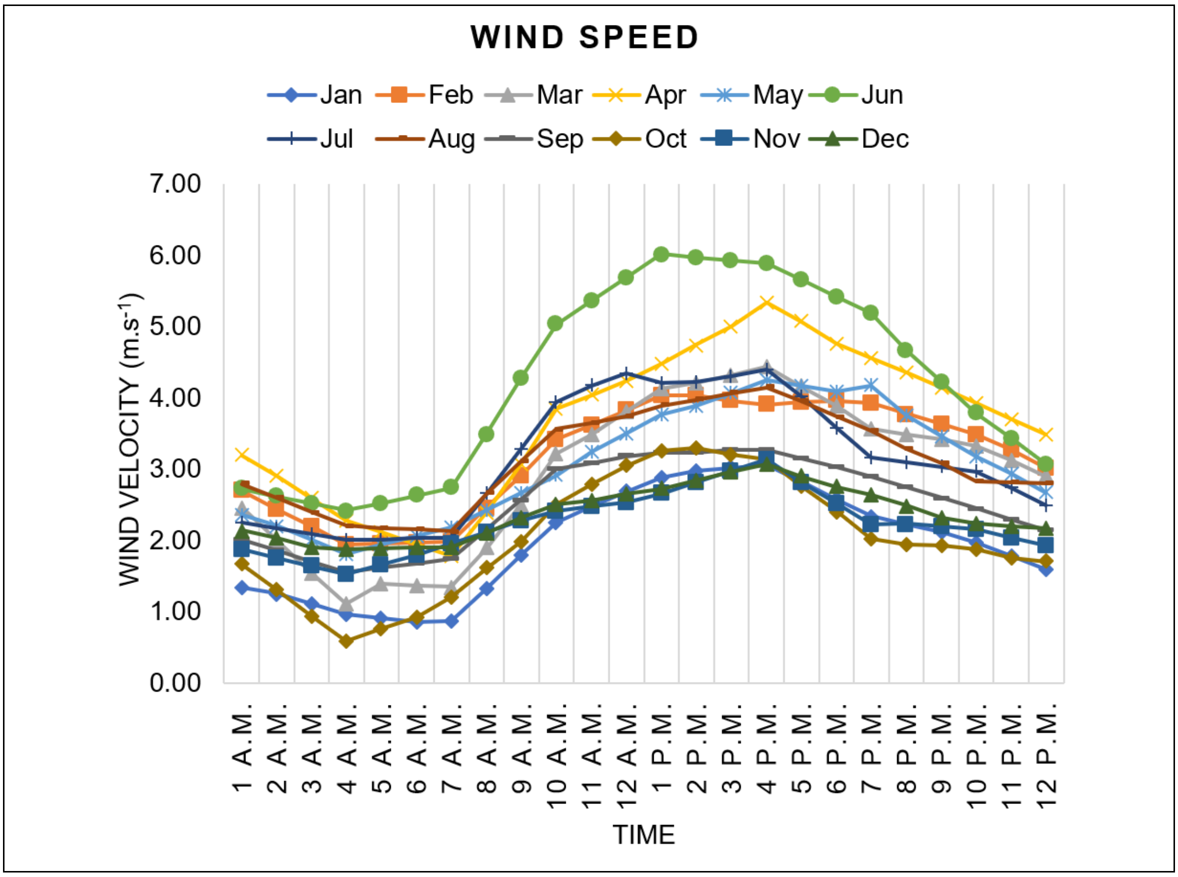


Figure 2- 3 shows the monthly wind speed in Thailand.
(Source: Author adapted data from Climate Consultant 6.0)

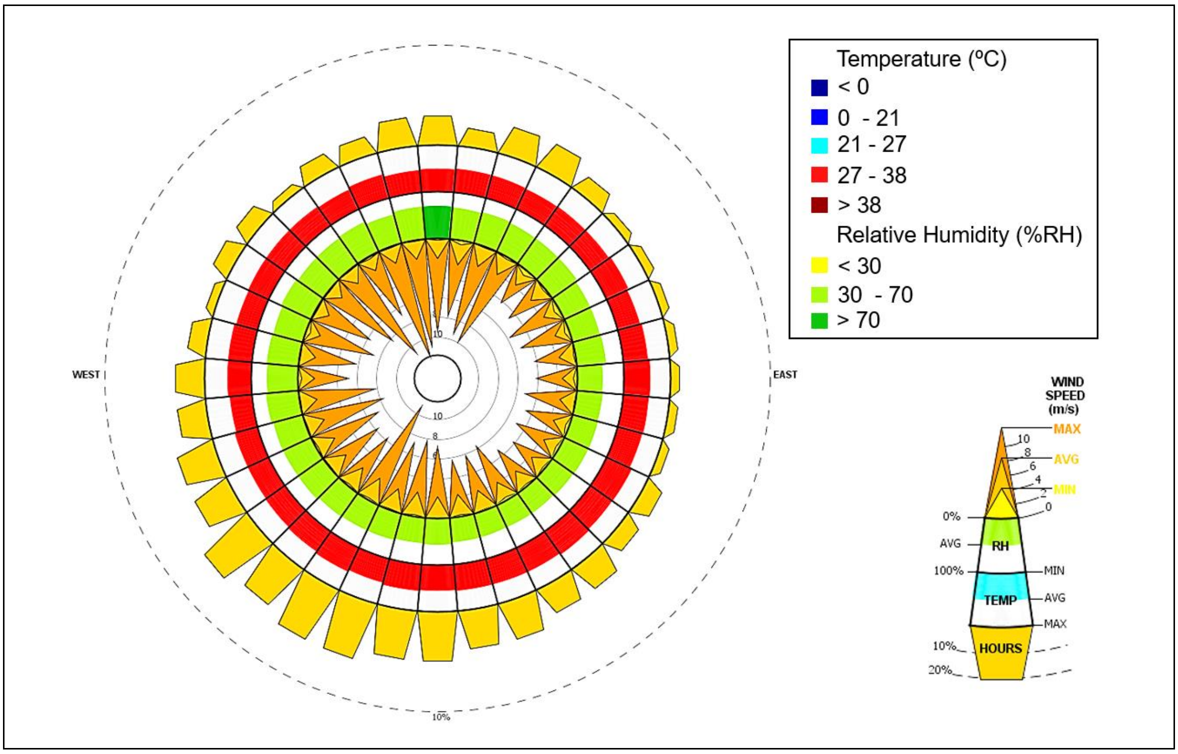


Figure 2- 4 shows the relationship between wind speed and direction in Thailand.
(Source: Climate Consultant 6.0)

2.2.1 Wind direction and wind speed

2.2.1.1 Wind direction frequency

Chiang Mai's wind data from Meteonorm 7.3.2 is analysed to determine annual and seasonal wind speed and direction distributions. The wind direction in Chiang Mai is highly directional. The most common wind in summer and winter blows from the south and north, respectively, while the wind frequently comes from both the south and south-west in the rainy season. The annual wind speed is commonly between 2-4 $m.s^{-1}$ (see Figure 2- 5). The wind speed rarely rises above 10 $m.s^{-1}$.

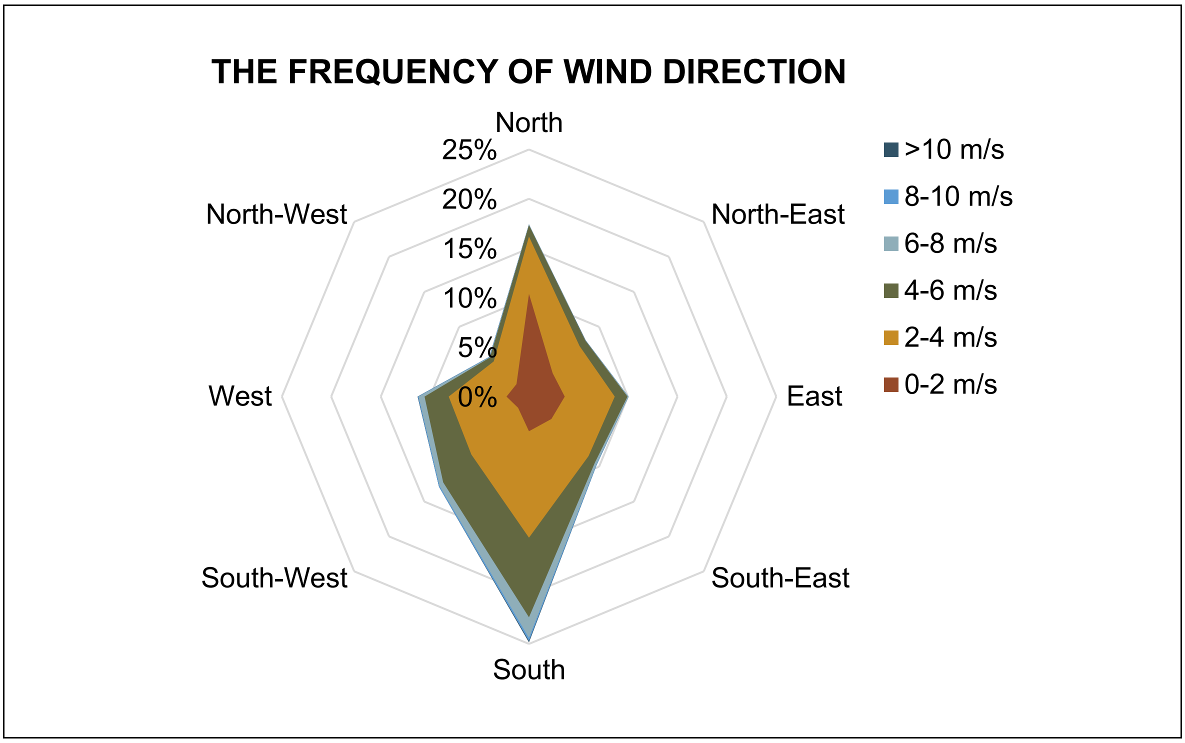


Figure 2- 5 The annual wind direction frequency in Thailand.
(Source: Author adapted data from Meteornorm 7.3.2)

Thailand's climate can be divided into three seasons which are:

- Summer (mid-February to mid-May)

The south wind mostly prevails over Chiang Mai in summer. The most common wind speed is between 2 to 4 $m.s^{-1}$. However, the wind rarely reaches above 8 $m.s^{-1}$ in this season (see Figure 2- 6).

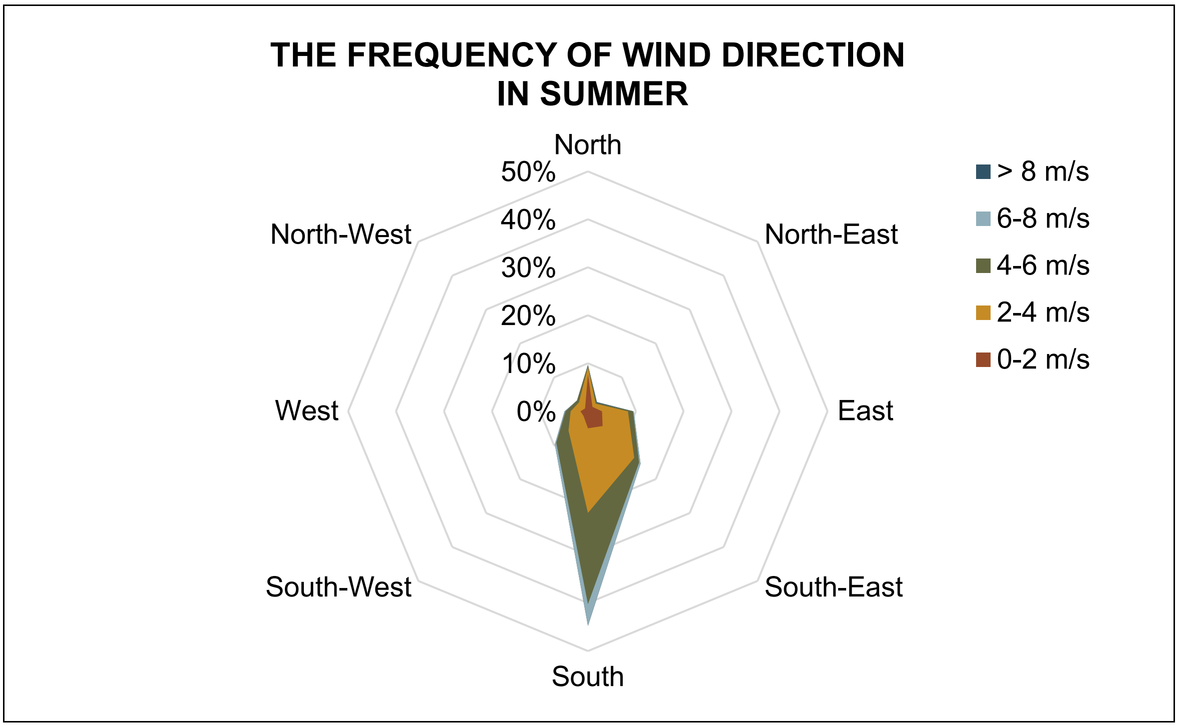


Figure 2- 6 The wind direction frequency of summer season in Thailand.
(Source: Author adapted data from Meteonorm 7.3.2)

- Rainy season (mid-May to mid-October)

The wind is almost coming from the south and south-west respectively. The most common wind speed is between 2 to 4 $m.s^{-1}$ (see Figure 2- 7). The south and the southwest never rise over 8 $m.s^{-1}$.

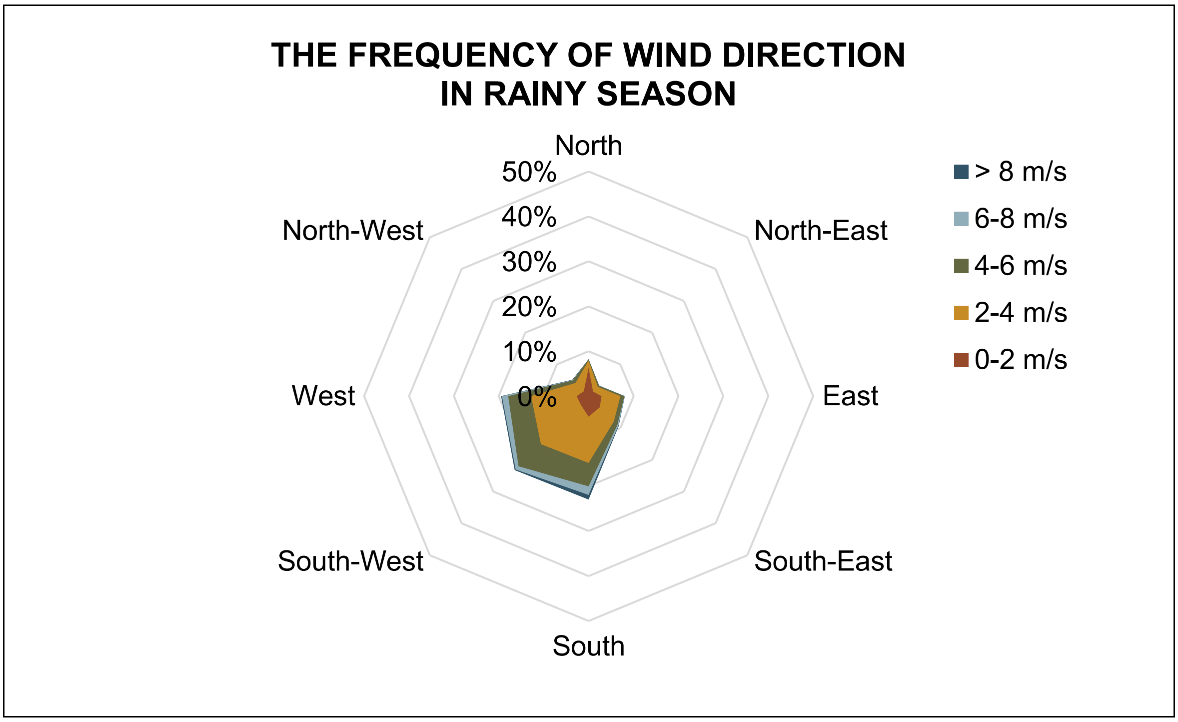


Figure 2- 7 The wind direction frequency of rainy season in Thailand.
(Source: Author adapted data from Meteonorm 7.3.2)

- Winter (mid-October to mid-February)

The wind direction frequency comes from North. The most common wind speed is yellow colour, which is between 2-4 $m.s^{-1}$ (see Figure 2- 8), in contrast, the wind hardly ever reaches above 8 $m.s^{-1}$ in this season.

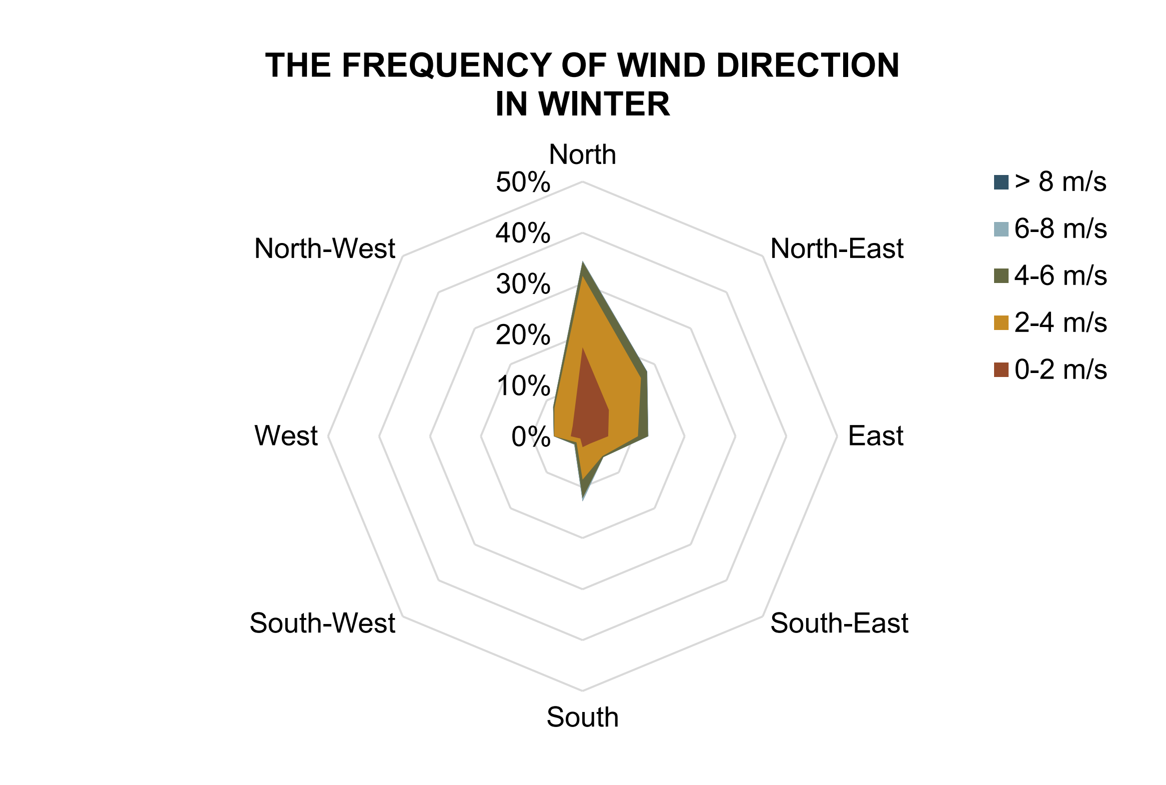


Figure 2- 8 The wind direction frequency of winter season in Thailand.
(Source: Author adapted data from Meteornorm 7.3.2)

The rapid growth of urbanisation creates congested locations, which has a significant effect on reducing wind velocities and changing wind patterns. Apartment blocks in a metropolis also interrupt the wind flow, which leads to insufficient air ventilation in the room (Ng and Cheng 2012; Gan and Chen 2016) (see Figure 2- 9). According to Thai's Ministerial Regulation No 55 of Interior Floor Building Control (Interior 2000), each unit of apartment must have a minimum area for dwelling purposes of not less than 20 m^2 and must have the height of not less than 2.6 m for a room used for residential purpose and 1.5 m for balcony, in addition, the minimum width of building corridor of the apartment is 1.5 m. In terms of natural ventilation system, Thai regulation no 39 indicates that a room in a free-running building must have a total area of doors, window or air vents on the side adjacent to outside air not less than 10 % of the area of such room, not including the area of the void adjacent to other room or corridor within the building (JapanInternationalCooperationAgency 2003). Indoor air speed in tropical climate conditions should be at least 0.4 m.s-1 to increase the evaporation rate of human skin for achieving thermal comfort, and the open planning design could improve air velocity inside buildings (Tantasavasdi et al. 2001), as cited in (Aflaki et al. 2015). However, apartment room planning with a double-load corridor in Thailand typically has single-sided natural ventilation, which can be categorised into three types (see Figure 2- 10). The single-sided ventilation design limits the indoor wind speed inside apartment blocks (Farea et al. 2012). These residential buildings are merely planned regarding the environmental and geographical matters; this, consequently, leads to inefficient thermal comfort of the residents (Humphreys 1978). Since the effective depth for single-side natural ventilation is a measure of the extent of fresh outside air into living space, the deepest from penetration in certain rooms can decrease fresh air velocity until 0 $m.s^{-1}$ (Allocca et al. 2003).

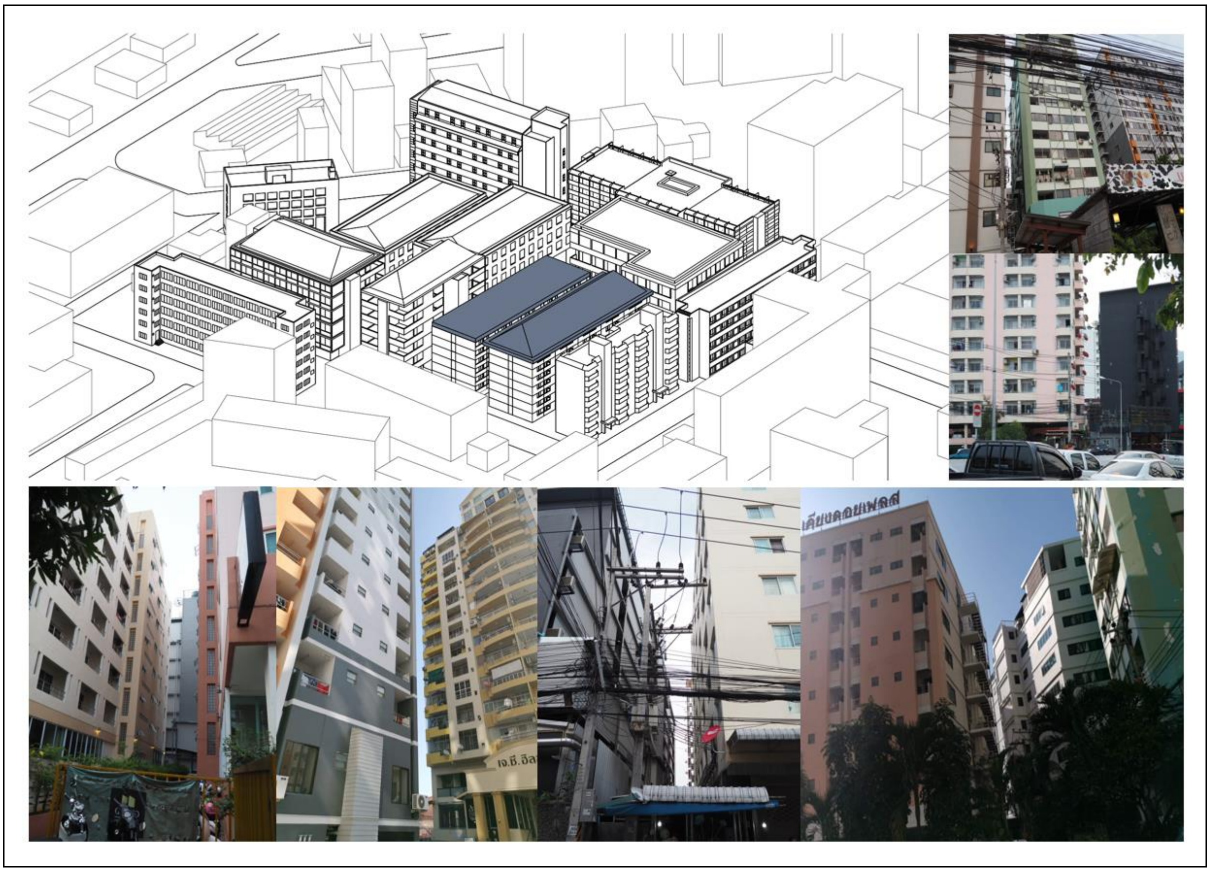


Figure 2- 9 Sample features of the actual situation of complex and dense residential buildings in Thailand's urban areas
(Source: Author)

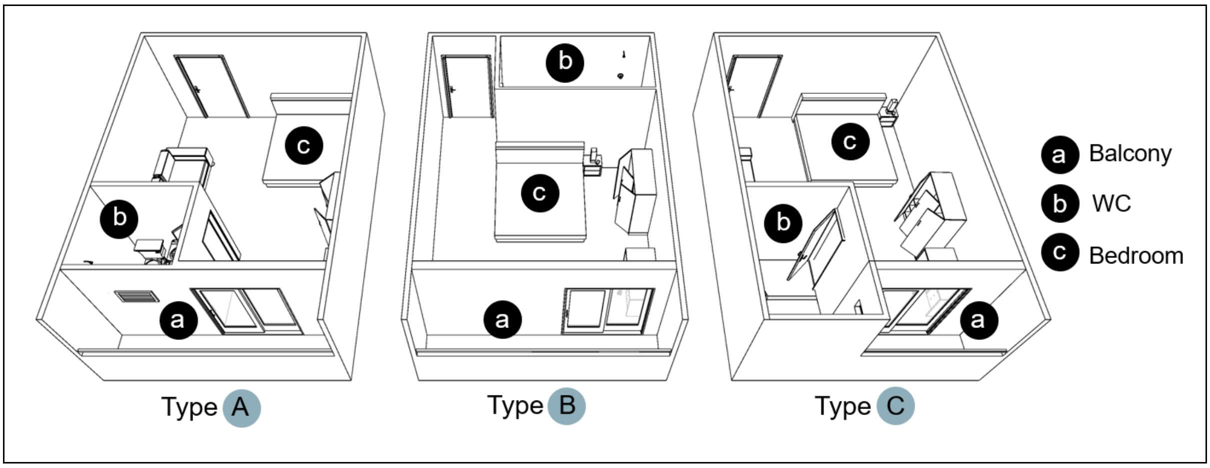


Figure 2- 10 Three room typologies constructed in the urban areas in Thailand, especially among low socioeconomic residential building zone.
(Source: Author)

Thermal Comfort is generally based on the inhabitants' satisfaction with thermal sensation with certain environmental factors, including mean radiant temperature, air movement, air temperature, humidity, the activities being performed and the clothes worn (Fanger 1970), which is also a key parameter for healthy indoor air quality (Wagner et al. 2007). Bio-Climatic Chart was the first graphical thermal comfort index conducted by Olgyay in 1963; it was intended to apply to free-running buildings with natural ventilation and suggested that the summer comfort range could be shifted to higher relative humidity and temperature as wind speeds increase. The boundary of the comfort zone of the chart had been defined in the dimensions of 21-30 °C and 30-65%RH (Jitkhajornwanich 2006). In 1976 Givoni argued that the chart was only effective for less difference between indoor and outdoor temperature level or lightweight building. Givoni published a new chart called Building Bio-Climatic Chart, which showed the relationship between indoor temperature and passive design strategies and suggested that passive cooling could provide indoor thermal comfort for living in tropical areas. Many researchers attempt to find a thermal comfort prediction in the form of a single index, such as Fanger's proposed Predicted Mean Vote (PMV) (Fanger 1970). An extension of the PMV was suggested as an expectancy factor for naturally ventilated environments in hot regions (Fanger and Toftum 2002; Sadafi et al. 2011). Alternative theory, some researchers addressed that ASHRAE Standard 55, an adaptive model of thermal comfort for naturally ventilated building, is more practical than ASHRAE RP 884 because of the longer-term seasonal data collected (De Dear and Brager 2002; Toe and Kubota 2013). However, ASHRAE Standard 55 is effective in winter conditions, with a mean radiant temperature (MRT) above 19°C (Andrew Corney et al. 2018). Many thermal comfort studies have discovered that the comfort ranges differed from the predictions of the thermal comfort standard based on the predictive equation. Thermal satisfaction is a complex subjective response to the environment, meaning the range of thermal comfort is not fixed (Djongyang et al. 2010). It depends on the perception of people and climate factors indicated by a new thermal comfort zone. Recent studies review the perception of the thermal comfort level of people who live in tropical regions, which may be more acclimated to their environment and shift their thermal comfort sensation from other climates(Busch Jr 1990). Additionally, once acclimated with heat tolerance, body performance in heat improves, so the time to reach a state of body exhaustion can double(González-Alonso et al. 1999).

Due to the acclimatisation effects, Jitkhajornwanich, 2006, who surveyed, measured and distributed questionnaires of thermal sensation and responses from Thai people in vernacular buildings, thermal comfort could be shifted into a new dimension which reported that 25.6-31.5 °C for temperature range and 62.2-90.0% RH for relative humidity which was higher in the range of temperature and relative humidity than the original Olgyay's comfort zone (Jitkhajornwanich 2006). This new comfort zone might be acceptable for the thermal comfort range in tropical climates; however, a significantly higher percentage of relative humidity can contribute to mould growth in buildings. Other field studies in naturally ventilated buildings in tropical climates are presented in Table 2- 1. These showed that the range of temperature, relative humidity and indoor air velocity preferences were 21-35°C, 20-90%RH and 0.09-1.60 $m.s^{-1}$, respectively. Tantasavesdi et al. recommended that the upper limit of thermal comfort in Thailand can be extended to 29.1°C, 29.9°C and 31.3°C when increasing airspeed of 0.2 $m.s^{-1}$, 0.4 $m.s^{-1}$and 1.0 $m.s^{-1}$respectively (Tantasavasdi et al. 2001). In tropical areas, people tend to prefer more air movement between 0.3 $m.s^{-1}$and 0.9 $m.s^{-1}$ when air temperature ranges from 28-34 °C and the humidity exceeds 60%RH (Gong et al. 2006; Buonocore et al. 2018). The upper-temperature limit can rise by 1 °C when increased air speed of 0.275 $m.s^{-1}$. ASHRAE 2017 identified the optimal airspeed range for the cooling effect to be between 0.2 $m.s^{-1}$ and 1.0 $m.s^{-1}$ (ASHRAE 2017). The required ventilation rate was 10 L.s-1 or 0.01 $m^3.s^{-1}$. In addition, the required airspeed for light or primarily sedentary activities should not exceed 0.8 $m.s^{-1}$. The Bio-Climatic chart also suggested that natural cooling can maintain indoor thermal comfort. It allows for adjustment of air temperature, defining thermal comfort zone regarding acclimatisation effects. Therefore, this research has selected this thermal comfort range as a baseline and applied it as a criterion for the study in CFD sensitivity: indoor (Chapter 7). The annual relationship between temperature and relative humidity of Thailand on the Bio-Climatic chart shows that a great number of the times are out of the “accepted” comfort zone (See Figure 2- 11). The temperature ranges between 22.3°C and 29.3 °C. Relative humidity ranges from 20 %RH to 80%RH. Natural ventilation from 0.2 $m.s^{-1}$ to 1.0 $m.s^{-1}$ can extend the thermal comfort range to 22.3°C-34.3 °C and 20%RH-100%RH (Givoni 1992).

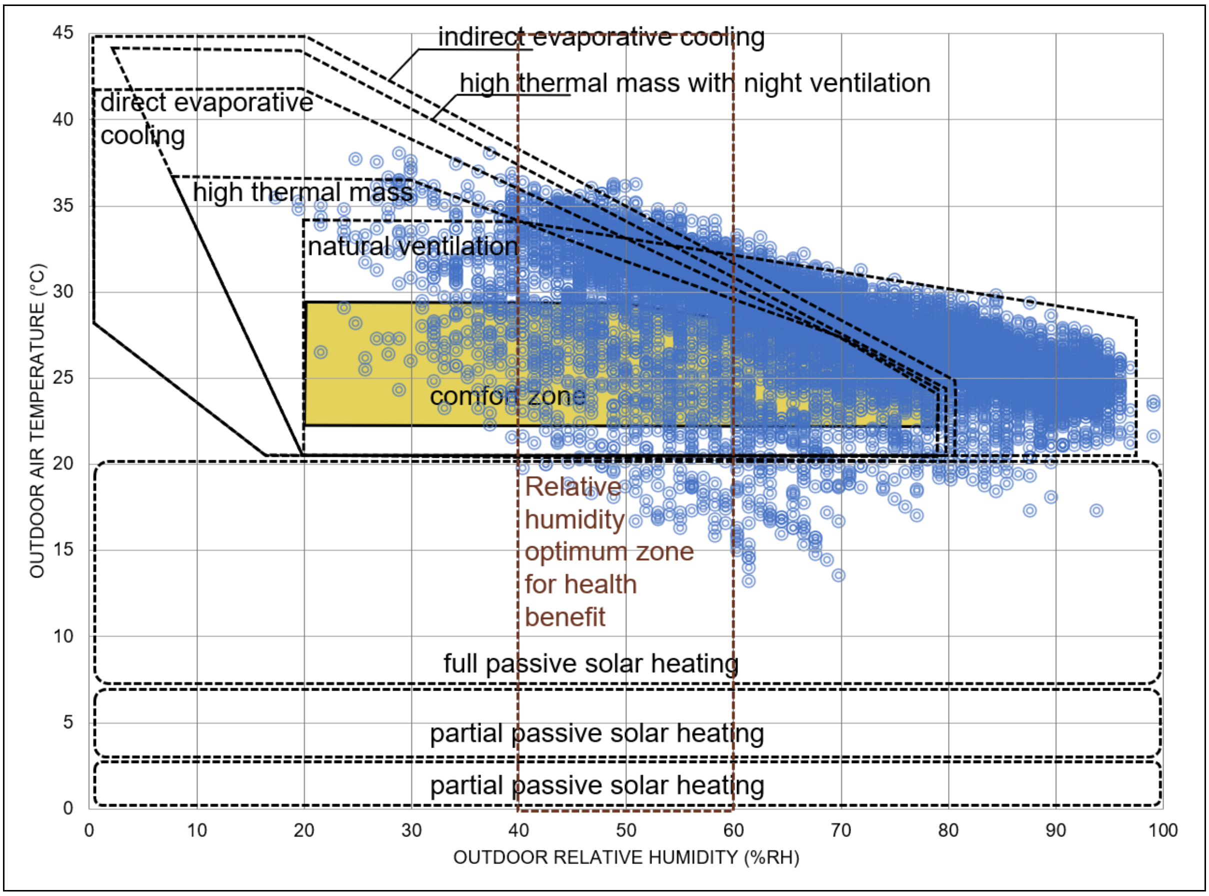


Figure 2- 11 Annual relationship between outdoor air temperature and outdoor relative humidity in Thailand
(Source: Author adapted data from Climate Consultant 6.0)

Table 2- 1 Thermal comfort preference in ventilated buildings in tropical climates

Year	Building Type	Type of Study	Location	Air Temperature (°C)			Relative Humidity (%Rh)			Air Movement (m.s^{-1})	Ref.
				Min	Max	Average	Min	Max	Average	Min-Max	
1963	Residential			21.0	35.0		35.0	65.0		0.10.-0.40	(Olgyay 2015)
1976				20.0	30.0		20.0	80.0		2.00	(Givoni 1992)
1991		thermal chamber	Singapore			27.9			70.0		(De Dear and Leow 1990)
1998	Educational	field study	Malaysia			26.3			73.0		(Zain-Ahmed et al. 1998)
2000	Educational	field study	Bangkok			27.2	70.0	80.0		0.20	(Khedari et al. 2000b)
2003	Residential	field study	Bangkok	25.6	31.5		62.2	90.0			(Jitkhajornwanich 2006)
2010	Educational and Residential	field study	China	23.5	27.4				70.0		(Zhang et al. 2010)
2013	Office	field study	China			30.0			60.0	1.60	(Zhai et al. 2013)
2018	Residential	thermal chamber	China	22.9	30.7		50.0	70.0			(Zhang et al. 2018)
2018	Educational	field study	Brazil	29.0	30.0				60.0	0.20-1.00	(Cândido et al. 2011)
2019	Educational	field study	Mexico	25.6	28.2		48.8	60.0		0.09-0.17	(López-Pérez et al. 2019)
2019	Educational	field study	Mexico	26.7	31.9		48.8	60.0		0.11-0.17	(López-Pérez et al. 2019)

Poor natural ventilation is reported as a significant challenge to residential occupancy, which increases the chance of indoor mould growth and also increases sick building syndrome, such as increasing respiratory illness, short-term work absence among office workers, and other health illness (Milton 2000; Heseltine and Rosen 2009). To explicate this notion, referring to Juangjandee, 2017 collected data of outdoor and indoor temperature and humidity level of the room in complex residential buildings area, Thailand; it shows that the temperature and humidity level outside the apartment are inverse relation. However, the result in indoor area is that the temperature is stable with a typical indoor humidity level of 80% RH which exceeds the comfort zone of bio-climatic chart (see Figure 2- 12). Moreover, mould can be found in these places (Juangjandee 2017). Sedlbauer showed that the internal air temperature 20-30°C along with the humidity 80%RH occurring at least 6 hours was the ideal range of enhancing mould growth in buildings (Sedlbauer 2001). Udawattha et.al addressed that poor ventilation in building, tropical climate, with the circumstances of temperature from 15 to 30°C and relative humidity above 60%RH could promote mould emergence (Udawattha et al. 2018). The majority of mould proliferation is due to environmental and climatic condition.

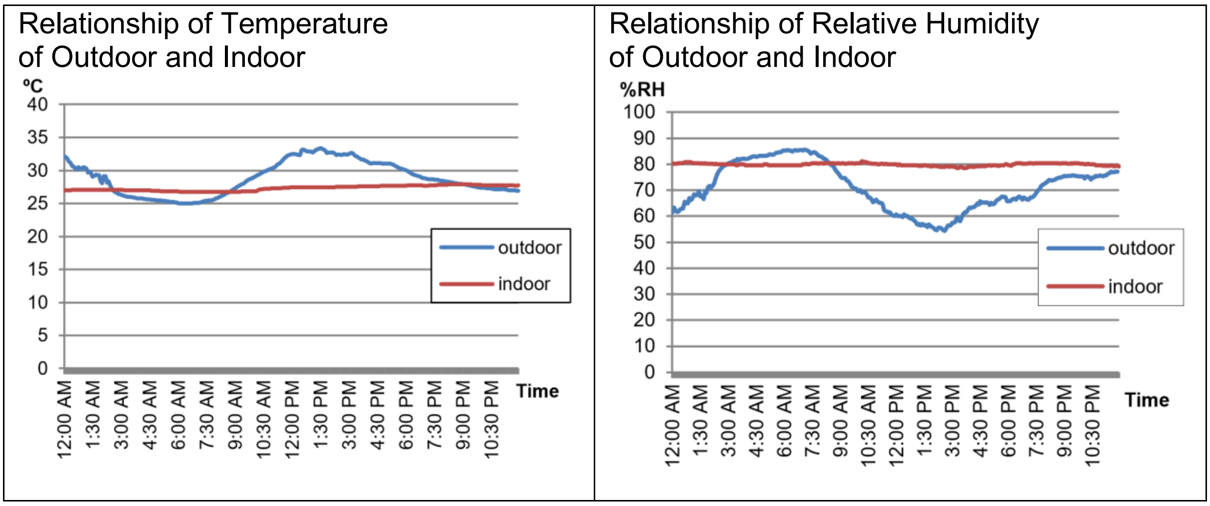


Figure 2- 12 Temperature and Relative Humidity Level of Outdoor and Indoor Complex Residential Buildings
(Source: Juangjandee, 2017)

2.3 Dehumidification

World Health Organisation (WHO) 2019 identified “Moisture can be transported in both vapour and the liquid phase by diffusion, convection, capillary suction, wind pressure and gravity”(Othman et al. 2015). Moisture influences the performance and durability of building materials, and moisture transmission significantly impacts the construction and maintenance of buildings (Cengel 2007). Environmental Protection Agency (EPA), 2013 recommended 2 ways of controlling moisture problems: preventing water condensation and limiting wet areas (Othman et al. 2015). Basic humidity parameters can be defined into 3 types (Cengel 2014);

1. Specific humidity (γ) is the mass of water vapour to total mass of the moist air
2. Absolute humidity (dv) is the water vapour density
3. Relative humidity (ϕ), is one of the humidity parameters involving saturation, is the percentage of water vapour in the room air relative to the total amount of vapour in the same atmospheric room air at a particular temperature and also a measure of air ability to absorb moisture. Warm air can hold more moisture than cold air, which means that the capacity to hold moisture increases following the increase in temperature. While the moisture content remains the same, relative humidity decreases.

Relative humidity is considered as a significant impact on human thermal sensation and thermal comfort; for example, people would feel hot and sticky and skin moisture tends to increase discomfort at high relative humidity in tropical climate(Level 2017).

In addition, when the internal space of buildings reaches high relative humidity levels for long periods, this can lead to mould and bacteria growth in such rooms. Building occupants may notice odours and various health problems such as breathing difficulties, allergic responses and aggravation of respiratory. Furthermore, in hot and humid climates, even air conditioning units are unable to control latent load and relative humidity of the exceeding thermal comfort (Karagiozis and Salonvaara 2001). While Thai' shifted thermal comfort informed that the range of satisfactory in relative humidity was 62.2-90.0% RH, many researchers suggested that the relative humidity should be between 40-60%RH in habitable areas to minimise bioaerosols' growth level (see Figure 2- 13). This rises the need of specific building design or application to reduce the internal moisture in the air.

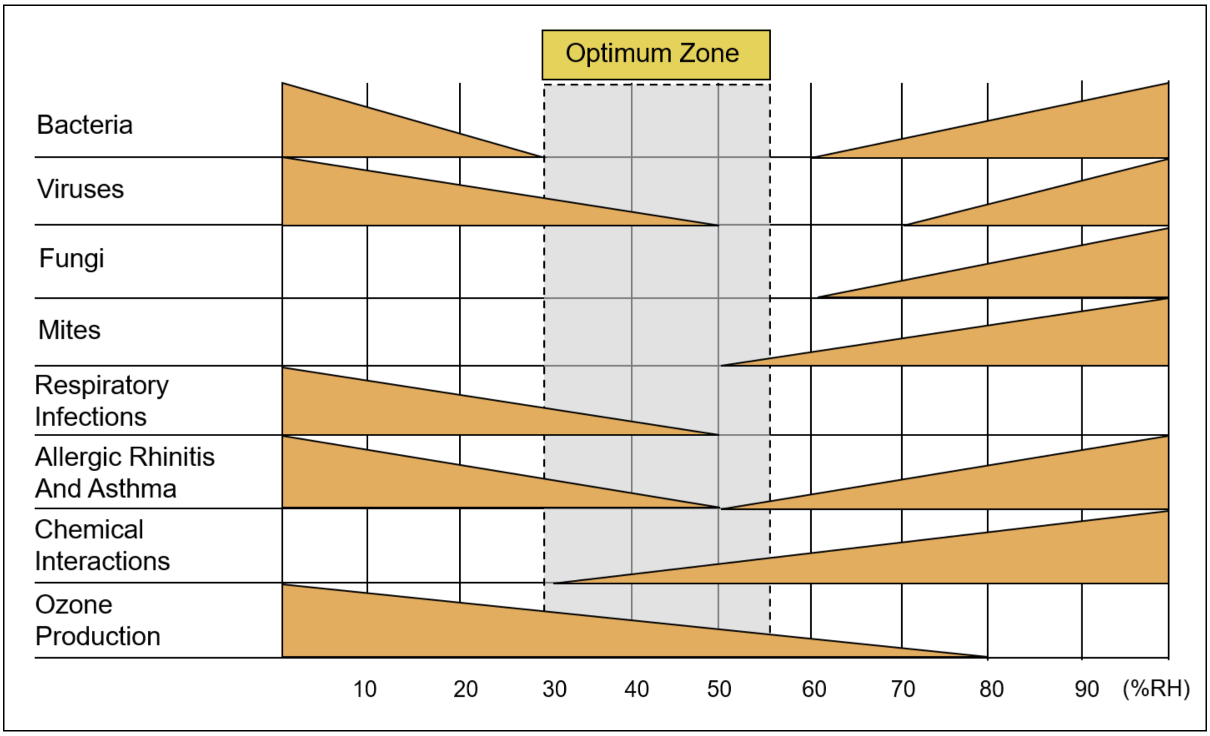


Figure 2- 13 Recommend indoor relative humidity for optimal health benefit (Source: Arundel et.al, 1986)

Relative humidity has a significant effect on thermal comfort since it is a measure of air ability to absorb moisture, besides human body dissipate heat through the evaporative process (Cengel 2007). High relative humidity reduces heat rejection by evaporation while low relative humidity spurs it up. According to the bio-climatic chart representing relationship between temperature and moist air, relative humidity can be curbed by raising indoor temperature or reducing moisture content (Davies 2004). Raising indoor temperature is the strategy of increasing the air capacity comparing with the moist air in such rooms, this solution is not suitable for occupied space in tropical climate because it would bring people feel overheated which leads to discomfort. In tropical area, ventilation plays the key role in heat exchange between body and the environment. Indoor moisture content can be reduced to outdoor levels by inducing the air movement. This also has the advantage of making human body can feel cooler (1 ºC temperature reducing for air movement of 0.6 $m.s^{-1}$) (Khat et al. 2015).

The ventilation factor also causes air and moisture to flow through building openings. However, naturally ventilated buildings tend to receive thermal diversity and extend a wider range of thermal perceptions, both preferences and tolerances. The appropriate air movement is required to achieve a comfortable condition.

2.4 Passive Cooling

Passive Cooling refers to the techniques used to transfer indoor heat to natural heat sink (Santamouris and Asimakopoulos 1996) . These techniques aim to provide a satisfactory level of comfort condition with minimum energy consumption. Passive cooling techniques can be categorised into 5 methods, which is heat avoidance, earth coupling, evaporative cooling, radiative cooling and ventilative cooling (Cook 1989).

- Firstly, heat avoidance is classified into microclimate and solar control-based methods. The building microclimate is significantly affected by the atmospheric condition around the building, such as designing a landscape or green roof for achieving internal cooling effect and using roof pond to reduce heat flux. Solar control is the technique of reducing internal solar heat gains and achieving more efficient daylight through building envelopes, such as shading devices, aperture control, glazing design and building orientation. This method is suggested for high solar radiation areas, such as Thailand.
- Secondly, earth coupling is useful in temperate climates where the ground temperature is in the comfort zone. The average Thailand ground temperature (26.1-29.2ºC (ThaiMeteorologicalDepartment)) is the upper limit of the comfort zone which is probably unsuitable for Thailand.
- Thirdly, evaporative cooling is commonly used in hot-dry and temperate climates where the sensible heat in the air stream can easily exchange for the latent heat of wet surfaces. This method is unsuited for buildings in tropical climates like Thailand because of further mould problems.
- Fourthly, radiative cooling is the process of diurnal heat absorbing and then radiating to the cooler or night sky which is limited in hot-dry climates (Bhamare et al. 2019).
- The last method is ventilation for passive cooling, which uses surrounding air as a heat sink, dissipating the excess heat of the building to atmospheric air via various modes of air movement. The ventilation technique is normally used in tropical climates for physiological cooling by promoting convective heat transfer and evaporative heat loss from the human skin and preventing thermal discomfort due to moist skin (Sreshthaputra 2003; Prajongsan and Sharples 2012). Additionally, increasing the ventilation rate can reduce the condensation

rate, which is a major factor in mould proliferation in buildings (Silveira et al. 2019).

Ventilation is considered the most applicable to the tropical climate of Thailand and will be considered in more detail in Section 2.4.1.

2.4.1 Natural Ventilation for Passive Cooling

Natural ventilation potential, as a passive cooling strategy in building, is based on air movement from three climate phenomena, namely wind speed, wind direction and the temperature difference between indoor and outdoor air. This is seen as an effective method to increase the degree of thermal comfort, reduce operation costs and improve air quality and a viable alternative to air conditioning (Aflaki et al. 2015). According to experimental analysis of residential ventilation, Zhang suggested that high relative humidity can be reduced by increasing natural ventilation (Zhang et al. 2019). Natural ventilation can be categorised into 2 types which is 1) wind force and 2) stack effect ventilation of thermal force.

2.4.2 Wind Force Ventilation

The operation of wind force ventilation is closely related to the position of opening in the space to be ventilated. These can be considered as cross and single-sided ventilation.

Cross ventilation is normally the primary strategy for cooling building, for example opening on different walls, where the amount of air going inwards and outwards through the different apertures. While single-sided ventilation is known to be less efficient than cross-ventilation because it is difficult for wind to move inwards and outward through the same opening on the same side of the building (Caciolo et al. 2011) (see Figure 2- 14a, b).

Considering this in application, we find that apartments with double-loaded corridor often have to rely on one opening to a space and therefore, only have single-sided ventilation. For some periods in tropical climates, there are less difference of air pressure between inside and outside buildings, limiting air movement (Wahab and Ismail 2012). In addition, over the past few decades, passive ventilation strategies are less practiced in complex residential buildings since the wind-flow is obstructed by the surrounding buildings in high density urban areas (Rajagopalan et al. 2014). People normally spend the majority of their time indoors, and most of the time spent indoors is at their residences (Klepeis et al. 2001). Unfortunately, the space and air ventilation in an apartment are limited, resulting in inadequate indoor environmental quality (IEQ), which would affect the occupants wellbeing (Nitmetawong et al. 2019). Due to the many limitations, wind forced ventilation can only applied to certain climates conditions (Levermore 2002; Allocca et al. 2003). Architects tend to continue design free-running buildings to obtain a maximum of natural ventilation without a proper understanding in climate patterns. The penetration can even bring unwanted heat and moisture from outside the building causing decrease the indoor comfort condition, especially when the outdoor temperature is higher than the indoor temperature, the room tends to receive more heat from the rule of heat transfer. Hence, this should make more natural forces of wind or buoyancy to introduce fresh air and distribute it into buildings for the benefit of the occupants (Sreshthaputra 2003).

Faced with these difficulties, it is appropriate to investigate stack ventilation as an alternative strategy to provide air flow through the space.

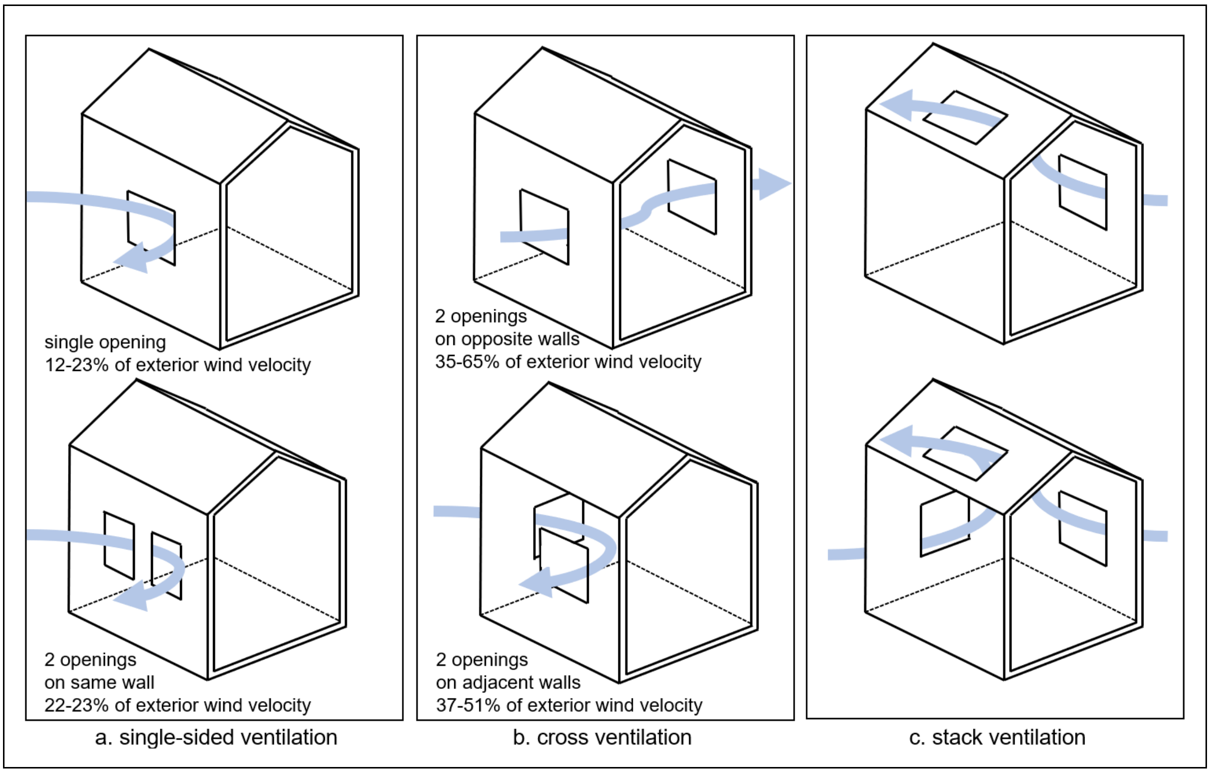


Figure 2- 14 Different types of ventilation: a. single-sided ventilation, b. cross ventilation and c. stack ventilation.
(Source: Author adapted data from Dekay,2014)

2.4.3 Stack Ventilation

Stack ventilation relies on the difference between the air pressure at upper and lower levels and is sometimes called buoyancy-driven flow (see Figure 2- 14c). Whereas previous research concurred that cross ventilation is more effective than stack ventilation in tropical regions, indoor air of single-sided ventilated room still fewer differences in temperature between the indoor and outdoor environments (Aflaki et al. 2015)Buoyancy-driven flow can enhance the effective ventilation pass through the single-sided ventilation room design. The efficiency of these techniques depends on significant factors, such as the temperature difference, vertical distance between inlet and outlet, pressure discrepancies between the leeward and windward sides of a building, and other factors like building material, internal layout, and division.

Previous studies showed that stack ventilation in building can replace hot and moist air with fresh air. Aflaki et al. reviewed that ventilation shaft as a component of building façades can improve the performance of buoyancy-driven ventilation of the building in the tropical region (Aflaki et al. 2015). Prajongsan and Sharples investigated that the average wind speed in the room without a ventilation shaft was insufficient to produce a cooling effect in Bangkok tropical climatic conditions compared with the room with the ventilation shaft installed. The ventilation shafts could extend comfort level hours by 37.5-53.6 % (Prajongsan and Sharples 2012). Termah and Shenashir showed that buildings in compact urban areas in Iran could have more air circulated by the application of ventilation shaft which was suggested for tropical climate (Aflaki et al. 2015). Much research provided information that storey buildings could improve indoor air quality and comfort conditions and reduce energy use in buildings.

While natural stack ventilation can offer a weak stack effect, various passive strategies have been proposed to enhance the buoyancy effect to achieve a satisfactory degree of thermal comfort, such as a Trombe wall, double-skin façade, and solar chimney.

Trombe wall is the strategy of absorbing solar energy. The energy can be used for heating at a later time and at the same time to power a convection current in the building (Zamora and Kaiser 2009). Trombe wall mainly consists of an exterior glazing cover, a massive wall and an air channel between them (Zhang et al. 2016) (see Figure 2- 15). The stored solar heat gained is released to the indoor space through heat conduction, convection and radiation between massive wall and indoor space. In part of air circulation, the low temperature air from the room enters into air gap through the lower vent, then is heated and flows up and returns back to the interior space via upper vent with high temperature(Zamora and Kaiser 2009). Trombe wall can be adapted to different climates such as hot-dry and temperate regions. However, the radiated part of Trombe wall would promote over-heated interior space in the tropical areas due to the reversing thermo-circulation. Many researchers have studied to improve the efficiency of the Trombe wall. For example, they propose reducing heat loss in the wall, extending the transferring time of the solar absorption, enhancing the air flow rate in the air channel, and implementing a Trombe wall for dehydrating fruit (Dimoudi 2009; Zhang et al. 2016).

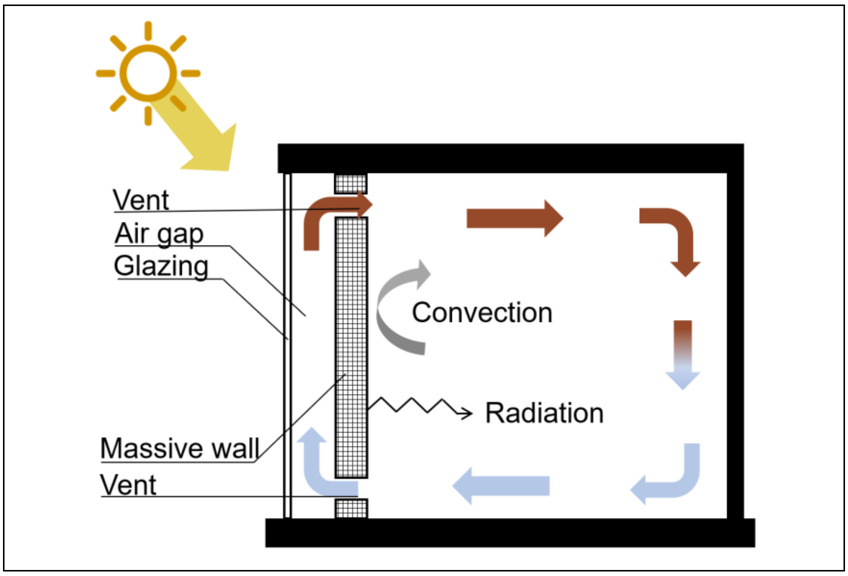


Figure 2- 15 Schematic diagram of Trombe wall
(Source: Author)

Double-skin façade (DSF) is defined as a particular type of exterior building envelope comprising an external glazing layer, an air cavity and internal plane glass (Barbosa and Ip 2014). The air movement in the air gap is mainly due to the buoyancy of the warm air inside the cavity compared to the cooler air outside. The air inside the cavity is heated by solar radiation and then exhausted to the top of the cavity which is adapted for improving thermal condition under various climates. In cold regions, DSF is expected to provide heat exchange and store heat in the internal skin layer to improve thermal comfort; in contrast, DSF can reduce solar heat gain in the hot regions for the desirable indoor temperature (Barbosa and Alberto 2019). For promoting fresh air in natural ventilation building, the opening is usually designed in different wall of a DSF for enhancing the air pass through the occupant space before exhausting through the DSF (Ding et al. 2005) (see Figure 2- 16). The main advantages of DSF are providing natural ventilation, improving thermal comfort, and promoting daylight without electricity consumption (Pasquay 2004). However, DSF has the disadvantage of high construction and maintenance costs. Since there is little difference between indoor and outdoor temperatures in tropical regions, DSF is not as effective and results in poor ventilation, which can lead to unwanted heat transfer into the interior space(Gratia and De Herde 2004; Wong et al. 2008).

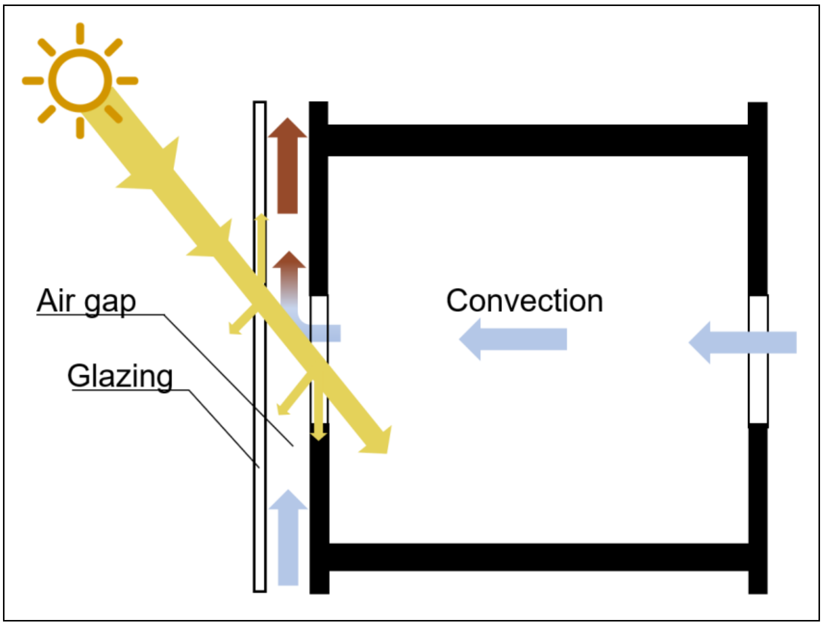


Figure 2- 16 Schematic diagram of Double-skin facade
(Source: Author)

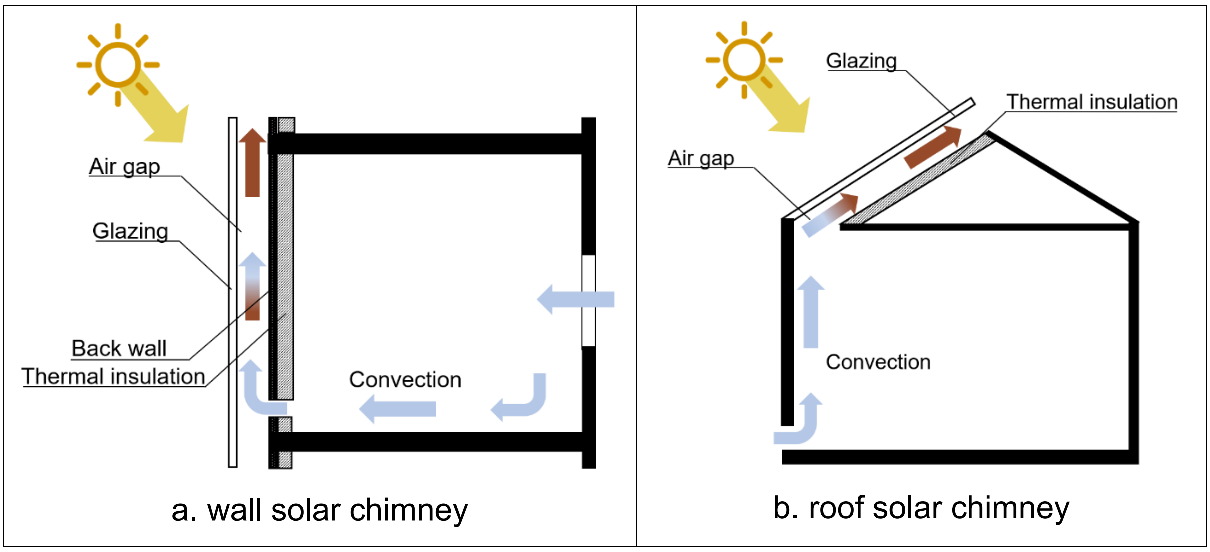


Figure 2- 17 Schematic diagram of solar chimney: a. wall solar chimney and b. roof solar chimney
(Source: Author)

The solar chimney is a strategy to maximise indoor-outdoor temperature differences by utilising solar heat gain, where there is usually a small temperature difference between the inside and outside of the building. The combined convection and radiation inside a solar chimney contribute appreciable air movement and enhances ventilation. Solar chimney is considered to be more advantageous in ventilation than Trombe wall and double- skin façade because solar chimney can be extended over the height of the building, also more flexible in the width to integrated with new buildings and existing buildings (Chatzipoulka 2011). This strategy is considered suitable for the tropical climate and is explained in more detail in Sections 2.4.3.1 and 3.1.

2.4.3.1 Solar Chimney

Solar chimney is based on natural air movement forced by the pressure stratification caused by air density variation in the chimney defined as a thermo-syphoning air channel driving. The buoyancy of the air is a result of air warming through solar energy. The chimney is mainly utilised ventilation for enhancing passive cooling or passive heating (Bhamare et al. 2019). Solar chimney operates in three different functions, including natural ventilation (air gap), passive heating (a glass cover with high solar transmissivity) and thermal insulation modes (see Figure 2- 17, Figure 2- 18). Main advantage of solar chimney is easy integrating to building which does not require specific architectural needs and construction. Solar chimney can be a ventilated façade for inducing indoor air exhausted to the outdoor through the upper opening (Dimoudi 2009). Furthermore, solar chimney is flexible to combine with other passive cooling strategies, e.g. Trombe wall and ventilation façade to further thermal comfort condition.

The major disadvantage of solar chimney is difficult controlling the indoor air from bringing unwanted heat and humid air into the building as well as other natural ventilated devices(Dimoudi 2009). There are two main types of chimney attached to buildings which are a wall and a roof solar chimney (see Figure 2- 17). A wall solar chimney is a vertical channel attached to the external wall of a building, while solar chimney based on roof is the application integrated with gable roofs. This research will mainly investigate on a solar chimney attached building’s wall because the chimney can provide more ventilation for multi-storey building.

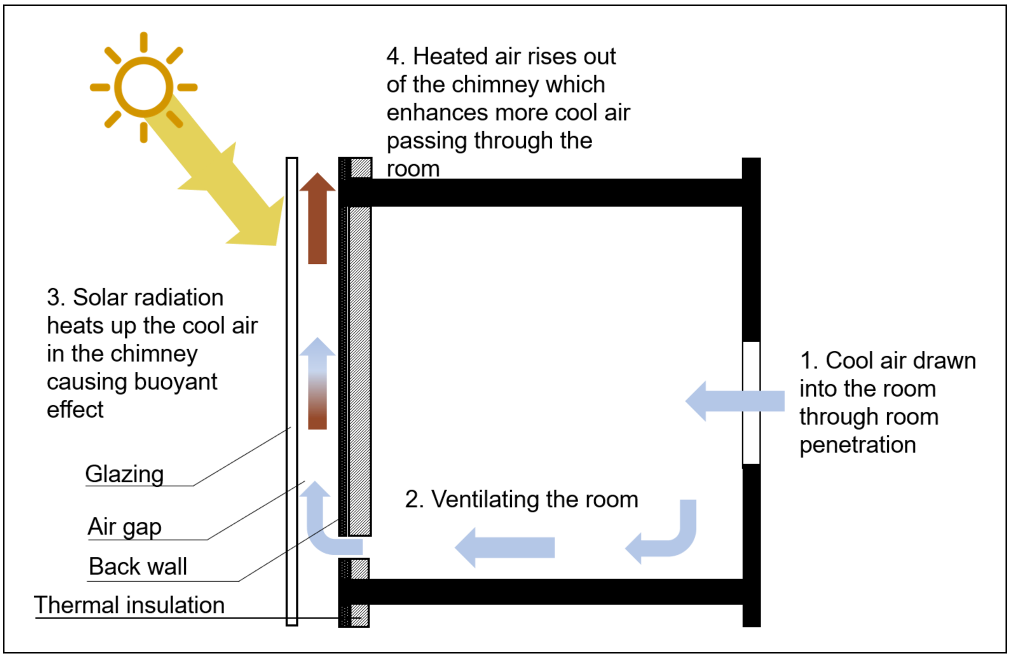


Figure 2- 18 Solar chimney work
(Source: Author)

This technique consists of an external glass cover, air gap at the middle and opaque wall. Many researchers have studied different solar chimney typologies, environment, materials, and configuration to discover a better alternative to a passive ventilation building (see Table 2- 2). For example, Hirunlabh et al. investigated a modified wall solar chimney consisting of a glass cover, air gap, and black metallic plate, insulation and plywood at the internal wall in a single-room test house in Thailand, and found that it increased the air mass flow rate reach 0.01-0.02 $kg.s^{-1}$ (Hirunlabh et al. 1999). Another experiment on a solar chimney with a glazed external surface adjoining a painted matt black wall in Malaysia showed that there was no reverse airflow if changed the air gap from 0.1 m to 0.3 m (Ong and Chow 2003). Using solar chimney could reduce annual energy consumption by 50%(Miyazaki et al. 2006).

Interestingly, the Coănda Effect is the phenomenon of surface effect. This effect promotes a change in pressure at the parallel surface for enhancing the ventilation to cling room surfaces, such as ceiling or wall, from a hydraulic feedback circuit (Boyes 2009; Richardson 2020). The more movement of mass flow along the surfaces creates the more distributed ventilation in the room (ZHIVOV et al. 2001; Zhao et al. 2004). In addition, this jet discharging effect supplied at some surface area or wall angle can become attached (ZHIVOV et al. 2001).

Previous research has shown that an inclined ventilated chimney can enhance natural ventilation, identifying 45 degrees as the optimal angle (Bassiouny and Korah 2009). The design of ventilated chimneys can draw parallels with many aspects of duct design, particularly concerning duct angles and layout. It is essential in ductwork design to minimise turns or bends, as each deviation can significantly reduce airflow efficiency. However, it is challenging in building design to completely avoid incorporating turns or angles due to the complexities and limitations of building layout. The recommended angle range for fluid flow is between 30 and 45 degrees (ASHRAE 2009).Triangular corners in ventilated chimney results in higher thermal performance for natural ventilation compared to other configurations (Dhahri et al. 2021).

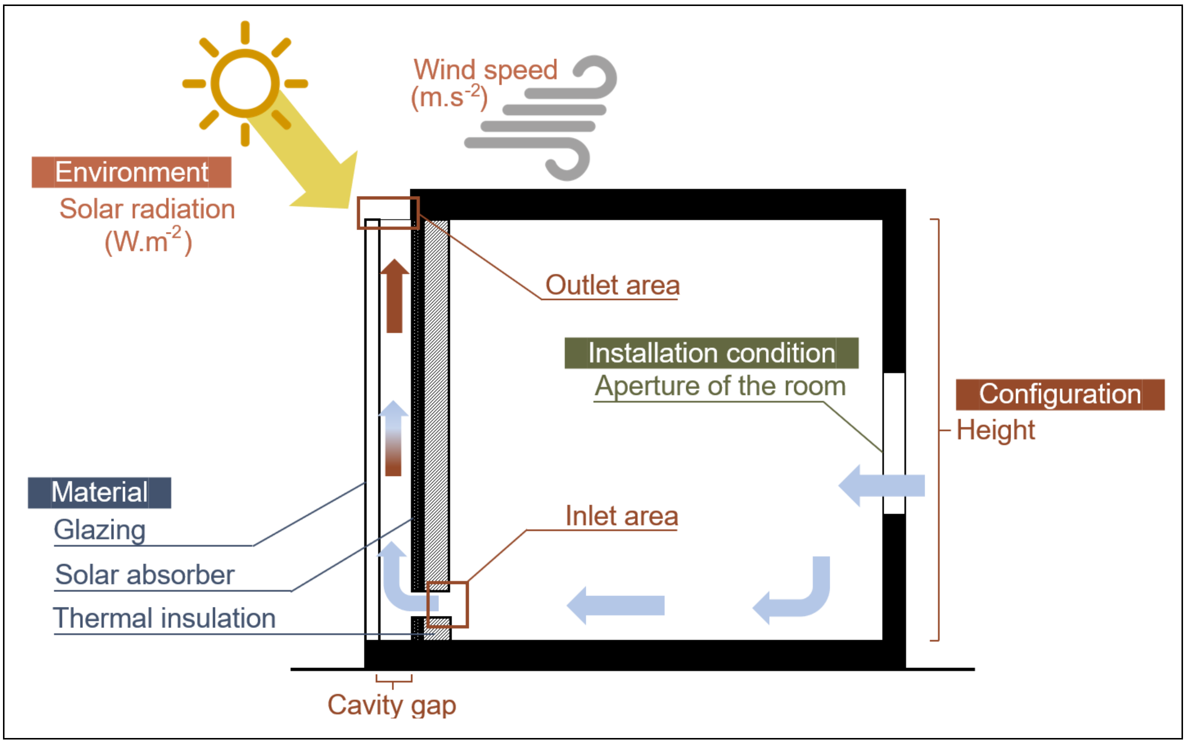


Figure 2- 19 four main factors of solar chimney performance
(Source: Author)

The performance of solar chimney depends on four main factors, which are environment configuration, installation condition, and materials (Shi et al. 2018) (see Figure 2- 19). These factors are explained below.

<u>Environment</u>

The environment relates to weather and climatic conditions such as **solar radiation, external wind speed and direction.** The intensity of **solar radiation** is the most essential factor of the solar chimney performance. The higher solar heat flux results in the higher air temperature inside solar chimney cavity which can enhance more ventilation mass flow (Manca et al. 2014). However, the relationship between the heat input and heat gains depends on the thermal efficiency of the system, such as material property, dimension (Chatzipoulka 2011). Manca 2014 found that doubling solar radiation from 300 W.m-1 to 600 $W.m^{-1}$ could increase almost 30% of air speed at the outlet. The air speed in the cavity can be raised almost 40% in case of increasing solar radiation from 200 $W.m^{-1}$ to 600 $W.m^{-1}$(Chen et al. 2003). Mathur et.al specified that there is a linear relationship between air speed in the cavity and solar radiation (Mathur et al. 2006).

External **wind speed** significantly influences on the solar chimney performance since the wind can induce negative or positive pressure at the solar chimney outlet. Some analytical studies on solar chimney define the effect of wind as windless condition. However, an experimental studies also point out that even the solar chimney without considering the wind effect could produce natural ventilation by 1.13-2.26 ACH, the solar chimney analysing wind effect could enhance up to 7.5-15.1% comparing with the other one (Khedari et al. 2000a; Chungloo and Limmeechokchai 2007). Dai et.al suggested that the building can be designed by considering solar radiation and ambient temperature to enhance ventilation during windless condition (Dai et al. 2003). Some researchers addressed that the effect of wind speed would reduce the solar chimney performance when solar radiation is higher than 700 W/m^2 (Al-Kayiem et al. 2014; Shi et al. 2018).

The direction is another relevant climate condition of solar chimney performance. The orientation must be carefully determined according to the location. For example, south-west and west orientations are the most useful for northern latitude (Dimoudi 2009). Koronaki discovered that the performance of solar chimney facing to the west and east received almost 50% solar radiation higher than the chimney facing to the south in Mediterranean regions (Koronaki 2013). Various solar chimney studies were designed the chimney facing to the south (See table 2-2). The orientation must be carefully chosen according to the site of operation.

<u>Configuration</u>

The **height** of the solar chimney wall refers to the vertical air gap. A higher height can promote a better performance because the high-pressure difference in the chimney cavity causes rising mass flow rate. Al-Kayiem et.al (Al-Kayiem et al. 2014), Lee and Strand (Lee and Strand 2009) also identified that extending the chimney height resulted in obtaining higher air speed in the chimney cavity.

The **cavity gap** strongly influences the mass flow rate. A higher cavity gap could enhance of mass flow rate (Balocco 2002; Ong and Chow 2003). In contrast, It was argued that the flow rate in the cavity not always increases by a greater size of the air gap. This is because a larger cavity gap would cause reversing heat flow back to the room (Lee and Strand 2009).

The **inlet** opening connected to the room area can be used to regulate the ventilation and isolate the chimney from the room (Dimoudi 2009). Many experimental studies design inlet width homogenise to the chimney width (Chatzipoulka 2011). Whereas an equal inlet and **outlet** areas is beneficial the improvement of solar chimney performance, the larger outlet area can lead more mass flow rate comparing to the equal size one (Shi et al. 2018). Much research has not included the outlet geometry as a parametric analysis because the outlet is normally designed at the top of the solar chimney wall with the equal plan and area as chimney cavity. Previous studied have showed that the total range of inlet-to-outlet area ratio is between 0.13 and 7.50 (See Table 2- 2).

Some studies explored the effect of the chimney height and depth separately, while the others studied the effect of the relationship between the chimney height and depth called **height-to-gap ratio**. While certain previous research investigated that the optimum height/ gap ratio was 10 (Bouchair 1989; Li et al. 2004; Wei et al. 2011), the suggested optimum height/gap ratio was not applicable for all solar chimney types (Chatzipoulka 2011). Mathur et.al 2006 experimented nine different combinations of the stack height and air gap width in spite of non-reporting the most suitable aspect ratio. Another experimental study discovered that extending the air gap area where remaining all other conditions results in the increasing mass flow rate significantly (Chen et al. 2003).

<u>Installation condition</u>

The installation condition represents the aperture of the room, such as window, door, or other opening which can bring fresh air to the room. The **aperture of the room** can promote circulated airflow.

Materials

The materials represent the materials used for **glazing, solar absorber, and thermal insulation**.

Although several properties of **glazing material** are important to the performance of a solar chimney performance which are transmissivity, reflectivity and absorptivity, transmissivity is more important to the performance comparing to the other factors. High glazing transmissivity is significant for increasing the outlet temperature and also inducing ventilation rate (Lee et al. 2015; Shi et al. 2018). Harris and Helwig, 2007 found that using a low-emissivity coating at internal surface of the glazing could improve 10% of the mass flow in the chimney. Low-emissivity finishing refers to allowing radiation to transmit but limiting the emission of radiation back to the surrounding. Determination of the ratio of transparent and opaque envelope ratio and the properties of glazing materials are integral to minimize heat gain in high temperature areas, such as tropical climates (Kim and Todorovic 2013). In addition, transparent property of glazing can improve indoor illuminance. Most of previous selected studies chose glass as a glazing material for the solar chimney (see Table 2-2).

Higher solar absorptivity of the stack wall is one important factor on the solar heat gain in the air gap – it controls how much of the solar radiation can get to the air gap. The higher heat gain can promote higher mass flow in the chimney (Chatzipoulka 2011). Lee and Strand found that increasing absorptivity of the back wall of a ventilation stack from 0.25 to 1.0 would rise the mass flow rate up to 57% (Lee and Strand 2009). An experimental study on the impact of solar absorber combined with solar chimney showed a linear relationship between absorptance property and mass flow rate (Pavlou et al. 2009). Emissivity of the **solar absorber** is another key factor to the solar chimney performance. Consequently, various researchers selected different materials to be the stack wall of the chimney, such as aluminium, brick and cement plaster, however most of them determined black painted covering on the wall (see Table 2- 2). Several researchers have employed metal back wall to be the stack wall because of the low inertia property of its material (Adam et al. 2002; Chen et al. 2003; Bansal et al. 2005; Mathur et al. 2006). Metal back wall can improve higher mass flow rate during daytime, while high thermal mass in the cavity, such as concrete and bricks, can retain heat to facilitate mass flow rate for nighttime (Chatzipoulka 2011). Thus, the material selection depends on activity, purpose and location of its building.

Thermal insulation material is used for reducing the transmission of heat flow. Thermal insulation is recommended for resistance of heat transfer in the chimney cavity. High thermal insulation, low thermal conductivity, can improve the mass flow by retaining heat in the cavity (Miyazaki et al. 2006).While certain researchers did not identify the insulation properties or types, they still located to be the part of the solar chimney in their studies. The insulation materials in previous research showed that several materials were chosen i.e. mineral fibre, polystyrene, glass wool (see Table 2-2).

Table 2- 2 A summary of influencing factors and methods in previous selected solar chimney studies

Environment			Material usage						Configuration								Method Ref.
orientation	climate	solar radiation ($w.m^{-2}$)	glazing material (mm)		stack wall (mm)		thermal insulation (mm)		width (m)	stack height (m)	air gap (m)	ratio (height/ gap)	Inclination (º)	inlet area (m2)	outlet area (m2)	ratio (inlet/ outlet)	
south	Temperate	671-843	glazed surface	N/A	brick wall	100	N/A	50	0.20	2.00	0.20	10.00	90	N/A	N/A	N/A	E, A (Afonso and Oliveira 2000)
N/A	Temperate	100-500	glass	N/A	aluminium	N/A	heavily insulation	N/A	1.00	2.00	0.10-0.30	6.70-20.00	30-90	0.10-0.30	0.10-0.30	0.33-3.00	E, A (Adam et al. 2002)
N/A	Temperate	200-1,000	polymethyl methacrylate	N/A	matt black aluminium	N/A	N/A	100	0.93	1.03	0.02-0.11	9.30-51.30	90	0.02-0.10	0.02-0.10	0.20-5.00	E, A (Burek and Habeb 2007)
south	Temperate	1,367	glass	3	black painted aluminium	1.5	fibreglass	50	0.74	1.00	0.11	9.09	30-90	N/A	N/A	N/A	A (Sakonidou et al. 2008)
N/A	Temperate	120-650	N/A	N/A	asbestos board	5	glass wool Blanket	10	0.50	1.50	0.10-0.50	3.00-15.00	75-90	0.05-0.25	0.05-0.25	0.20-5.00	E, A (Zhai et al. 2005)
south	Temperate	205-762	float glass	4	black painted aluminium	1	thermocol (EPS) sheet	50	1.00	1.00	0.13-0.33	3.01-7.69	90	0.13-0.24	0.13-0.33	0.40-1.85	E, A (Bansal et al. 2005)
N/A	Temperate	200-1,000	polymethyl methacrylate	5-10	matt black aluminium	2.5	mineral fibre	100 - 130	1.00	0.50-2.00	0.02-0.15	3.33-100.00	90	0.02-0.15	0.02-0.15	0.13-7.50	E (Ryan and Burek 2010)
south	Temperate	289.96	glass	6	black coating material	N/A	N/A	50	1.10	14.00	0.20	70.00	90	N/A	N/A	N/A	A, C (Wei et al. 2011)
N/A	Temperate	200-400	heated Wall	N/A	high density board	15	mineral fibre	50	1.00	2.00	0.40-1.20	1.7-5.0	90	0.40-1.20	0.40-1.20	0.33-3.00	E (Jing et al. 2015)

E: Experimental Method, A: Analytical Method, C: Computational Fluid Dynamics

Table 2- 2 A summary of influencing factors and methods in previous selected solar chimney studies (continued)

Environment			**Material usage**						**Configuration**								**Method Ref.**
orientation	climate	solar radiation ($w.m^{-2}$)	glazing material (mm)		stack wall (mm)		thermal insulation (mm)		width (m)	stack height (m)	air gap (m)	ratio (height/ gap)	Inclination (º)	inlet area (m^2)	outlet area (m^2)	ratio (inlet/ outlet)	
N/A	Continental	120-958	endothermic glass	N/A	cement-sand plaster	9.5	polyurethane	100	1.00	1.00	0.1-0.6	1.67-10.0	90	0.1-0.6	0.1-0.6	0.17-6.00	E (Liu et al. 2015)
south	Tropical	988	glass	6	cement plaster and clay brick	140	-	-	2.00	5.55	1.00	5.55	90	2.25	2.00	1.13	C (Leng et al. 2019)
south	Tropical	200-650	glass	4	matt black painted laminated polyurethane sheet	22	polystyrene	50	0.45	1.88	0.10-0.30	6.25-18.75	90	0.05	0.05-0.14	0.36-1.00	A (Ong and Chow 2003)
N/A	N/A	200-600	Plexiglass	3	stainless steel shim	N/A	polystyrene	50	0.62	1.50	0.10-0.60	15-25	90	0.68	0.68	1.00	E, A (Chen et al. 2003)
south	Arid	700	glass	N/A	black painted aluminium	1	thermocol (EPS) sheet	250	1.00	1.00	0.35	2.86	90	0.30	0.35	0.86	E, A (Mathur et al. 2006)
south	Arid	N/A	glass	5	black painted galvanized sheet	0.4	polystyrene	60	1.00	2.00	0.10-0.30	6.67-20.00	30-45	0.10-0.30	0.10-0.30	0.33-3.00	E (Saifi et al. 2012)
south	Arid	1,000	glass	3	absorber plate	N/A	N/A	N/A	2.13	4.57	1.83	2.50	90	1.12	1.12	1.00	E (Lal et al. 2013)
N/A	Arid	240-800	glass	4	black painted ductile steel plate	1	glass wool	50	0.97	2.25	0.15	15.00	90	0.24	1.07	0.23	E, A (Amori and Mohammed 2012)
south	Arid	0-820	glass	4	matt black painted reinforced concrete	300	plywood	150	1.00	4.50	0.30	15.00	90	0.20	0.07	2.86	E (Arce et al. 2009)

E: Experimental Method, A: Analytical Method, C: Computational Fluid Dynamics

Table 2- 2 A summary of influencing factors and methods in previous selected solar chimney studies (continued)

Environment			**Material usage**						**Configuration**								**Method Ref.**
orientation	climate	solar radiation ($w.m^{-2}$)	glazing material (mm)		stack wall (mm)		thermal insulation (mm)		width (m)	stack height (m)	air gap (m)	ratio (height/ gap)	Inclination (º)	inlet area (m^2)	outlet area (m^2)	ratio (inlet/ outlet)	
N/A	Arid	240-800	glass	4	black painted ductile steel plate	1	glass wool	50	0.97	2.25	0.15	15.00	90	0.24	1.07	0.23	E, A (Amori and Mohammed 2012)
south	Arid	0-820	glass	4	matt black painted reinforced concrete	300	plywood	150	1.00	4.50	0.30	15.00	90	0.20	0.07	2.86	E (Arce et al. 2009)
N/A	Arid	150-750	glass	4	matt black aluminium	1	-	-	2.00	2.00	0.05-0.15	13.3-40.0	15-60	0.06-0.37	0.10-0.30	0.20-3.70	E, A (Imran et al. 2015)
Total range		0 - 1,367							0.02-2.00	0.50-14.00	0.02-1.83	3.00-70.00	15-90	0.02-2.25	0.02-2.00	0.13-7.50	

E: Experimental Method, A: Analytical Method, C: Computational Fluid Dynamics

Many researchers have investigated the solar chimney integrating with other techniques for inducing higher air flow rate, maintaining more comfortable indoor thermal conditions (Zhai et al. 2011) or other environmental conditions. These include integrating solar chimney with double skin façade (DSF), or Trombe wall.

Integrating solar chimney with DSF

The glazed solar chimney comprised of two layers of glazing walls with air gap in between could induce air speed up to 0.13-0.28 $m.s^{-1}$ (Zhai et al. 2011). The technique of glass-glass wall allows daylight to pass through the building which can improve daylight level in the building. Sung et.al. 2013 studied the enhancement of natural ventilation through DSF with a solar chimney channel for a multi-storey building in Korea. The result of this research showed that natural ventilation inside the double skin façade connected with solar chimney would be increased and the annual cooling load could be decreased by 2.84% compared to a non-solar chimney. The effect of configuration of solar chimney combined with DSF were investigated and the result showed that DSF can enhance natural ventilation (Gan 2006). For multi-storey buildings in Thailand, solar chimney was investigated by Punyasompum et.al. 2019, which the result showed that connected solar chimney was more effective than the separated one (see Figure 2- 20). Ding et.al, 2005, Sung et.al, 2013 and Abraham, 2018 studied solar chimney connected with DSF to enhance the stack effect, they found that applying solar chimney to the upper part of DSF could enhance airflow rate, additionally increasing the chimney height would stimulate more airflow rate of the intermediate space of multi-storey building. Numerous studies have established that DSF utilisation combined with solar chimney can enhance the chimney performance. However, DSF is more advantage for heating ventilation in winter and not practical for cooling ventilation in summer because it would induce overheat and high cost (Gan 1998; Harris and Helwig 2007).

Solar chimney combined with Trombe wall

Research on solar chimney combine with modified Trombe wall for a house in Thailand condition was conducted by Khedari et.al. 2003, this would save cooling energy consumption up to 30%.

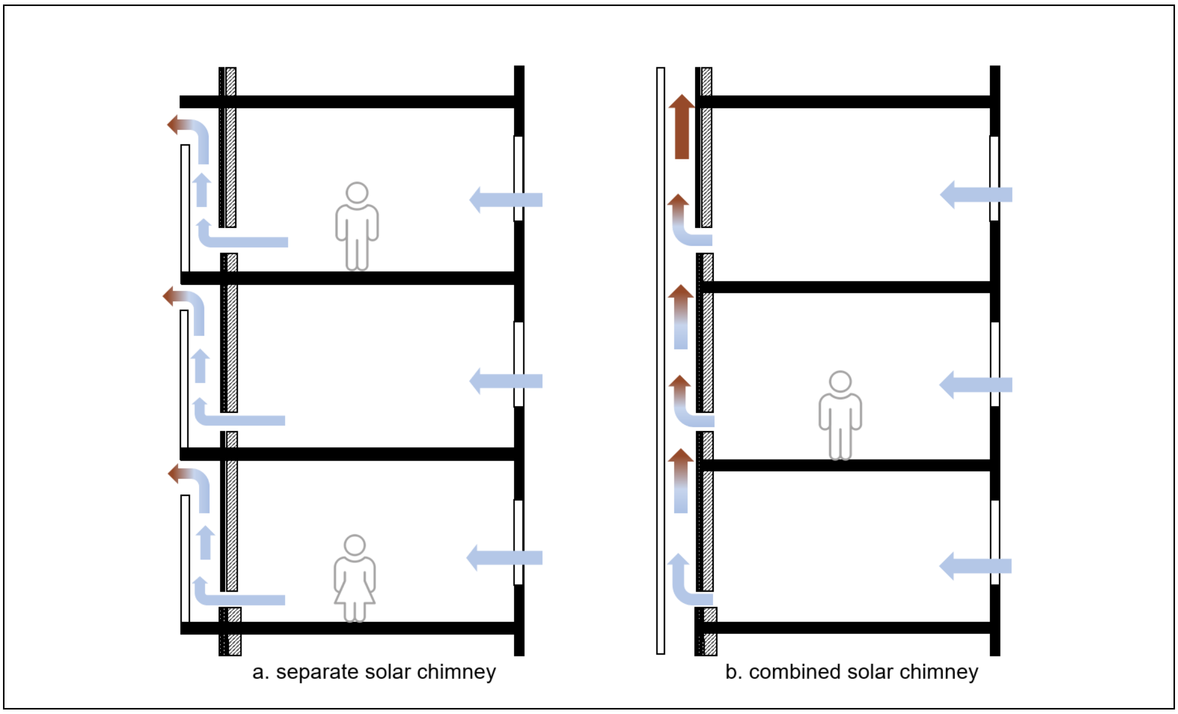


Figure 2- 20 Schematic diagram of wall-based solar chimney in multi-storey building: a. separated solar chimney and b. combined solar chimney
(Source: Author)

Three main methods have been used to investigate the performance of air flow in solar chimney, these are:

- **Experimental investigation** of airflow in real or controlled laboratory conditions. This has been used to test the ventilation effect of solar chimney geometry, inclination angle and meteorological parameters (Afonso and Oliveira 2000; Ziskind et al. 2002; Chen et al. 2003; Mathur et al. 2006). Some of them also use analytical or numerical modelling for validating their experimental studies (Barozzi et al. 1992; Spencer et al. 2000).
- **Analytical study** using mathematical models for predicting solar chimneys' performance. Mathematic models can be divided, by their inputs, into 4 types which are proportional relationship between airflow rate and individual parameter, volumetric flow depending on temperature differences, volumetric flow based on the difference of air density between inside and outside, and volumetric flow based on solar radiation (Shi et al. 2018). Most of the studies defined steady state heat transfer equations on their model, based on the uniform air temperature distribution along the chimney height (Chatzipoulka 2011). Many researchers developed a steady state with one-dimensional heat flow finite difference model (Zriken and Bilgen 1985; Ward and Derradji 1987; Bouchair 1989; Bansal et al. 1993). Ong,

2003 use a mathematical model setting up steady-state models in order to investigate performance of different solar chimney geometries under varying climatic conditions. Afonso and Oliveira, 2000 developed a simplified model and a computer programme to investigate the ventilative performance in the chimney, which was a development of mathematical and numerical model. Based on the classical opening equation, a number of empirical models for predicting single-sided natural ventilation were developed can be discovered in the literature (Ai et al. 2015; Zhong et al. 2022)

$$Q=C_dA\sqrt{\frac{2|\Delta P|}{\rho}}$$

where Q is ventilation rate ($m.s^{-3}$), Cd is discharge coefficient, A is the opening area (m^2), $|\Delta P|$ is pressure difference (Pa) and ρ is density ($kg.m^{-3}$). The limitation of analytical method is the study required assumptions and simplifications to generate a closed question, which could impact on the accuracy of the results.

- **Computational fluid dynamics (CFD)** – this technique has been increasing in popularity as computation power has become more available. CFD directly solves for the fluid dynamic properties governing airflow movement by solving the governing Navier-Stokes equations. Although the CFD is computational complexity, simulation result can provide a detailed description of airflow patterns around and in buildings. The computational method is defined as accurate temperature distribution, pressure and air velocity prediction. Some studies proved that an applying of both CFD model and analytical method was good for predicting the air flow and temperature distribution in the solar chimneys (Dimoudi 2009). Some studies used thermal model for predicting surface and air temperature and mean flow rate first, then entering the results into the CFD model for calculating the new stack flow and flow rate. Most of the CFD modelling investigation carried out in steady state (Zhai et al. 2011). The accuracy of CFD results is depended on the quality of grid size, boundary condition, turbulence model and numerical technique.

2.5 Recycled Materials

Recycled material is a product having been used before and then treated through a process to create a new material form (CambridgeUniversityPress 2020). This material usually differs from the original purpose usage of the material's previous life (see

Figure 2- 21), for example plastic drainpipes made from the reclaimed plastic drinking bottles, concrete made from recycled aggregate, and thermal insulation made from newspapers. There are 3 different sources of recycled materials: materials collected from manufacture of a primary material, materials collected from waste product in manufacturing processes, and material collected after use. Recycling not only reduce pollution released from waste disposal, but also decreases the need of conventional raw materials (Addis 2012; Asdrubali et al. 2015).

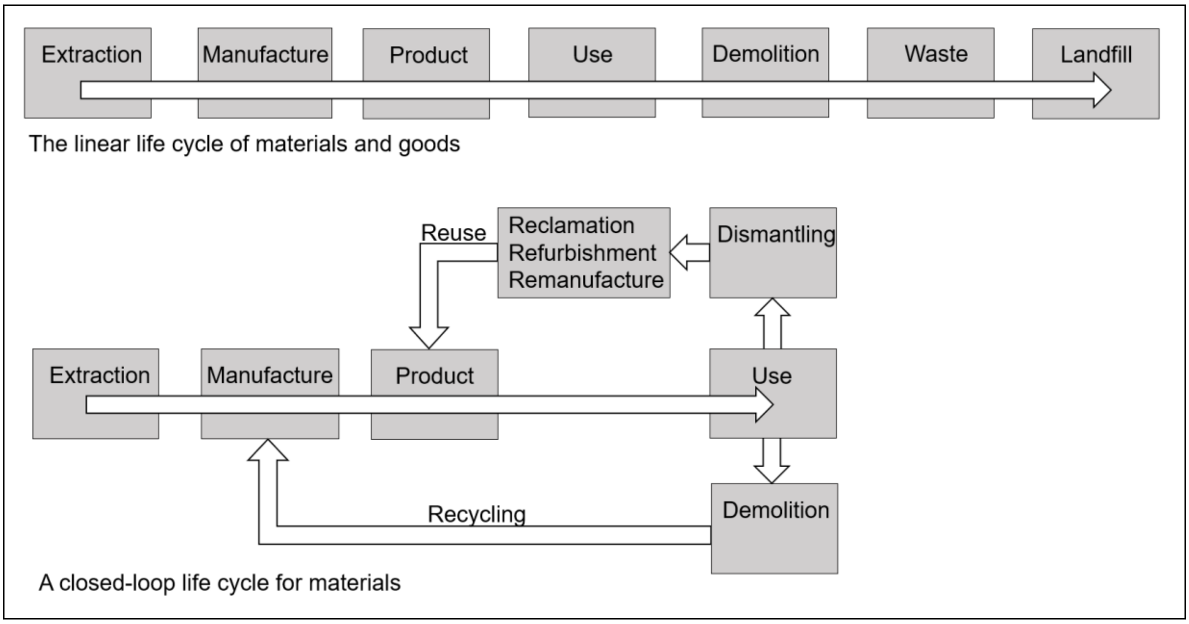


Figure 2- 21 Diagram of different life cycle of materials
(Source: Author adapted data from Addis, 2012)

The optimization of stack ventilation performance with lowest price is the main challenge of designing the chimney (Harris and Helwig 2007; Shi et al. 2018). Additionally, sustainable material selection should consider on factors impacting on the environment like embodied carbon or Life-Cycle Assessment (LCA). Both embodied and Life-Cycle Assessment of building components have become more and more essential, in order to take into account either the whole carbon producing or energy consuming from extraction to demolition (Dong and Ng 2015; Schiavoni et al. 2016). Embodied Carbon is the carbon footprint of a material which is used to assess greenhouse gases(GHGs) released from cradle to grave (Jones). Life-Cycle Assessment (LCA) is an analysing technique associated with environmental impacts through the material life cycle (Kubba 2012).

Recycled material is an alternative material that can provide the same properties as the raw material and correspond with sustainability, high quality, and appropriate budget for construction. Even much research determined that the price and exergy of using recycled materials are lower than that of the raw materials, designer or architects rarely specify recycled products to use as architectural materials. This is because the limited information of material specification, recycled material market and lower acceptance in construction industry (Mansikkasalo et al. 2014; Oyedele et al. 2014). Less progress in integration of recycled materials with construction projects. A theory of a circular economy has been introduced to the construction sector for enable the future building materials (Addis 2012). The understanding of recycled material conditions would implement circular solution in the built environment (Kozminska 2019).

Three influencing performance factors of solar chimney materials are glazing properties, absorber properties, and thermal insulation (Shi et al. 2018).

2.5.1 Glazing

Windows are glazed apertures of building envelope which typically consist of single or multi-layer glazing, e.g. glass or plastic. The solar heat gain through the windows is a correspondent of cooling load in high outdoor temperature regions (Cengel and Ghajar 2015). Whereas higher R-Value or thermal resistance shows a higher insulating of different temperature between indoor and outdoor, the higher U-value of the glazing plays an important role in increasing heat to transfer through its material. The higher glazing layers refer to the lower heat transfer, for example clear single glazing has more double times of u-value compare to double glazing (Kubba 2012). Glazing material of solar chimney would enhance higher temperature in the chimney cavity for buoyancy effect, that is why most of the solar chimney in previous research have been designed with single glazing (Chen et al. 2003; Chantawong et al. 2006; Arce et al. 2009; Saifi et al. 2012). Single glass also has the lowest embodied carbon comparing with other glazing materials (see Table 2- 3). Additionally, glazing type brings up the solar heat gain (SHGC) of the building which refers to transmitted, reflected and absorbed properties of such material. However, for improving indoor daylight in warm temperature, glazing material should allow the visible solar radiation transmitted, conversely limit the infrared solar radiation to prevent heat re-radiated in the interior (Cengel and Ghajar 2015). Thus, glazing material selection should be done in accordance with the building function.

Glass is a 100% recyclable and endless recycling, which means that the properties of this recycled glass has the same material property of the typical window glass. Recycled glass can be used to make a wide variety of purpose more than just bottles and containers, such as window float glass, walls, tiles, aggregate, and fences (Confederation 2020). The recycled glass has a 20% reduction in embodied energy compared with new glass (Munn and Soebarto 2004).

Table 2- 3 Embodied carbon and thermal properties of glazing materials
(Source: (Hammond and Jones 2019), (ASHRAE 2009))

Materials	Embodied Carbon	U-Value	Visible transmittance	SHGC
	$kgCO^2e.kg^{-1}$	$W.m^{-2}.K^{-1}$		
Glass, Single Glazing	1.44	5.91	0.90	0.86
Glass, Double Glazing, 6.4 mm air space	1.63	3.12	0.81	0.76
Glass, Triple Glazing, 6.4 mm air space	1.75	2.16	0.74	0.68
Polycarbonate	7.62	0.56	0.81	0.82

2.5.2 Absorber

Due to enhancing buoyancy effect in the solar chimney cavity, the absorptivity and emissivity of the absorber are the primal factors of chimney performance (Shi et al. 2018). Most of the studies design matt-black coated on the absorber because the absorptivity and emissivity of black coating are 0.98 and 0.98 respectively (see Table 2- 5). Additionally, much research has selected aluminium to be the material of stack wall in tropical climates, it is result from low inertia and low construction cost (Yusoff et al. 2010; Tan and Wong 2013,2014).

Recycled materials are alternative supplied which have equivalent properties as raw building materials. Unfortunately, few studies have designed absorber with recycled materials. Alvarez et.al 2004, Murali et.al 2020, and Rajesh and Choudary 2020 experimented using various recycled aluminium cans to be an absorber plate of solar collectors and discovered that the collectors increased thermal efficiency, which maximised the efficiency reaching 74%. Kishk et.al 2019 also applied reused aluminium cans and plate as absorber plate in the solar collector of agricultural drying process; these materials in the collector could improve thermal efficiency and reduce moisture content in the room. Absorber plate made from recycled aluminium imply to have sustainable environment (Rajesh and Choudary 2017).

Table 2- 4 Embodied carbon and thermal properties of aluminium
(Source: Hammond and Jones,2019 and Cengel and Ghajar,2015)

Material	Average Embodied Carbon	Effective recycled content	Density	Thermal Conductivity	Specific Heat	note
	kg CO_2e .kg^{-1}	%	kg.m^{-3}	W.m^{-1}.K^{-1}	kJ.kg^{-1}.K^{-1}	
Aluminium - All Data Collected	8.72	N/A	2739	222.00	0.90	Data on recycled aluminium is not provided
Aluminium profile	8.78					
Aluminium, Cast	6.16					
Aluminium, sheet	5.54					

Table 2- 5 Solar radiative properties of materials
(Source: Cengel and Ghajar,2015)

Material	Solar absorptivity	Emissivity at 300K	Ratio	Solar transmissivity
	α_s	ε	$\alpha_s.\varepsilon^{-1}$	τ_s
Aluminium				
Polished	0.09	0.03	3	
Anodized	0.14	0.84	0.17	
Quartz-overcoated	0.11	0.37	0.3	
Foil	0.15	0.05	3	
Galvanized sheet metal				
Clean, new	0.65	0.13	5	
Oxidized, weathered	0.8	0.28	2.9	
Glass, 3.2 mm thickness				
Float or tempered				0.79
Low iron oxide type				0.88
Metal, plated				
Black sulfide	0.92	0.1	9.2	
Black cobalt oxide	0.93	0.3	3.1	
Black nickel oxide	0.92	0.08	11	
Black chrome	0.87	0.09	9.7	
Paints				
Black (Parsons)	0.98	0.98	1	
White, acrylic	0.26	0.9	0.29	
White, zinc oxide	0.16	0.93	0.17	
Plexiglass, 3.2 mm thickness				0.9
Porcelain tiles, white (reflective glazed surface)	0.26	0.85	0.3	
Steel				
Mirror-finish	0.41	0.05	8.2	
Heavily rusted	0.89	0.92	0.96	

2.5.3 Thermal insulation

Thermal insulation can prevent substantial heat flow from one side of the insulation to another side (Li and Ren 2011). There are five mains different criteria to classify thermal insulation (Vrána 2007):

1) type of the substance: inorganic and organic insulation
2) structure: fibrous, porous, and granulated insulation
3) shape: loose (back fill, wool) and flat (board, felt, mat)
4) binder content: binder-free and containing binder
5) fire reaction: non-combustible, limited combustibility and combustible

Three characterisations of insulation materials are mostly considered (Schiavoni et al. 2016):

2.5.3.1 Thermal characterisation

The key parameters of thermal performance of insulation material are thermal conductivity and thermal diffusivity. Thermal conductivity refers to the insulation properties which is heat flow pass through a unit area of a material. A material is usually considered as a thermal insulator when its conductivity is lower than 0.07 $W.m^{-1}. K^{-1}$ (Asdrubali et al. 2015), thus all recycled materials in Table 2- 6 show that their thermal conductivities are below the maximum insulation conductivity requirement. The thermal diffusivity is the ratio between thermal conductivity, density and specific heat capacity (Schiavoni et al. 2016).

2.5.3.2 Reaction to fire

The behaviour of insulation materials responding to fire is needed for safety issues. The fire classification provides a data of material reaction to fire, such as EN 13501-1, DIN 4102-1, BS 476-6, ISO 1182 (Papadopoulos 2005). The EN 13501-1 is classified regarding to the material flammability described as followed (Hidalgo et al. 2015):

- A1 and A2 classes are no contribution to fire in any stage, such as cement, glass, fiberglass, rock wool.
- B class is very limited contribution to fire.
- C class is limited contribution to fire.
- D class is medium contribution to fire.

- E class is highly contribution to fire.
- F class is easily flammable.

2.5.3.3 Water vapour resistance factor

Water vapour diffusion resistance factor shows the ability of a material and water permeation. The lower resistance value refers to the higher vapour permeability (Schiavoni et al. 2016). In terms of durability and indoor air quality, selection of materials is the most important in order to minimize issues such as mould growth (Kim and Todorovic 2013). De Flander and Rovers revealed that some materials (eg. Textile fibres) are more prone to attack from fungi, mould, microbes and insects in high relative humidity area, so textile fibre insulation would promote mould emerging in a room (De Flander and Rovers 2009).

Table 2- 6 A summary of thermal properties and μ-value of recycled material insulation

Type	Recycled material	Density	Thermal conductivity	Specific heat	Water vapour diffusion resistance factor, μ-value	Fire classification (EN13501-1)	Ref.
		$kg.m^{-3}$	$W.m^{-1}.K^{-1}$	$kJ.kg^{-1}.K^{-1}$			
textile fibre insulation	cotton (recycled - general)	25-45	0.039-0.044	1.6	1-2	E	(Asdrubali et al. 2015; Schiavoni et al. 2016)
	recycled textile (commercialised)	30-80	0.0358-0.042	1.2-1.6	2.2	E, F	(Asdrubali et al. 2015; Schiavoni et al. 2016)
	recycled textile fibres (polyester and polyurethane)	203-491	0.044	N/A	very high	B,C	(Zia et al. 2007; Briga-Sa et al. 2013)
	recycled textile fibres (polyester)	62.50	0.035-0.040	1.0	5	B,C	(Pfundstein et al. 2012; Patnaik et al. 2015)
	recycled textile fibres (polyurethane)	30-80	0.020-0.027	1.38	very high	B,C	(Zia et al. 2007; Pfundstein et al. 2012; Hadded et al. 2016)
	recycled textile fibres (synthetic)	200-500	0.041-0.053	N/A	N/A	N/A	(Valverde et al. 2013)
	recycled textile and paper	433	0.034-0.039	N/A	N/A	E, F	(Asdrubali et al. 2015; Schiavoni et al. 2016)
	recycled glass foam sandwiched between glass fibre layers	450	0.031	0.83	N/A	A1	(Asdrubali et al. 2015; Schiavoni et al. 2016)
recycled product insulation	recycled glass fibres (commercialised)	100-165	0.038-0.05	1.0	very high	A1	(Asdrubali et al. 2015; Schiavoni et al. 2016)
	recycled PET bottles (75%) with virgin PET	30	0.036	0.24	N/A	N/A	(Ingrao et al. 2014; Schiavoni et al. 2016)
	recycled PET (commercialised)	15-60	0.034-0.039	1.2	3	B	(Asdrubali et al. 2015; Schiavoni et al. 2016)

2.6 Summary and Research Gap

Due to the need to improve thermal comfort and mitigate health risks in Thailand multi-storey residential buildings in Thailand, passive cooling via ventilation is a potential technique to acquire thermal comfort conditions in a sustainable environment. Solar chimney is one of the passive cooling techniques which can induce buoyant effect to augment room ventilation to solve the obstructed airflow problems of the residential buildings in urban areas. Numerous researchers have developed innovations to enhance natural ventilation. However, the majority of these developments have focused on buildings with fewer nearby buildings, thereby limiting their practical applications (Zhang et al. 2022). In addition, these studies rarely consider buildings in dense areas, where wind speed and direction can significantly differ (Caciolo et al. 2011). The integration of solar chimneys in multi-storey buildings is a viable strategy for enhancing natural ventilation in tropical climates, such as in Thailand. Previous research has investigated the use of solar chimneys in multi-residential buildings within the region. For instance, Punyasompun et al, 2009 have shown that incorporating a solar chimney into a multi-storey building can improve natural ventilation and reduce indoor temperatures by approximately 4-5°C. Their study, primarily based on a mathematical model, focused on stack ventilation on building facades. However, this approach may have limited effectiveness in urban areas where buildings are often overshadowed by nearby buildings, potentially reducing the chimney's efficiency. Prajongsan et al, 2012 investigated ventilation shafts in high-rise multi-residential buildings in Thailand. Their studies revealed a considerable increase in thermal comfort hours throughout the summer in Bangkok's high-rise buildings. However, this study was primarily focused on reducing AC energy consumption rather than explicitly focusing on thermal comfort in naturally ventilated rooms. The findings in this chapter indicate the research gap in understanding the effectiveness of solar chimneys and natural ventilation strategies specifically in thermally free-running buildings in Thailand. There is a need for further exploration into designs that optimise thermal comfort without relying on air conditioner under the limited external air movement due to the proximity of the buildings and single-sided window. Recycled materials are alternative supplies for the integrating application that have equivalent properties to raw building materials. This offers a sustainable option in the context of solar chimney implementation.

In conclusion, it is essential to investigate the potential of passive design strategies to enhance indoor environmental quality in thermally free-running apartment dwellings in Thailand.

2.7 Exploring methods

To investigate the potential of passive design solutions for improving indoor environmental quality in thermally free-running apartment buildings in Thailand, it is necessary to initially evaluate the current environmental conditions of multi-residential buildings in Thailand. Passive design approaches can be efficiently adapted to local climate conditions and building characteristics (Wang et al. 2021). Subsequently, factors influencing the performance of these passive design options can be investigated in order to develop and validate designs.

Exploration of research methods involves a systematic process of seeking and analysing appropriate research methods for each phase of the study. The exploration of methods is divided into three main phases. Phase 1 is investigating the current context for multi-residential buildings in Chiang Mai. Phase 2 involves evaluating the potential design options by evaluating factors affecting natural ventilation performance. Phase 3 focuses on validating options for design solutions.

2.7.1 Phase1- Exploring methods for multi-residential building context in Thailand

For Phase1, the research needs to understand the building context in order to investigate the passive design options. Building context involves physical factors, such as climatic zone, building characteristics, law and regulation; and socio factors including occupant behaviour characteristic, social demographic, and cultural variables. Based on these approaches, data gathering can be categorised into two groups, which are primary and secondary data. Primary sources involve original data specific to a particular research approach, while secondary sources are based on existing research and data. Secondary resources can be derived with less cost and time than conducting primary research. However, the secondary source requires the availability and validity of data.

2.7.1.1 Secondary sources

The available secondary sources in relation to multi-residential building context in Thailand can be derived from government documents and reports, official climate data and previous research. Thailand government publishes Thailand Building Regulation providing the minimum requirement of building design and construction to ensure the building is safe, healthy and supports welfare, which can be used to understand the minimum requirements of building context. Weather data is one of the most important factors in integrating passive design to building. Thailand weather data can be obtained from providers, such as Thai Meteorological Department, Climate Onebuilding, and EnergyPlus.

Building regulation of Thailand can be used to understand the building context in Thailand and generate base cases in the study.

The investor tends to comply to the minimum requirement of the building regulation in order to maximise profit. However, Building regulations minimum requirements (e.g. minimum distance between buildings, or minimum room size) do not guarantee good indoor environmental quality. This can be seen from previous research which states issues from high density building areas include low ventilation, people not able to achieve thermal comfort, and sick building syndrome especially for multi-residential building (Wong et al. 2009; Naing et al. 2017; Tao et al. 2020). Lower socio-economic group tends to suffer from building syndrome more than other socio-economic groups. Referring to the minimum requirement of aperture area for natural ventilation of Thai building regulation, building is normally designed the room doors at both balcony and to the corridor as the aperture for complying the regulation. However, in practice, occupants shut the opening the door for privacy, which influences the room to have very low natural ventilation in the room.

Weather data is crucial when considering environmental factors influencing passive cooling design. In order to create accurate and realistic models of the environmental factors, CFD simulation also needs weather data for generating boundary conditions, such as temperature, humidity, wind speed, wind direction etc. Chiang Mai weather data can be derived from several organisations.

- Thai Meteorological Department is the Thai government organisation providing weather data, including outdoor air temperature, relative humidity, wind speed and wind direction (ThaiMeteorologicalDepartment 2021).
- EnergyPlus Weather (EPW) file provides a comprehensive collection of weather data, for instance temperature, humidity, wind speed, solar radiation

and precipitation, which is necessary for precise occupant comfort modelling and energy consumption (EnergyPlus 2023).

Census data provided by the government only stated the number and type of Thailand residential buildings, however, little evidence addresses Thailand multi-storey residential building characteristics. There is even less evidence showing occupants' opinions about their accommodations. The building configuration are important to contribute the building context. Due to the limitation of secondary sources, material must be investigated using primary source collection techniques. This requires both the qualitative and quantitative study.

2.7.1.2 Primary sources

Several methods below can be used to gather the information of typical apartment character and user satisfaction, such as observation, interview, questionnaire monitoring data (Kothari 2004).

Observation is a purposeful and selective method that involves observing and recording to an interaction or phenomenon (Kumar 2018). The observation technique has many advantages, for example investigate behaviour and collecting data without interfering or affecting the occupants. Observation method is typically applied to explore facts about specific people or group but is not effective in measuring people attitudes. Additionally, the method has limitations in providing information of large populations and typical apartment character, especially, private living spaces.

Interviewing is a research method of gathering information from people, which involves face-to-face interaction, which can provide in-depth and personal insights into the participant's experiences, attitude and building used satisfaction. However, interviewing is less anonymous, which raises concerns for many respondents. It is also cost and time- consuming for gathering data from large numbers of participants (Kumar 2018).

Questionnaire is a method for gathering data for extensive enquiries that can be used with a variety of people. Questionnaire offers the flexibility to utilise a variety of response formats and collected data types. Additionally, a questionnaire is a self-report measurement (GlobalEvaluationInitiative 2023). Questionnaire can reveal the details of how space is used as well as the perception of the occupants. The occupant behaviour characteristics, such as cooking, hanging cloth for drying, and taking a shower, significantly influence building performance (Feng et al. 2016). Many researchers have used a questionnaire to reveal building context and occupant behaviour (Park and Kim 2012; Mohamed et al. 2015; Delzendeh et al. 2017), occupants' satisfaction (Indraganti et al. 2015), occupancy behaviour in relation to energy consumption (Hu et al. 2019), Post-Occupant Evaluation (POE) (Mundo-Hernández et al. 2015; Brown 2016). POE is a method of obtaining feedback about building performance in use (Li et al. 2018). The POE gathers information of energy use in building, user experience, indoor environment quality, building materials etc. Different type of buildings uses different purpose of POE. POE used in residential building focuses on occupants satisfaction and facilities. POE methods can include physical measurement, occupant survey questionnaire, energy performance, and interview (Li et al. 2018).

Physical measurement is a process of examining quantitative data, which can be applied to evaluate building's performance. In contrast, investigating internal parameters affect occupants' room perception requires a deep interpretation of the occupant's room and occupant characteristics, which needs physical measurement for providing insight to cause-and-effect in building. The measurement data still requires an understanding of occupancy behaviour characteristics in order to visualise the actual indoor thermal environment (Tuniki et al. 2021). Occupant's perception and characteristics in building can help to establish the building context and to define the internal parameters affecting occupants' room perception and the building's environment in use. Keeping a diary on daily activities related to thermal environments is a self-report, which can provide feedback on a building's performance in use after it has been occupied. Gathering monitoring data to supplement either occupant's diary or survey can be practical to clarify the internal parameters affecting the indoor environment (Hänninen et al. 2017).

According to ASHRAE Standard 55-2017 (ASHRAE 2017), measurement shall be taken in areas which have potentially different conditions, e.g. near occupied area, near aperture and in corner. Air temperature and average air speed shall be measured at 0.1, 0.6, and 1.1 m high from floor for seated occupant and at 0.1, 1.1, and 1.7 m high from floor for standing occupant. Measurement periods must be at least two hours and must reflect a sample of the total occupied hours. Measurement requires to collect data at less than of five-minute intervals for air temperature, humidity and mean radiant temperature and three minute intervals for air speed.

2.7.2 Phase 2- Exploring methods for evaluating the potential design options

It is important to evaluate the improved thermal comfort and indoor environmental quality achieved by the passive design options. This section initially carries out a technical evaluation of the impact of the passive natural ventilation strategies.

Natural ventilation is air exchange between outdoor and indoor spaces, which is caused by pressure change due to different forces, wind force effect and buoyancy (Aflaki et al. 2015). The external wind force is affected by environmental contexts, such as wind speed and direction, building orientation, nearby building, location and vegetation around building. While the internal air flow results from indoor space parameters, such as ventilation aperture size and location, partition and temperature changes (Jiru and Bitsuamlak 2010). Investigating the factors influencing natural ventilation requires exploration of both outdoor and indoor parameters of apartment block.

In order to understand how natural ventilation can improve indoor environmental quality in Thailand context, flow and interactions of air movement demonstration is necessary. The demonstration can show the performance and factor influencing on natural ventilation. In addition, the flow performance of a building can be used to determine the internal environment's characteristics, such as thermal comfort and Indoor Air Quality (IAQ) (Omrani et al. 2017). Therefore, appropriate methods should be used to assess a building's ventilation performance.

The performance of natural ventilation can be evaluated by experimental study (Bu et al. 2010; Bady et al. 2011; Ji et al. 2011; Calautit and Hughes 2014; Elshafei et al. 2017), analytical study (Hussain and Oosthuizen 2012; Dehghan et al. 2013; Elshafei et al. 2017; Ma et al. 2017) and CFD modelling (Tan and Glicksman 2005; Asfour and Gadi 2008; Zhang et al. 2013a; Calautit and Hughes 2014; Duy and Pham 2021). Experimental study can provide a high level of control and can be more flexible in testing different parameters but the process of conducting experiment is costly and requires space and specialised equipment for experiment. Analytical study using mathematical model processes is only possible for simplified situation, which cannot represent all aspects of building. CFD modelling uses data of specific physical boundary conditions and can simulate flow parameters that are rarely accessible by experiment. CFD can perform at full scale to provide detailed flow field data (Gilani et al. 2016). CFD simulation can visualise flow patterns, pressure variation and temperature distribution for both outdoor and indoor environment. The cost of CFD modelling is usually lower than the experiment cost (Zhai et al. 2011). The accuracy and reliability of CFD modelling remain important concern, therefore the modelling requires a process of verification and validation. Determining parameters related to the building influence on natural ventilation needs detailed and systematic sensitivity analyses.

Sensitivity analysis is a method to evaluate the influence of different independent variables on a particular dependent variable under a given set of assumptions. Sensitivity analysis is generally used to investigate critical control point, prioritise data collection and verify and validate a model (Christopher Frey and Patil 2002). CFD sensitivity analysis has been used as a method in investigating ventilation performance in much research (Zhai and Chen 2006; Montazeri and Blocken 2013; Gilani et al. 2016; Castillo et al. 2019). This is because CFD sensitivity analysis can perform the impact of computational parameter, turbulence model, iterative convergence and geometrical parameter on the predicted temperature and ventilation.

CFD can be combined with other methods to simulate air velocity and thermal characteristic in model. Many researchers used CFD coupled with airflow network model (Wang and Chen 2008; Zhang et al. 2013a; Kato 2018).

<u>CFD coupled with multizone:</u> multizone model is based on method of dividing building into several zones. Airflow network model has been developed to solve airflow in the entire building through numerical model between each zone (Johnson et al. 2012). Zone conditions, including air velocity, humidity and temperature are then calculated based on the pressure difference between each specified zone, and steady state conditions is commonly used to solve the solution. Multizone models can predict ventilation performance in a whole building because of bulk solutions; however, the model cannot provide more details about flow patterns within each zone. Integrating CFD with multi-zone model improves simulation accuracy(Mora et al. 2003; Chen and Wen 2010). There are successful examples of previous research using CFD model

integrated with multizone models (Wang and Chen 2007; Lo Brano et al. 2011; Tagade et al. 2013; Zhiyi et al. 2021).

CFD coupled with Building Energy Simulation (BES): BES model is the combination of airflow network model (multi-zone model) and thermal model. BES model can provide natural ventilation result (same as multi-zone model). In addition, the model can also provide thermal performance in building, such as heating, cooling and lighting, which can then be used to study thermal comfort and indoor air quality (Han et al. 2015; Kwok et al. 2020). There are successful examples of previous research used CFD model coupling with BES(Zhang et al. 2013b; Barbason and Reiter 2014; Yu et al. 2019).

The accuracy and reliability of CFD model is due to not only theoretical principles but also on experience of user, which is the combination of theory-based and process-based method (Rong et al. 2016). The sources of errors and uncertainties in simulation results can be divided into two categories, including numerical and modelling. Numerical errors and uncertainties are caused by numerical solutions of mathematical equations, such as grid convergence, discretization, artificial dissipation, incomplete iterative, internal and external boundary noncontinuity and insufficient mass, momentum, and energy conservation. Error and uncertainties in modelling are caused by assumptions and approximations in the mathematical representation of the physical issue, such as geometry, mathematical equation, boundary condition, turbulence model, material properties, etc. (Stern et al. 2001). The procedure of assessing error and uncertainties in the numerical modelling is called verification and validation. Verification is the process of determining accuracy of the computational model by assessing simulation numerical uncertainty in relation to:

- Turbulence model is the crucial effect in fluid flow simulation [54]. Turbulence models in CFD are mathematical models including the effect of turbulence in fluid flow simulation. which can be mainly categorised into three groups including, Direct Numerical Simulation (DNS), Large Eddy Simulation (LES) and Reynolds-average Navier-Stokes (RANS). DNS models apply Navier-Stokes equations in numerically solving method and to resolve all scales (Zhou 2018). DNS method requires fine grid resolution and very small-time steps for simulating indoor air distribution, which then requires powerful computer in CFD process (Zhai et al. 2007). LES can provide instantaneous airflow and turbulence details with considerable computational resources. LES models are more computationally expensive than RANS models (IdealSimulations 2023). RANS models are based on time-averaging of Navier-Stokes equations, which provide computationally efficient of turbulent flow. RANS is a LES model which aims to directly simulate the large-scale eddies in turbulent flows while replacing micro eddies with turbulence model. RANS is more common method for simulating indoor air distribution because it requires less computer time and user skills (Zhai et al. 2007),(Franke et al. 2011). Selecting a correct turbulence model is very important in CFD simulation process, for example k-ε model for stratified flows, a low-Reynolds-number k-ε model for transport processes close to surfaces, and an LES model for simulating very high detailed detail of flow (Baharvand et al. 2013). Nielsen (Nielsen 1998) studied different turbulent models and suggested that the k-Ɛ model for stratified flows. The researcher also stated about low Reynolds number that k-Ɛ model for transport processes close to surface are useful for a provisional model. Chen (Chen 1995) suggested that standard k-ε and RNG k-ε can estimate airflow more accurately. Tablada et.al(Tablada et al. 2009) found the positive effect of natural ventilation and thermal comfort in building courtyard in tropical climate by using CFD programme coupled with BES and the numerical model is RANS with k-ε model.

- Computational grid size is discretized grid used to depict the fluid region in the numerical modelling. Many CFD programmes support either unstructured or structed grids (Yunus 2010). Unstructured grid consists of cells of different forms, such as triangular, quadrilaterals (2-D) and hexahedrons (3-D). Unstructured grid is typically much simpler for the creating grid generation code. Structured grid, on the other hand, includes of planar cell with four edges (2-D) or volumetric cells with six edge (3-D). Structured grid has some advantages in some CFD codes as codes written for structured grids, which results in more quickly and accurately. Smaller grid size is typically generated with structured grid than with unstructured grid.
- Numerical models refer to finite difference in CFD. The numerical techniques classically used in CFD are finite difference method (FDM), finite element method (FEM) and finite volume method (FVM) (Tezuka 2006; Sjodin 2016). FDM is point based method which direct approach to discretizing the partial differential

equations. FEM is based on element. FEM applies weight residual error in integral form and then used solution function over each finite element domain. FEM is typically used to simulate solid model. FEM can solve complex shape better than FDM, however, if the boundary is not stable, FVM should be applied. FVM is similar to FEM, which is commonly used to simulate fluid model. FVM is a method for solving partial different equations in the form of differential algebraic equation (Madhlopa 2022).

- Boundary condition refers to the specification of boundary value problems in computational domain. Appropriate boundary condition is needed to acquire an accurate CFD result. Boundary conditions must be thoroughly implemented at all boundaries of the computational domain, including Wall Boundary Conditions, Inflow and Outflow Boundary Conditions, Miscellaneous Boundary Conditions, and Internal Boundary Conditions (Yunus 2010). Wall Boundary is set to be zero for air velocity because of the no-slip condition. Wall temperature, wall heat flux and wall material property also must be specified. Inflow and Outflow Boundary Condition typically classified as either velocity-specified conditions or pressure specified conditions. Miscellaneous Boundary Conditions are the boundaries neither walls nor inlets or outlets, but rather enforce symmetry or transitionally. Internal Boundary Condition refers to a condition existed inside the computational domain.
- Wind pressure coefficient (Cp) is an essential factor influencing on natural ventilation in BES and EnergyPlus Airflow Network. Cp is dimensionless of number used to describe the relative wind pressure distribution over a building surface to the wind-induced pressure (DesignBuilder 2023). The source of Cp data used in BES typically come from primary sources, e.g. experiment study and CFD simulation, and secondary sources, e.g. other research and databases derived from experimental study (Cóstola et al. 2009). Using Cp data accurately is crucial in order to obtain more precise estimates of natural ventilation rates. Default template of Cp in DesignBuilder is supplied by database from Liddament, M. W., AIVC (Liddament 1986). In addition, Cp is frequently incorrectly used in BES, which lead to uncertainty in natural ventilation rate up to 19% (Xie et al. 2023). Wind speed regarding to site terrain and opening height should be taken into consideration in the BES.

- Other numerical techniques include numerical approximations, the round-off error, time step size, iterative convergence, pressure coefficient

Validation is the process of determining accuracy degree of a model by assessing simulation model uncertainty. There are some common methods for validating the CFD model by comparing the computational results to other source data (Committee 1998), such as experimental data (Oberkampf and Roy 2010), real-site data (Van Hooff and Blocken 2012), related case study (Hong et al. 2017), and numerical study (Martins and da Graça 2016). Validation method is essential not only to ensure accuracy of CFD model but also to establish credibility of the model. There are many methods to validate CFD model, for example as follow (Jauregui and Silva 2011):

- Experimental data validation is the most widely used method because the measurement result can provide the consistency of the model with reality (Oberkampf and Roy 2010). The experimental data can be derived through either primary sources or secondary sources, such as conducting full-scale experimental or real-site data, small-scale experiment and experimental data from related case study.
- Analytical solution validation is the method of comparing the CFD model with the solution, such as Navier-Stoke equation. This method is typically used to validate code of numerical method. However, the main disadvantage of such method is the CFD model needs to simplify model's geometries because it is extremely challenging to discover analytical solution to the actual problems.
- Numerical solution validation is the process of determining the accuracy of CFD model in solving fluid mechanics equations with numerical methods. In order to affirm that the numerical solution is entirely compatible and accurate, the mathematical model must include every aspect of reality and the numerical method must precisely solve the equation of the mathematical modelling.

2.7.3 Phase 3- Methods for validating options for design solutions

The integration of all findings including, literature review, survey and measurement, external and internal factors on natural ventilation performance, and Thailand context can conduct a guideline and design framework of improving internal natural ventilation in Thailand context. However, proposing the design framework still need to validate the potential design options. Despite the validation of natural ventilation performance mentioned in Section 2.7.2 is essential for proposing and validating potential design options, the design options still need to concern users' or stakeholders' requirements and expectations.

To obtain more comprehensive understanding of the proposed design options from various perspectives, it is critical to consider opinions of built professionals on construction in relation to local context. Professionals can deliver a wealth of knowledge and experience in their field. In addition, the professionals can provide valuable insights on the functionality, aesthetic, performance and feasibility of the proposed design options, which can be used to validate that the options meet both principles and practices. There are some methods for obtaining built professionals' opinions.

Interview is a method of collecting information from people, which can provide in-depth information and feedback of specific topic, which involves either individual or small groups. Interview can be divided into three types, including unstructured, structured and semi-structured (Kumar 2018). Unstructured interview is useful in offering flexibility while exploring information, however, this approach reduces reliability. Structured interview is based on a predetermined set of questions before interviewing. The structured interview provides the information, which can be compared and validated. Semi-structured interview allows the process of collecting data of both predetermined questions and open-ended questions. Semi-structured interview not only provides the opportunity for achieving the comparable data but also allows the respondent to provide more flexible and extensive information (Kallio et al. 2016).

Focus group is a method of discussion with a group of people. Focus group encourages the interaction between participants to discuss and provide their opinion on particular topic. Focus group provides the benefit of group discussion; however, the dynamics of a group can also lead to the suppression of opposing opinions and strengthening of established opinions (Plummer-D'Amato 2008).

Delphi method is a process to collect and collate expert opinions. This method typically involves with several rounds of data collection to elicit feedback and opinions on the specific issue. Each round's outcomes are analysed and used to improve the questions for the next round as well as being fed back to the expert participants. This procedure is repeated until the experts reach an agreement. The Delphi Method is especially effective for validating complicated frameworks or models (Saffie and Rasmani 2016).

Questionnaire is a method of collecting data which can be used to gather built professionals' opinions. A questionnaire allows anonymous data collection from a wide range of built professionals. Questionnaire is less time consuming in comparison to other data collection method. However, the professionals need to fully comprehend the context and goal of the questionnaire, any misunderstanding of the questionnaire context results in incorrect response and potentially untrustworthy data (Krosnick 2018).

2.8 Summary Literature Review

The initial literature review focuses on Thailand's climate conditions and thermal comfort considerations. Thailand's climate is characterised by high temperatures and relative humidity. The minimal temperature differences between indoors and outdoors contributes to inadequate air circulation within buildings. While tropical countries such as Thailand ideally require an airspeed of at least 0.2 $m.s^{-1}$ for comfort, single-sided ventilation in multi-residential buildings often results in significantly reduced airflow down to 0 $m.s^{-1}$. Adequate ventilation is crucial for extending the thermal comfort range by providing a cooling effect. Ventilation is a crucial factor in influencing air and moisture flow through building openings. Enhancing air circulation is critical for producing a comfortable condition. Relative humidity also influences human thermal experience and comfort, with high levels generating risks to health. Thus, it is appropriate to investigate specific building designs in relation to mitigating internal moisture and minimising the growth of bioaerosols. The study sets thermal comfort and relative humidity ranges for health benefit as criteria for CFD sensitivity analysis in Chapter 7.

Passive cooling through ventilation is a potential strategy for achieving thermal comfort sustainably. Solar chimneys, in particular, utilise buoyant effects to improve room ventilation and enhance airflow for urban residential buildings. The following factors have been identified as influencing the performance of solar chimneys, such as environmental conditions, configuration, installation, and materials. Recycled materials were thoroughly investigated for their capacity to give comparable properties to raw materials while adhering to the concept of sustainability. These passive cooling strategies were used in design options analysed in CFD sensitivity analysis in Chapter 7, with recycled materials assigned for material properties in the CFD model.

The research methodology was divided into three major phases. The exploration of research methods (Section 2.7) involves a systematic process of identifying and analysing relevant research methods for each phase of the study. The selected methods were then analysed in Section 3.2.

3 Methodology

3.1 Introduction

In the literature review, the research explored the potential of the passive cooling technique (Section 2.4), Thailand's climate conditions and Thailand's thermal comfort (Section 2.2). The literature review indicated that improving airflow can possibly enhance the residential unit to achieve acceptable indoor environmental quality (IEQ) in relation to temperature and relative humidity. However, investigating the potential of passive design strategies to improve indoor environmental quality in thermally free-running apartment dwellings in Thailand is required. Passive design strategies can be effectively selected based on climate conditions and building characteristics (Wang et al. 2021). The performance of the passive design options can then be evaluated.

This chapter presents the research methodology employed to collect and analyse data. The detailed analysis of the selected methods for this study is described in Section 3.2. The selected method is divided into three main phases, each aligning with the methodological exploration as detailed in Section 2.7.

<u>Phase 1</u>- Selected methods for multi-residential building context in Chiang Mai (Section 3.2.1): This initial phase focuses on the contextual analysis of multi-residential buildings in Chiang Mai, which is essential for achieving Objectives 1, 2, and 3. It involves evaluating the current situation and characterising the key features of typical buildings in the area.

<u>Phase 2</u>- Selected methods for evaluating the potential design options (Section 3.2.2): This phase is established to obtain objectives 4 and 5. To evaluate the potential design, it seeks to explore both outdoor and indoor factors that influence ventilation.

<u>Phase 3</u>- Selected methods for validating options for design solutions (Section 3.2.3): This final phase involves validating the proposed design options. This phase is to fulfil Objective 6.

3.2 Selected Research Methods

The main criteria for selecting methods in this research are (in order of importance)

1) to achieve the research aim

2) tool availability

3) optimise research efficiency

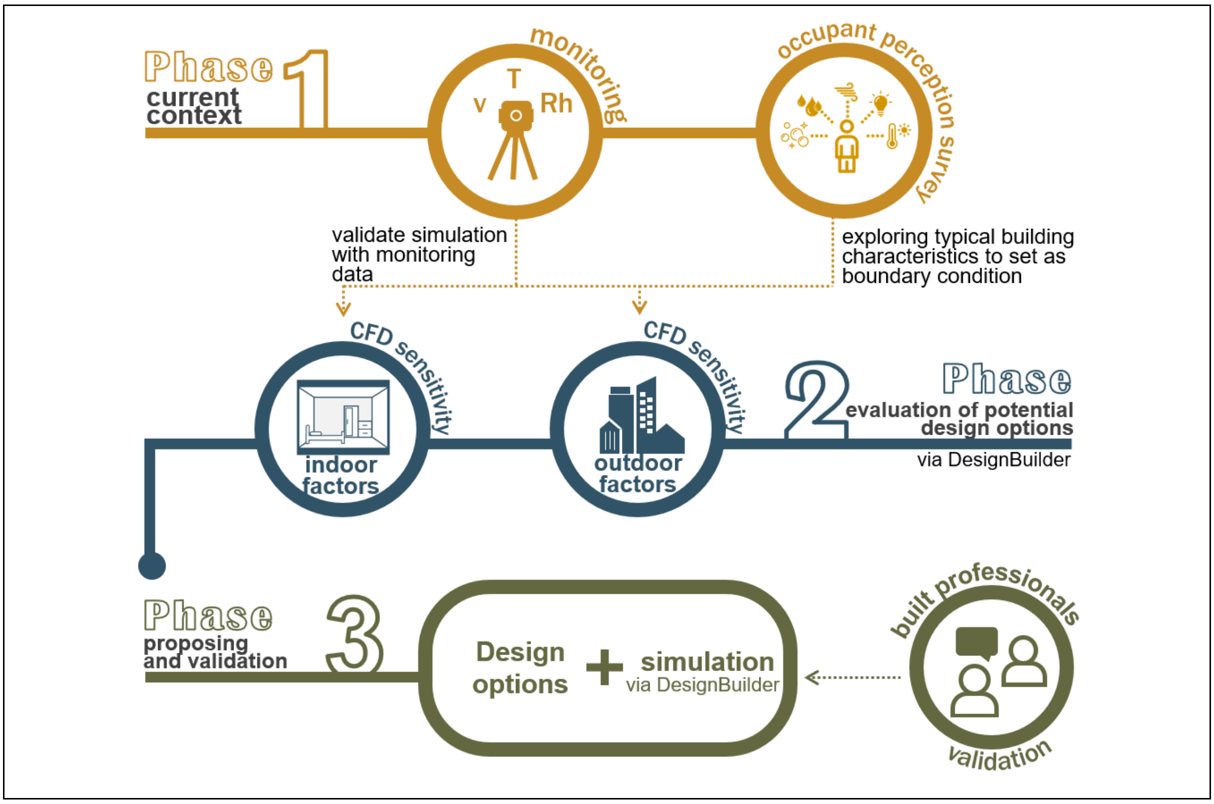


Figure 3- 1 summary of research methods
(Source: Author)

3.2.1 Phase 1- Selected methods for multi-residential building context in Chiang Mai

Referring to the aim of the research of investigating the potential of passive design options to improve indoor environmental quality, identifying typical apartment block characteristics and occupant satisfaction is crucial for understanding the context and investigating the appropriate solution.

Chiang Mai was chosen as a case study location for this research. The research focussed on multi-residential buildings in urban areas. Chiang Mai is characterised as a densely populated city in Thailand, with a population density of around 1,540 people per square kilometre (AdministrativeStrategyDivision 2018). Furthermore, travel restrictions imposed during the Covid-19 pandemic in Thailand posed challenges for conducting research in other cities. Hence, Chiang Mai emerged as a viable and accessible case study location with significant potential for exploration.

In order to investigate the actual environment in a multi-residential building context, monitoring physical measurements can provide insights into internal parameters affecting occupants. To classify the key features of typical apartments in Thailand, high quality and relevant secondary sources are available to support this investigation. These include Thailand Building Regulation, weather data, and census data, detailed below:

Building regulations will be used to understand the minimum requirement for a multi-residential building context in Thailand. The regulation will be used to form the base case in the research, for example, minimum space between site boundary, building height, the minimum size and dimension of the room, etc. Two main categories of building regulations in relation to multi-storey residential building design are the Building Control Act (2015) and the Town Planning Act (MinistryofInterior 2012).

Building Control Act (MinistryofInterior 2015) prescribes the minimum requirement of both exterior and interior of the building. For the exterior space, the regulation establishes the minimum distance between the site boundary, road, and neighbour, as well as the open space ratio. Some key factors include:

- the wall or balcony must keep a distance of at least 3 metres from the site boundary for a building built taller than 9 metres but not over 23 metres high.
- the setback distance of a building from a public road shall be determined based on the width of the road (See Figure 3- 2).

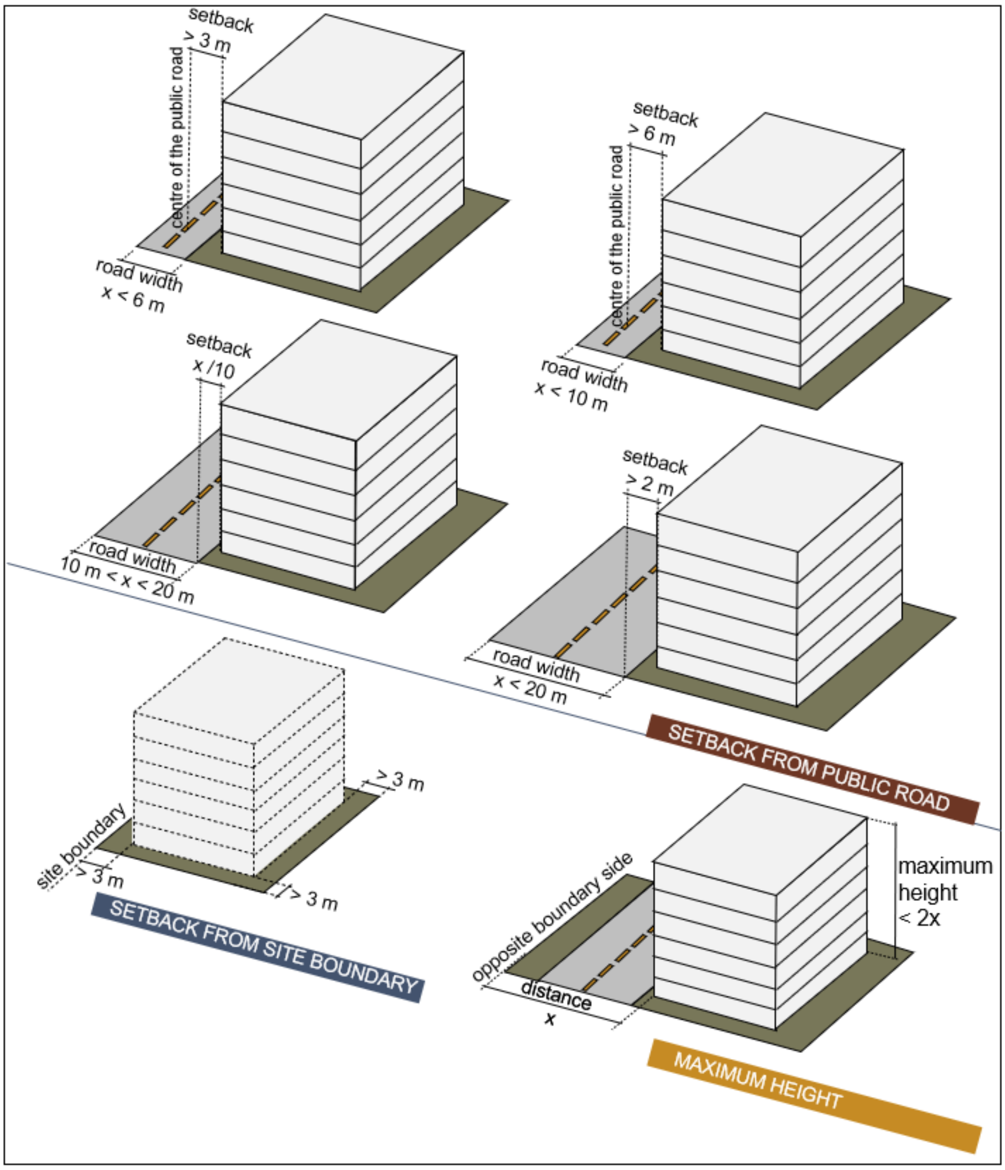


Figure 3- 2 The regulation for building boundary and setback dimension of Building Control Act
(Source: Author)

For residential interior space, key factors include:

- interior floor space minimum area of 20 square metres
- minimum 2.5 metre width of the narrowest side of the bedroom
- minimum 2.6 metre ceiling height
- minimum 1.5 metre width of corridor
- refractory material for building structure
- minimum 10 % of room floor area for natural ventilation aperture area (Interior 2000) (See Figure 3- 3).

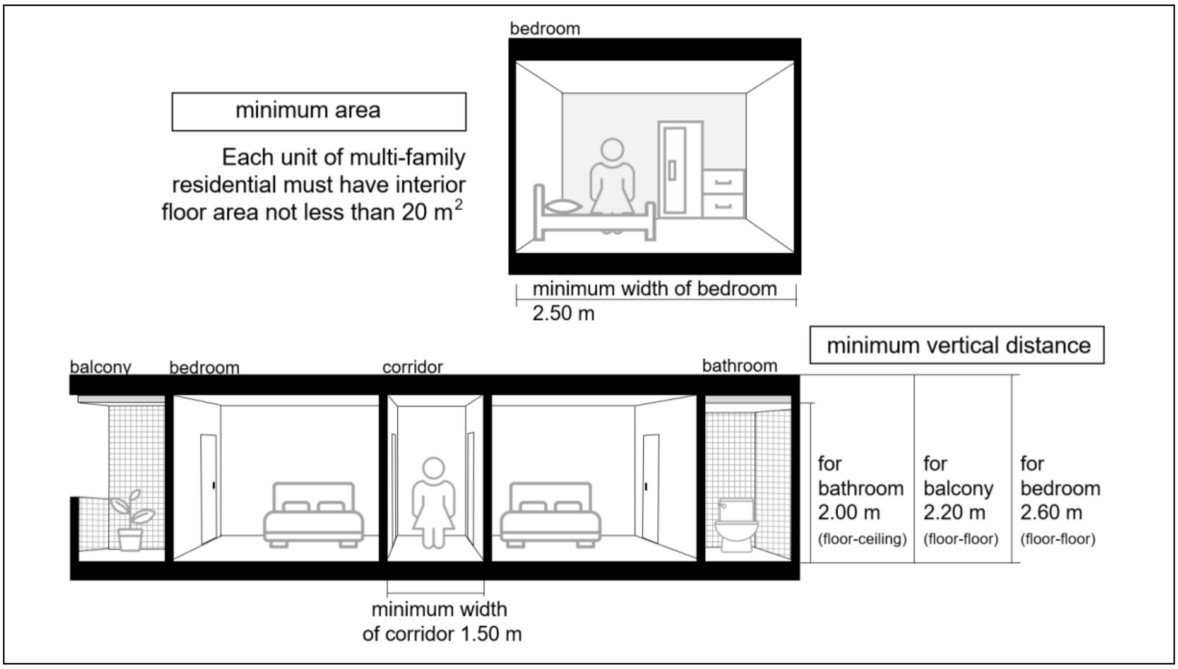


Figure 3- 3 The regulation for indoor dimension of Building Control Act. No.55
(Source: Author)

The Town Planning Act prescribes colour coded for permissible usage and also regulates the Open Space Ratio and Floor Area Ratio (MinistryofInterior 2012). Department of Public Works and Town and Country Planning regulates the use of land and living of residents. Different zones have different limitations for land uses, adjacent lots and building height. In Figure 3- 4, red and orange zone are regulated for being high-density residential zone and commercial zone, and medium-density residential zone. These areas also often have issues with environmental quality (Edussuriya et al. 2011). This regulation outlines the scope of town planning, thereby guiding the selection of zone for monitoring data collection. The focus of this study is on low-rise buildings in Thailand, which are defined as buildings lower than 23 meters in height according to Thailand's Ministerial Building Regulations No 33 (MinistryofInterior 1994). These buildings are typically set back only 3 meters from the site boundary, which can result in a dense and obstructed environment. Additionally, the minimum requirement for room aperture (10% of room area) can cause further problems in the room.

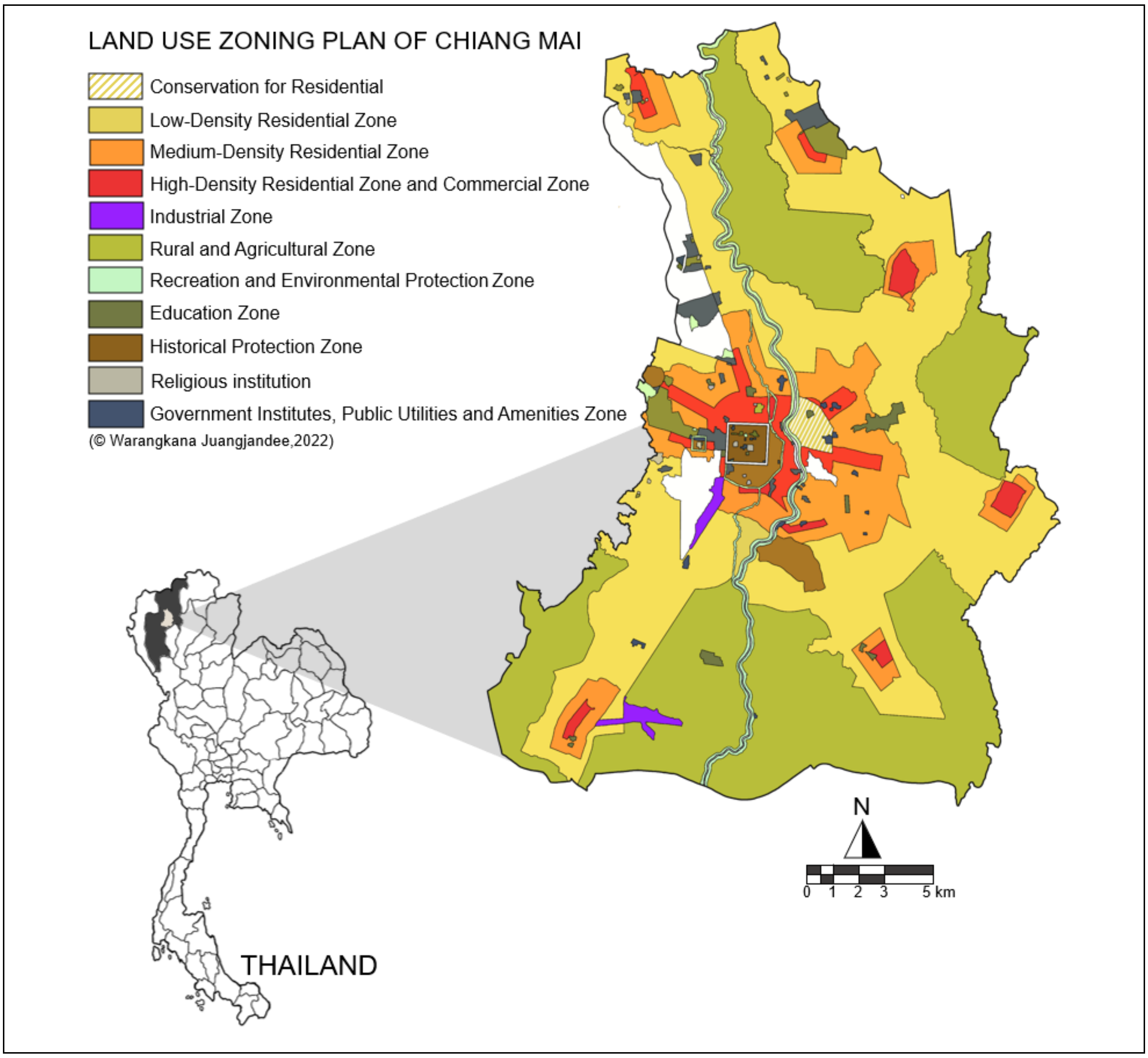


Figure 3- 4 Chiang Mai Planning Act.
(Source: Author)

<u>Weather data:</u> As mentioned in Section 2.7.1.1 about Chiang Mai weather data providers, the Thai Meteorological Department is an official organisation providing reliable weather data. However, there are some data limitations, particularly in relation to global radiation, direct normal radiation, diffuse horizontal radiation, total sky cover etc. Other Chiang Mai weather data was available from OneBuilding and PVGIS, which had solar data but not available from the Thai Meteorological Department. The OneBuilding and PVGIS dataset were compared to the data from Thai Meteorological Department. The data which had least difference from the Chiang Mai data from the Thai Meteorological department would be used in the study.

Both Regression and Root Mean Square Error (RMSE) were used to evaluate the accuracy of each weather data set. Regression is used to determine the relationship between two variables and to develop the mathematical model for predicting the relationship (Olive 2017). Regression is useful tool for analysing trend of the data. Regression is calculated as of square R. The square R is a statistical measure that represents the proportion of the variance in the dependent variable that is explainable by independent variable and the closer this value is to 1, the stronger relationship (Sternstein 1996). RMSE, on the other hand, is typically used to evaluate the difference between two datasets and assess accuracy of the data. To ensure the accuracy of the weather dataset, the research compared weather data from different providers with the climate data from the Thailand Meteorological Department by applying the Regression and RMSE method (see Table 3- 1). The OneBuilding data showed the lowest errors when compared to the data from Meteorological Department and has been chosen for using in this research.

Table 3- 1 weather data source and details

meta data	Source	**Meteorological Department**	**OneBuilding**	**PVGIS**
	Location	Chiang Mai	Chiang Mai	Chiang Mai
	Period	20 years	15 years	10 years
		2001-2020	2004-2018	2007-2016
	Methodology	n/a	TMY/ISO 15927-4	TMY/ISO 15927-4
	Type	hourly	hourly	hourly
available data	Dry bulb	✓	✓	✓
	Wet bulb	✓	✓	✓
	Relative Humidity	✓	✓	✓
	Global horizontal radiation		✓	✓
	Direct norm radiation		✓	✓
	Diffuse radiation		✓	✓
	Wind speed	✓	✓	✓
	Wind direction		✓	✓
	Sky cover		✓	
	Total surface radiation		✓	✓
	Ground temperature		✓	
	Illumination data		✓	
data accuracy	Temperature - Square R		0.92	0.99
	Temperature - RMSE		0.08	1.51
	Relative humidity - Square R		0.89	0.98
	Relative humidity - RMSE		2.00	12.19

Building characteristics: Despite the limitation of typical multi-storey residential building information in Thailand, information related to the building's environment is still needed to define the internal parameters affecting occupants' room perception. A questionnaire can be used to visualise the typical apartment block characteristics and occupant perception of their room.

In addition, investigating internal parameters affecting occupants' room perception requires a deep interpretation of the occupant's room and occupant characteristics, which needs physical measurement to provide insight into cause-and-effect on the building. Physical measurement is a process of examining quantitative data, which can be applied to evaluate building's performance. However, only conducting physical measurement cannot visualise the actual indoor thermal environment relation to occupancy behaviour characteristic. The occupants' behaviour characteristic is also a crucial factor for understanding the indoor environment. To identify the internal parameters affecting indoor environments, physical measurement was conducted in participant rooms and the participants were required to keep a diary on daily activities related to thermal environments.

3.2.2 Phase 2- Selected methods for evaluating potential design options

Having established the context for the current building situation, the next step is to explore factors which can improve indoor environmental quality through natural ventilation. Sensitivity analysis will be carried out separately for external (Section 3.5) and internal factors influencing natural ventilation (Section 3.6).

CFD will be used to carry out a sensitivity analysis of factors affecting the performance of natural ventilation. Varying input parameters and assessing the impact can help to identify the most influential parameters on the natural ventilation performance (Tian 2013). In addition, CFD sensitivity can also be used to identify uncertainty in the model, which is typically used as initial validation of CFD model (Anderson et al. 2007). CFD analysis can be used to simulate fluid flow, air movement and thermal properties for both outdoor and indoor(Gilani et al. 2016; Liu et al. 2017).

CFD analysis can be combined with Building Energy Simulation (BES) to model the complex interactions between airflow, temperature, and energy usage within a building. This method can be used to optimise building design and operation by providing valuable insights into the factors that influence building performance.

There are some available CFD programme supporting BES, for example, ANSYS Fluent, OpenFOAM, Fluent BES, and DesignBuilder etc. CFD in DesignBuilder programme can be used to simulate airflow and temperature distribution for both external and internal analyses. DesignBuilder has been selected as it provides visualisation and analysis and has a well-designed user interface (DesignBuilder 2019). DesignBuilder has been successfully used in various previous studies for simulating residential buildings (Daemei et al. 2016; An-Naggar et al. 2017; Elshafei et al. 2017; Arumugam et al. 2022) and multi-storey buildings (Azarbayjani 2013; Anđelković et al. 2016; Ayegbusi et al. 2018; Omrany et al. 2023). DesignBuilder is less time consuming in setting up the geometry and boundary conditions of the model compared to other conventional CFD programme coupled with BES. In addition, boundary condition of model in DesignBuilder can be derived from temperature, airflow, and heat flow in EnergyPlus (DesignBuilder 2023a). CFD analysis in DesignBuilder uses the following: This section will explain the specific components used with DesignBuilder as following:

- Turbulence model utilises k-epsilon (k- ε) turbulence model. The turbulent kinetic energy (k) and rate of dissipation (ε) are modelled and solved for the model additionally to the continuity and momentum equations. In the k-ε model, turbulence can be represented by a uniform eddy viscosity proportional to the kinetic energy and dissipation rate. The model is often used for building energy simulation.
- Computational grid is a non-uniform rectilinear Cartesian grid. The grid is automatically generated when creating a CFD model. The grid lines are parallel to the main axes, and the space among the grid lines allows for non-uniformity.
- Numerical method utilise Finite Volume Method, which involves the solution of set of equations of conservation of heat, mass and momentum (DesignBuilder 2019).The temperature equation uses the k-ε turbulence model for turbulence kinetic energy and its dissipation rate. The velocity component in the equations uses Navier-Stokes equation. The equations are a collection of coupled nonlinear second-order partial differential equations with the general form shown below:

$$\frac{\partial}{\partial t}(\rho\varphi) + \mathrm{div}(\rho u\varphi) = \mathrm{div}(\Gamma \mathrm{grad}\ \varphi) + S \qquad \text{(Equation 1)}$$

where φ represents the dependent variables, $\frac{\partial}{\partial t}(\rho\varphi)$ represents the rate of change, div(ρuφ) is convection, div(Γgrad φ) represents diffusion and S is a source term (DesignBuilder 2023a).

- Boundary condition: DesignBuilder does not only allow to indicate local boundary condition of airflow and temperature manually but also imports EnergyPlus simulation as boundary condition (DesignBuilder 2019). The data that can be imported are such as surface inside temperature of floor, window, door sub-surfaces and flow in and out of the opening. Importing EnergyPlus as a boundary condition helps for more accurate thermal simulation of building. EnergyPlus is a building simulation programme that can provide thermal load analysis and energy consumption (EnergyPlus 2023).
- Wind pressure coefficient (Cp): The default template for Cp in DesignBuilder has limitations as it is only suitable for building up to three storeys (DesignBuilder 2023b). However, this study focuses on taller buildings (23 metre / eight floor maximum). Hence, the default Cp template in DesignBuilder is not compatible for this study and external Cp data is required.

  MacroFlo is a module for analysing natural ventilation and infiltration in building within the IESVE software suite. The Cp data in MacroFlo is an open source and derived from wind tunnel experiments. It takes various local topography aspects into account, including exposure type, wind direction, building geometry, roof type, and nearby obstruction (Limited 2013). In previous research, wind pressure coefficient data obtained from MacroFlo was used to determine the coefficient for simulation purposes (Good et al. 2008; Wang et al. 2012; Spentzou et al. 2018), thereby enable to supplement DesignBuilder. The Cp data in MacroFlo incorporates the calculation method with the consideration of particular point of height and location to ensure the accuracy of simulations. As Cp is a key input for natural ventilation calculation in BES and multi-zone airflow model, it is essential to use Cp accurately for the appropriate reference height and building opening height.

  The pressure at particular point on a building surface can be calculated from the equation below:

$$P_w = 0.5 \cdot \rho \cdot Cp \cdot v^2 \quad \text{(Equation 2)}$$

where Pw is the surface pressure due to wind (Pa), ρ is air density (kg.m^{-3}),·Cp is wind pressure coefficient, and· v^2 represent the wind speed at height Z (m.s^{-1}).

$$v = uKh^a \qquad \text{(Equation 3)}$$

where u is meteorological wind speed measure at height 10 m (m.s^{-1}), h is height above the ground (m), a and K are coefficient representing different terrain types (See more detail in Appendix A)

This study will use two different data sources to validate the simulation model of DesignBuilder. Firstly, the model will be validated to real site data of multi-storey residential building in Thailand in the part of exploring the building in Thailand context (methodology described in Section 3.3). Secondly, to ensure the accurate result of DesignBuilder with Cp data, the model will be validated against results from different simulation programme. Regarding the limitation of DesignBuilder default template, EnergyPlus cannot provide data in relation to microclimate and cannot model physical terrain feature, such as ground inclination, vegetation and nearby buildings. Therefore, the model using the microclimate data from Envi-met and inputting the data into DesignBuilder will be used to validate DesignBuilder with MacroFlo Cp data (see more detail of validation in Section 3.6.1).

3.2.3 Phase 3- Selected methods for validating options for design solutions

To achieve the passive design options, the research requires the assessments from built environment professional (BEP) judgements on improving indoor environmental strategies and design techniques. The assessment will explore built professionals' opinions on the feasibility of proposed design options into a new multi-residential dwelling. The purpose of this phase is to achieve Objective 6 of the research.

Semi-structured interviews were used to explore the professionals perceptions on the proposed design options (detailed in Section 3.7).

3.2.4 Summary

The study applied physical measurement and occupant survey to establish the current situation faced by residents and correlated the data to Thai specific thermal comfort information from literature (Phase 1). Investigation of the possibilities was conducted by identifying factors affecting ventilation. External CFD sensitivity analysis was used to determine key influencing factors and how they relate to different locations within a building. Internal CFD analysis was conducted to explore design approaches to increase natural ventilation and minimising internal humidity gains (Phase 2). Based on the previous analysis, design options were developed and subsequently validated with built environment professionals in Thailand. (see workflow chart in Figure 3- 1)

Phase 1: current context.

- Monitoring physical measurement and keeping occupant's diary- the description in detail of the location, equipment and measurement strategy including diary and physical measurement to assess potential for stack ventilation (which validated literature info on difficulty of stack ventilation in this context) (in Section 3.3).
- Survey via questionnaire of occupants' opinion on thermal comfort satisfaction and indoor environment quality in the multi-storey buildings in Thailand (in Section 3.4).

Phase 2: evaluating the potential design options

CFD sensitivity analysis - the experimental procedure to analyse which parameters have critical effects on the focus building. The experiments can be divided into two main parts. External CFD sensitivity analysis (in Section 3.5) was to establish the potential contribution of wind ventilation in city centres. Indoor CFD sensitivity analysis (in Section 3.6) was to investigate indoor ventilation of Thailand typical apartment's room. The sensitivity analysis findings were then related to an actual site in Chiang Mai through further CFD analysis (in Section 3.6.1)

Phase 3: validating options for design solutions

Validating options for improving internal environment quality with thermally free-running apartments - narrations and definitions of design solution and developing a framework/guideline. In addition, the proposed solutions have been validated by seeking the view of Thail built environment professionals e.g., architects, academics and engineers (in Section 3.7).

3.3 Monitoring physical measurement (Phase 1)

To achieve objective 1, this study aims to investigate and interpret the actual indoor thermal environment in relation to occupancy characteristic. Physical measurement data will demonstrate actual data of indoor conditions in Chiang Mai at the time of occupant perception survey was taken. Additionally, some actual data will be used to validate CFD model in further steps (Section 3.6.1).

According to the finding reported in Chapter 2, single-sided ventilation in room can limit the effectiveness of natural ventilation. However, the buoyancy effect can enhance the ventilation pass through the room. Therefore, this study divided physical measurement into two parts, which are stack area and apartments' rooms. Monitoring physical measurement in stack area can examine natural buoyancy effect occurring in a building. Monitoring physical measurement in apartments' rooms can identify the actual indoor environmental quality. The physical measurement can also be used to evaluate building's IEQ performance in relation to temperature, relative humidity, and air movement. However, measurement alone cannot be used to relate indoor thermal environment in relation to occupancy characteristics. The occupants' behaviour characteristic is another crucial factor which affects the indoor environment. Combining building's performance in use with physical measurement data can be very useful to clarify the internal parameters affecting the indoor environment. Therefore, the study will collect occupant's diary in apartment's rooms as well as monitoring physical measurement.

Physical measurement was carried out in medium and high-density residential zone in Chiang Mai (see orange and red areas in Figure 3- 4).

3.3.1 Equipment

The monitoring equipment was installed according to ASHRAE 55 standard (ASHRAE 2010). Two types of equipment were employed for collecting data (see Figure 3- 5), which were Tinytag data logger for temperature and relative humidity monitoring and hot-wire anemometer (AM-4234SD) for measuring the air velocity. The intervals of the indoor environmental parameters recording were set at 1 minute. All devices were calibrated by Faculty of Architecture, Chiang Mai University on 12th December 2020.

Figure 3- 5 physical measurement equipment
(Source: Author)

3.3.2 Stack area

The stairwell of a 5-storey building exhibited some of the parameters of the stack chimney. Typically spanning the entire height of the building, a stairwell creates a natural pathway for air to rise. Additionally, this phenomenon can be empirically examined and compared to observe the effects of opening and closing building apertures in stairwell.

Monitoring equipment was installed at the stairwell of a 5-storey building in a high-density area of Chiangmai, Thailand (see Figure 3- 6, Figure 3- 7). The building is surrounded by 5-storey buildings. The nearest building is approximately 4.80 m away. The staircase is a U-shaped stair containing two flights of steps. The gap between the flights of the stair is 0.2 m (Figure 3- 8). Additionally, this concrete stairway has five doors connecting to each floor of the building and four awning windows facing west, located at each floor level's half landing.

The main purpose of this study is to investigate temperature, relative humidity, and buoyancy-driven air movement through the stairwell of a multi-storey building. The data for each parameter was collected at one-minute intervals from 19th December 2020 to 19th January 2021 (Thailand's winter season).

Figure 3- 8 indicates locations A to D where temperature and humidity data loggers (Tinytag) were located. In addition, hot-wire anemometers were placed at location B and D. The monitoring equipment was installed according to ASHRAE 55 standard (ASHRAE 2017). Location A, B, C, and D were 1.26 m, 4.50 m, 7.74 m, and 10.98 m high from the ground, respectively.

Several scenarios were chosen during the monitoring period (19th December 2020 to 19th January 2021) to evaluate the particular consequences of window openings at different levels of the stack. The field investigation collected data over period which was divided into 3 cases as followed. During this period, the weather conditions remained consistent across each day, with similar patterns of outdoor hourly temperatures and relative humidity.

- Case 1: only the window at the half landing between the 1st floor and the 2nd floor (W2) was opened. (19th December 2020 to 28th December 2020)
- Case 2: only the top window (W4) was opened. (29th December 2020 to 8th January 2021)

- Case 3: both W2 and W4 were opened. (9th January 2021 to 19th January 2021)

Figure 3- 6 model of a multi-storey building for collecting stack temperature, relative humidity, and air movement velocity
(Source: Author)

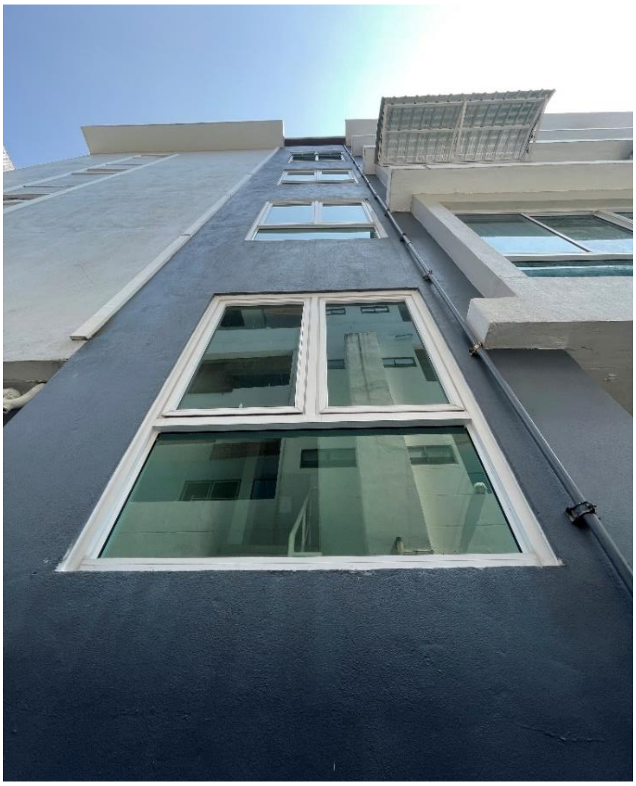


Figure 3- 7 actual exterior feature of a multi-storey building for collecting stack temperature, relative humidity, and air movement velocity

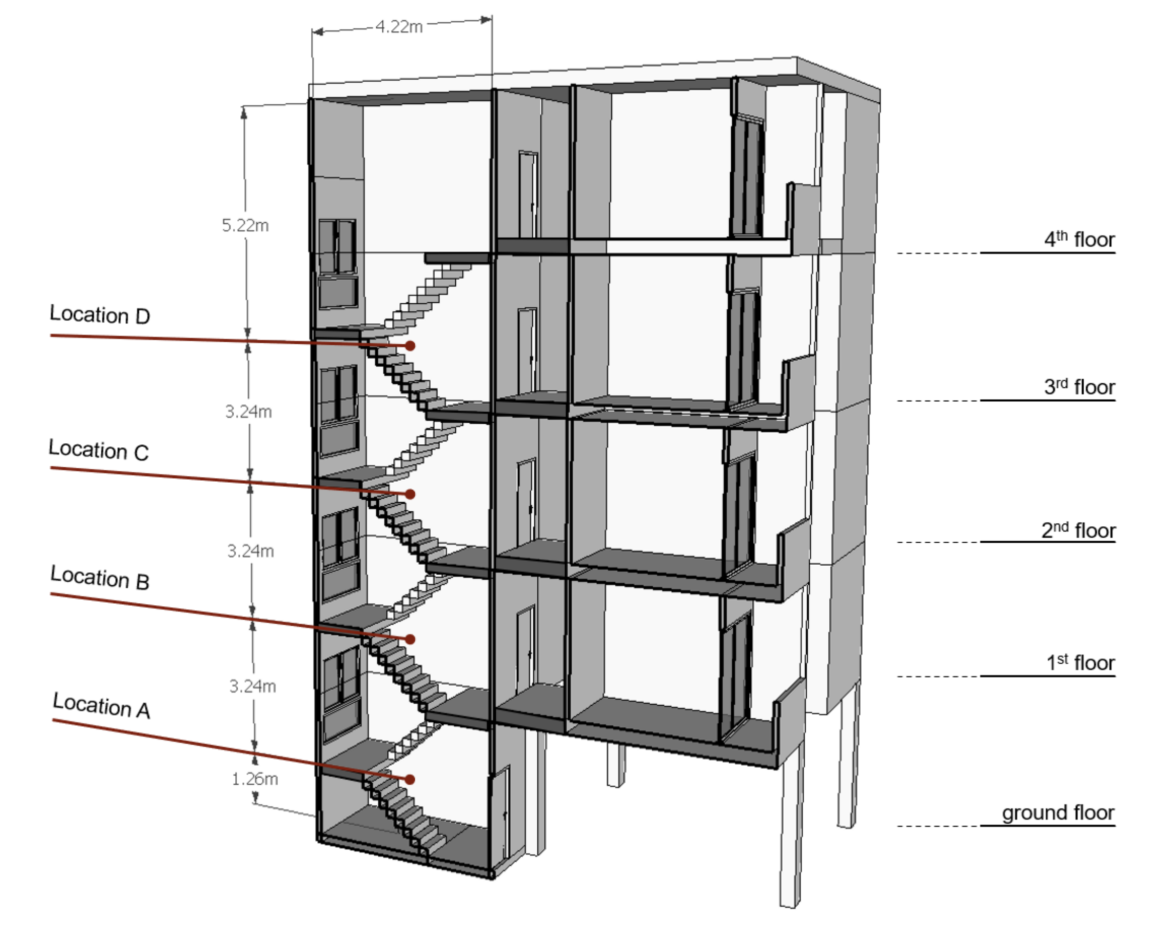


Figure 3- 8 schematic of the stairwell

Figure 3- 9 actual interior feature of the stairway

3.3.3 Apartments' rooms

Prior to this investigation, ethics approval (See Appendix C) was sought and received.

Requests for volunteers to participate in indoor monitoring and occupant diary research were sent to the people working in the Subdistrict Municipality. Subsequently participants were selected from two districts (clusters) of the urban area (also chosen for the occupant perception survey in Section 3.4). Purposive sampling method based on criteria of apartment location within the block was used to select specific participants. The participants were informed about project details, data protection, participant's right to withdraw, appropriate equipment location for monitoring and appropriate information to record in the diary. The measurement and data collecting took place without face-to-face interaction to reduce the risk of Covid-19 transmission. The participants received and returned equipment (temperature/ relative humidity monitors and anemometers) via post, while their diary was logged and transmitted in electronic form.

Monitoring and diary data was collected for four participants' rooms, in multi-storey buildings in Chiang Mai for 20 days in winter (between 16th January and 6th February 2021). The investigation collected data every minute. The rooms were in two multi-storey buildings with another multi-storey building in the vicinity. The buildings are approximately 4 km from each other and are situated in the city municipality. Open Space Ratio (OSR), percentage of open area relative to the building floor area, of both Building A and B are 5%.

Both buildings have a double-load corridor (see Figure 3- 3).

Room AC and AM are on the same side of the third floor in the same building, with AC representing a corner room and AM representing a mid-corridor room (see Figure 3-10). The building has five floors and is 4.8 m from its nearest neighbouring building which also has five floors. Room AC and AM have similar layout. The balcony width is half of the room width, and WC is located close to the balcony. However, room AC has openings on two sides, while room AM only has on one side. The area of room AC and AM are 30.18 m^2 and 23.48 m^2, respectively.

Room BC and BM are on the same side of the first floor of the same building, with BC representing a corner room and BM representing a mid-corridor room (See Figure 3-11). The building has 8 floors and 8 m from the nearest building which has six floors.

Both room BC and BM have balcony width with half size with room width and WC located close to room's door. Room BC is located at the corner, which has openings on two sides, while BM only has openings on one side. The area of room BC and BM is 30.28 m^2 and 30.28 m^2, respectively.

One Tinytag monitoring device was installed in each apartment's bedroom, 1.0 metre inward from the centre of the room's walls, according with ASHRAE 55 regulations. Furthermore, eight hot-wire anemometers were evenly distributed between the Room AC and AM, as shown in Figure 4-20. Both the Tinytag and hot-wire anemometers were set up as data loggers, automatically collecting data at one-minute intervals. Air temperature and air speed were measured at 0.6 m above floor level to represent conditions for sedentary occupants.

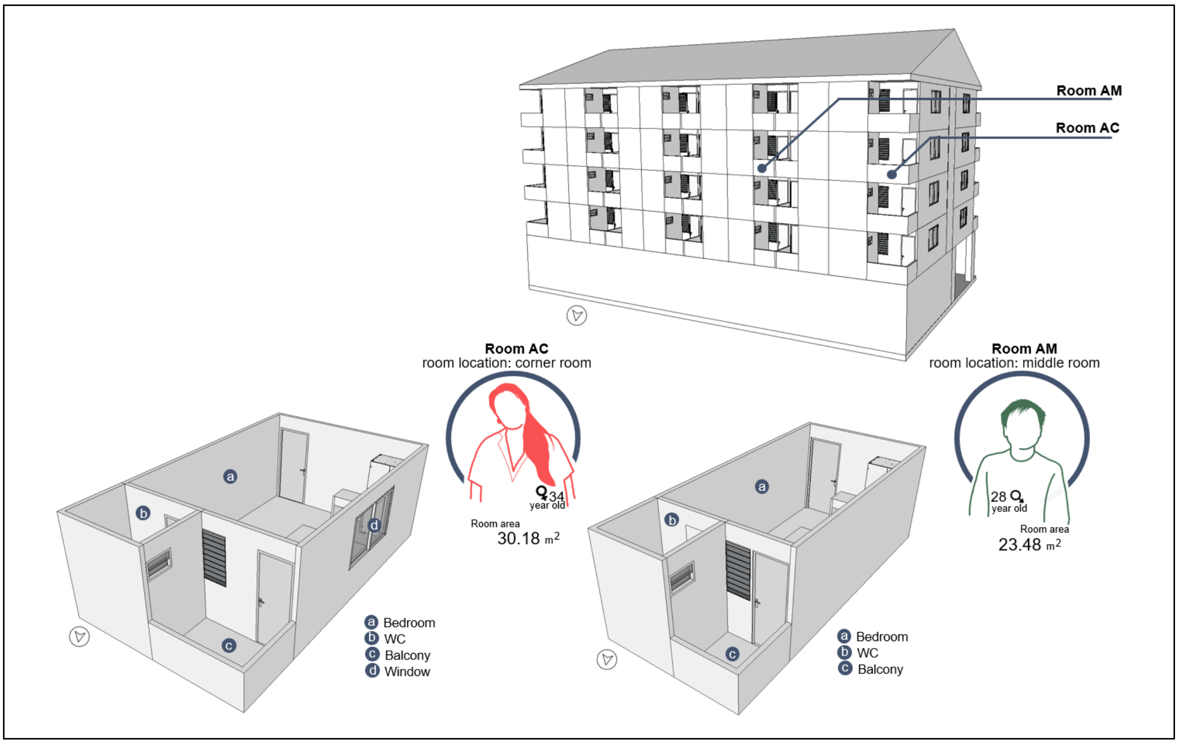


Figure 3- 10 schematic of occupants' rooms in building A (Room AM and AC)
(Source: Author)

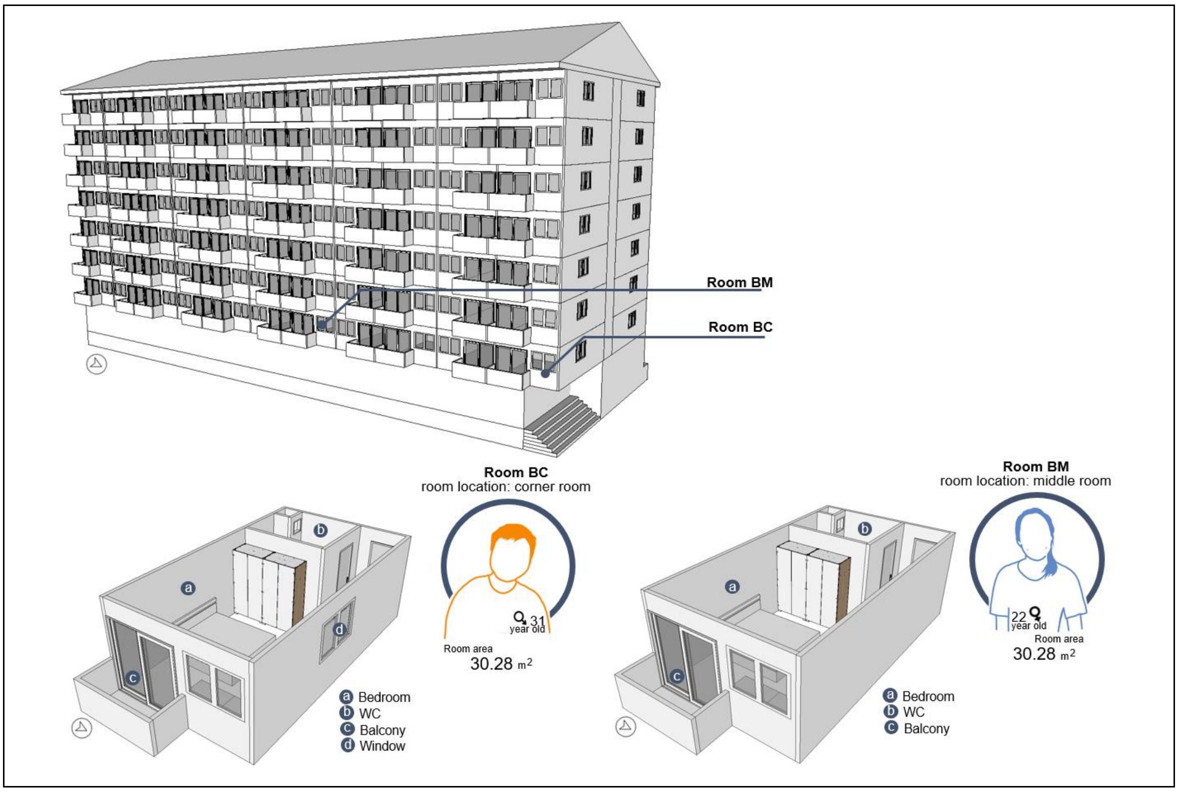


Figure 3- 11 schematic of occupants' rooms in building B (Room BC and BM)
(Source: Author)

<u>Occupant diary</u>

Referring from ASHRAE 55 (ASHRAE 2010), an effective solution to evaluate the indoor thermal condition is to occupant perception survey. An occupant was assigned to record occupant experience in the apartment room in a way that this data could be linked to the environmental condition being monitored in their room. This occupants' diary showed daily user behaviour and perceptions which facilitate the researcher to interpret the thermal environment (in conjunction with monitoring data) in relation to occupant behaviour within the spaces.

3.3.4 Data analysis

In order to understand the actual indoor environmental quality, it is important to consider multiple parameters affecting the room, including external factors and occupant behaviour characteristics. For stack area, the data analysis compared temperature, relative humidity and air movement at different heights within the stairwell. For apartments' rooms, the physical measurement data were analysed in relation to the occupant activities in the room. In addition, the data were evaluated basing on Bioclimatic chart to determine thermal comfort zone and were compared and air movement between each room's locations.

3.4 Occupant perception survey (Phase 1)

Questionnaire survey is a useful tool for assessing small and large populations. The addition of comment sections, provide an opportunity for respondents to elaborate on their answers (Ballal 2022). In addition, questionnaire is one of the self- report methods and serves as a tool for post-occupancy evaluation, gathering feedback on a building's performance in use after it has been occupied. Indoor environment quality issue and building performance can be defined by specific occupancy behaviour characteristics (Yan et al. 2015; Juangjandee et al. 2022). The behavioural pattern might develop due to a mixture of factors, including inside (gender, preference), and outside (air temperature, relative humidity, wind speed, and building features). Yik et al. (Yik et al. 2004) stated that survey could be used to define actual activities and moisture generation in the household. Xue et al. (Xue et al. 2014) applied questionnaire survey to explore the relationship between occupants' behaviour and lighting comfort in residential buildings. Therefore, questionnaire survey is used to reveal current typical apartment blocks characteristics in Thailand and also to understand occupant behaviour characteristics and perception of comfort of the room.

This survey is based on exploring the typical multi-storey residential characteristics, occupants' behaviour characteristics, indoor air environment perception on occupancy comfort in Thailand. Analysis of the data generated will allow comparison of the environmental performance experienced by occupants with satisfactory conditions.

The questionnaire has been approved by the Ethics Committee in Welsh School of Architecture, Cardiff University for avoiding any risk of any participants experiencing either physical or psychological discomfort (Appendix C). All the participants were informed about project details, data protection and, voluntary participation on a cover page.

3.4.1 Participant's criteria

Chiang Mai is selected as a case study.

This survey was carried out from February to May 2021. The respondent criterion is only adults (age range 18-60) living in multi-storey residential buildings in Chiang Mai. Yamane's formula (Equation 1) was used to calculate sample size. From this, the minimum number of necessary responses to meet the desired statistical constraints (confidence level with 95%) is 400 from the Chiang Mai metropolitan population of

190,199 people (ChiangMaiProvincialStatisticalOffice 2020), living in multi-storey residential buildings.

$$\text{Sample size (n)} = N/(1+N(e^2)) \quad \text{(Equation 4)}$$

Where n, N, and e are the sample size, population size and level of precision, respectively (Israel 1992).

Simple random sampling was conducted to select two districts (clusters) in Chiang Mai metropolitan. Then, the investigation used the cluster sampling method with Thai census data sources, who live in multi-storey residential buildings in Chiang Mai, for choosing samples. The questionnaires were sent to key people working in Subdistrict Municipality for further spreading the survey to local people. The questionnaire invited approximately 4,000 people to participate because the average online questionnaire response rate is approximately 10-15% of sample (Cleave 2021). 482 completed surveys were obtained, meeting the requirement to have a 95% confidence level in the results.

3.4.2 Questionnaire design

The purpose of conducting a questionnaire survey was to investigate the typical characteristics of apartment blocks in Thailand and explore the satisfaction level of their residents with the indoor environment of their apartments. Additionally, this questionnaire was translated into Thai.

The questionnaire (Appendix B) was divided into five parts (see Figure 3- 12). Part 1 included background information of the participants, which was gender, age, occupation, time in building. Demographic data can help to interpret the characteristics of the sample, which can identify any relationships related to these factors (Krosnick 2018). Part 2 comprised items regarding the physical living environment, such as orientation, room location, room layout and room materials. Exploring building characteristics could provide valuable building information relating to indoor environment quality. This information could also help to identify building design issues and opportunities for investigating potential passive design. Part 3 involved the residents' activities relating to their behaviour, including cooking and washing clothes. Occupant behaviour characteristics have significant impacts on building performance and indoor environmental quality (Yan et al. 2017). For example, cooking can produce heat, moisture content and particulate matter in room. Washing clothes in room also generate moisture content, which can negatively impact indoor air quality. Visualising occupant activity can help to identify potential impacts on indoor environmental quality.

The questions in part 1 to part 3 were multiple-choice question. Multiple-choice question is a type of closed-ended questions that has predefined response options. Closed-ended questions are typically useful for eliciting information, while open-ended questions are for exploring opinions, attitudes and perceptions (Kumar 2018). In addition, this type of question is useful for obtaining quantitative data as well as statistically analysing result.

Part 4 explored the participants' feelings toward their indoor environment. A 9-point Likert scale was used to analyse the feedback of the occupants. This is because the scale could be related to altitude and allow quantitative analysis of the result (Kumar 2018).

Part 5 investigated occupant comfort within their room. The participants answered on a five-point Likert scale on residents' overall satisfaction with factors relating to comfort. This five- point Likert scale was chosen as it can provide sufficient differentiation to reflect participant's satisfaction.

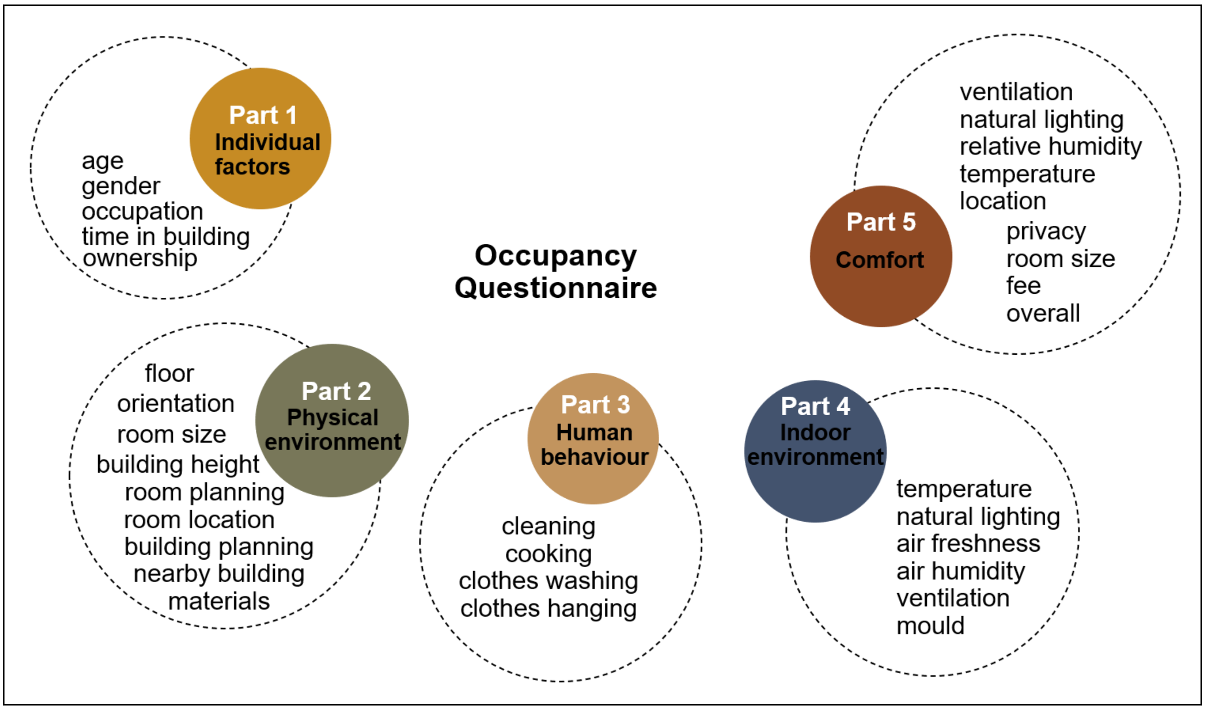


Figure 3- 12 Visualisation of the 5 parts within the occupancy questionnaire (Source: Author)

3.4.3 Data analysis

A quantitative survey is a statistical method which can use to systematically analyse, organise, and interpret data. This approach provides essential tools for evaluating trends, patterns, and relationship within the survey data (Sternstein 1996).

SPSS (Statistical Package for the Social Sciences) is a software programme widely used for quantitative analysis. It is a user-friendly interface for analysing data. SPSS provides a wide range of statistics tests, such as descriptive statistics, inferential tests and regression analysis (IBM 2023). This programme has been significantly used in previous research in field of occupant survey (Xue et al. 2016; Mustafa 2017; Bortolini and Forcada 2021; Rahanjam and Ilbeigi 2021).

All data obtained from occupant perception survey in this research were analysed via SPSS 27.0.

The consistency and stability of the measurement is important in demonstrating the questionnaire's reliability (Huck et al. 1974; Taherdoost 2016). Internal consistency is commonly used to ensure that the items in the questionnaire provide reliable and valid outcomes. Cronbach's alpha is the most commonly used to measure internal consistency (Taherdoost 2016). Cronbach's alpha ranges from zero to one, where Cronbach's alpha value higher than 0.7 indicates acceptable internal consistency. This study used Cronbach's alpha for assessing internal consistency of test items(Barnette 2000), such as occupants' comfort questions and satisfactory with indoor air environment level. (results in Section 5.2)

Descriptive analysis was used to evaluate general information of occupants, including age, gender, occupation, time in building and ownership. In order to investigate the relationship between two variables, Spearman's rank correlation was applied to measure the monotonic association (between ordinal scales) (Sedgwick 2014), while Pearson correlation was performed to measure the linear relationship (between ratio/interval scales) (Nettleton 2014) (results in Section 5.5). Both Pearson and Spearman correlation coefficients are measured on a scale varying between -1 and 1. The correlation coefficient greater than zero signifies a positive relationship, while the value less than zero indicates a negative relationship. Zero value means no correlation (Berman 2016). For Likert items, a correlation value that is close to -1 or 1 indicates a strong relationship. Those data having the coefficient value either lower than -0.5 or higher than 0.5 were then tested by multiple regression. Multivariance regression analysis was conducted to define the most significant variables influencing the outcome. The data in part 5 (occupants' comfort) in the questionnaire were analysed by multiple regression in relation to occupants' indoor environment quality scale, for example, level of fresh air, air movement level, and humid air level with room ventilation satisfaction level, temperature level in winter and summer with room temperature satisfactory level.

3.5 CFD sensitivity analysis: outdoor (Phase 2)

A hierarchical approach considering macroclimate, mesoclimate and microclimate is the basis for understanding site parameters (Sunarya 2020). Macroclimate level refers to meteorological data, such as temperature, relative humidity, precipitation, wind speed, wind direction, latitude, longitude and altitude. The mesoclimate data level is influenced by terrain. Microclimate level refers to nearby building and obstructions.

Meteorological data is used to simulate the microclimate. Topology data play a significant role in influencing site characteristics. The inclusion of buildings in topology data is crucial for a comprehensive understanding of site environment. While meteorological data is widely employed to depict microclimate conditions in research (Liu et al. 2015; Liu et al. 2017), site features, e.g. topography and surrounding parameters are recognised to have significant impact on thermal conditions at building level. Site data is crucial in CFD and BES. Site is also an important factor in selecting passive design strategies appropriate to the microclimate. Microclimate refers to the localised climate conditions unique to a particular area (Toparlar et al. 2017). Natural ventilation relies on the relationship between outdoor climatic conditions and indoor environmental conditions. The outdoor climatic conditions, such as air movement and wind direction can vary within a microclimate depending on the site features.

To achieve objective 4 of the research, this study aims to investigate the influence of external factors on natural ventilation in apartment blocks in Thailand. The exploration of air movement at the building envelope was not only to determine the feasibility of ventilation but also could be used to investigate boundary condition for internal CFD model (Chapter 6). The impact of the external factors on natural ventilation were explored through a sensitivity analysis.

DesignBuilder uses to calculate different engines, such as EnergyPlus, Radiance and CFD to calculate various analyses. The heat balance equation in EnergyPlus for external building and surfaces is (EnergyPlus 2016):

$$Q_{tsol}+Q_{LWR}-Q_{cond}+Q_{conv}=0 \qquad \text{Equation 5}$$

where Q_{tsol} is absorbed direct and diffuse solar radiation heat flux. Q_{LWR} is net longwave length radiation flux exchange with the air and surroundings, Q_{cond} is conduction heat flux (Q/A) into the wall and Q_{conv} refers to convective flux exchange with outside air.

Equation 5 demonstrates that surrounding environment of building can significantly impact its energy performance. The amount of solar radiation on building surfaces is influenced by adjacent obstructions. The heat transmits though building surfaces. The convective flux refers to the difference of the surface temperature and air temperature of nearby surfaces. The heat and moisture transfer via outdoor air into the building.

This study was designed to explore external factors. For macroclimate, the meteorological data of Chiang Mai was set and analysed to the model. Meso climate and microclimate factors were respectively investigated including apartment position within building, building height, proximity direction and density of nearby buildings. In summary, five independent factors and combinations of the factors were explored. The five independent factors are:

- Wind speed
- Position on Building (vertical and horizontal)
- Road width between buildings
- Building height
- Nearby building

Initially a sensitivity analysis was carried out to identify the parameters, which presented most impact on air movement at the building envelope. This required a base case to be set from which variants could be analysed.

As described in section 3.2.1, low-rise buildings in Thailand urban area context are typically in high- density contexts. The maximum height building of this category (23m/ 8-floors) An 8-floor building, with the dimension of 11.5 m width, 40 m length and 20.8 m height was selected as a base case for analysing the air movement at the building envelope. The measurement points were specified at two levels of the building (1st floor at 3.60 m height and top floor or 7th floor at 19.20 m height) and rooms representing building corners (C1, C2, C3 and C4) and middle -corridor (M1 and M2) (see Figure 3- 13).

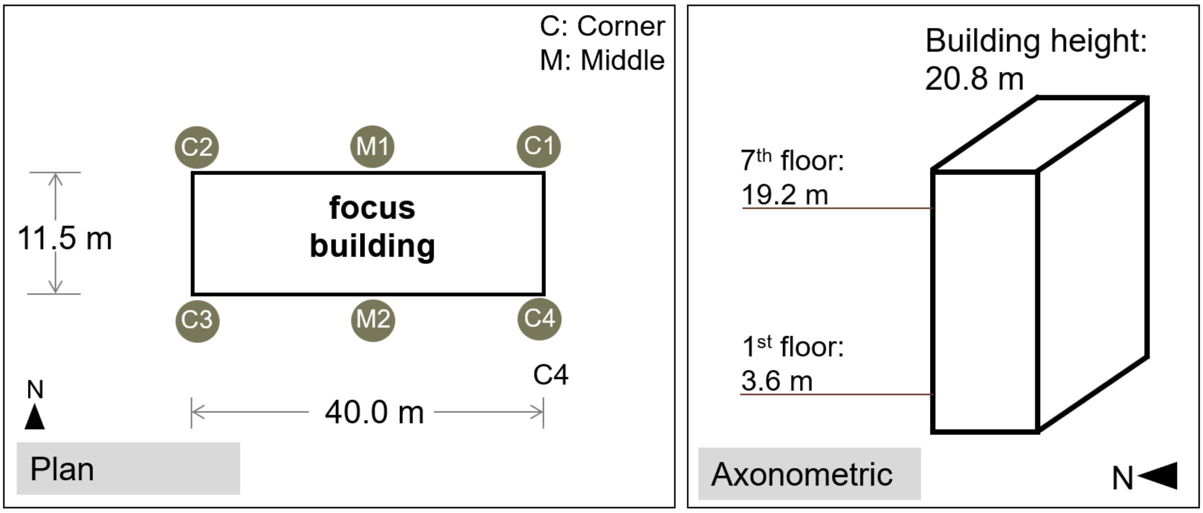


Figure 3- 13 Measurement points of air movement and room locations
(Source: Author)

3.5.1 Wind speed and position on building

This CFD sensitivity categorised wind direction into 3 parts, which were north direction (winter), south direction (summer) and south-east (rainy season) with initial wind speed of 1 $m.s^{-1}$, 2 $m.s^{-1}$, 4 $m.s^{-1}$ 6 $m.s^{-1}$ and 8 $m.s^{-1}$. This part aims to investigate air movement pattern at different room locations, such as room at the corner (C) and middle (M) of the buildings due to the different initial wind speed and wind direction (see Table 3- 2).

3.5.1.1 Wind direction frequency

From the analysis of wind speed and directional frequency in Chapter 2.1 the key directions of south and north were found to be representative of wind direction in summer and winter, respectively. South and south-west are the main wind directions for the rainy season. As south wind direction was already modelled for other seasons only south-west was needed specifically for the rainy season.

3.5.1.2 Wind speed

Referring to wind speed data, wind speed in Chiang Mai ranges between 0 $m.s^{-1}$ and 8 $m.s^{-1}$ (see Section 2.2.1). This study explores wind speeds of 1 $m.s^{-1}$, 2 $m.s^{-1}$, 4 $m.s^{-1}$ 6 $m.s^{-1}$ and 8 $m.s^{-1}$.

Table 3- 2 Variables considered in sensitivity analysis of wind speed and direction

independent variable		cases	
wind direction	summer (south wind), winter (north wind), rainy season (south-west wind)	3	180 cases
wind speed	1 m.s^{-1}, 2 m.s^{-1}, 4 m.s^{-1} 6 m.s^{-1} and 8 m.s^{-1}	5	
floor	1st and 7th floor	2	
Room locations	corner room – 4 positions, middle room – 2 positions	6	
dependent variables			
air movement velocity			
controlled variables			
Building size	40.0m (W) x 11.5 m (L) x 20.8m (H)		

3.5.2 Building height and Road width

The influence of surrounding buildings on the wind velocity and flow character around a focused building was analysed. This section will analyse air movement depending on buildings height and road width (see Figure 3- 14).

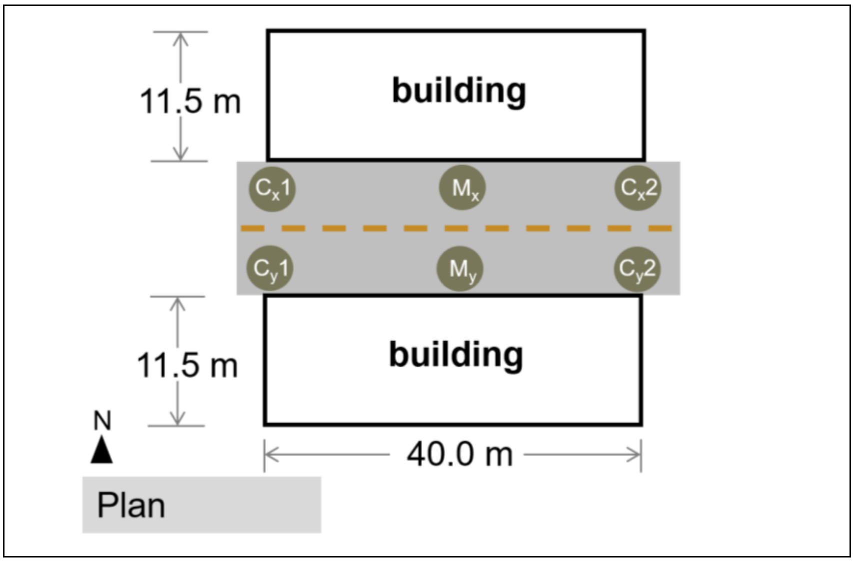


Figure 3- 14 measurement point of air movement on buildings' envelope in relation to building separation distance
(Source: Author)

Referring to Thai's Ministerial Regulation No 55 of Interior Floor Building Control (Interior 2000), building height must not higher than double of horizontal distance from the opposite site alignment of the closest public road. In addition, a building which is constructed close to public road must follow the following guidelines (see Figure 3- 2):

- If the width of the public road is less than 6 metres, the building shall be setback at least 3 metres from the center of the road.
- If the width of the public road is less than 10 metres, the building shall be setback at least 6 metres from the center of the road.
- if the width of the public road is between 10 metres and less than 20 metre, the building shall be setback at least 10 percent of the width of the road.
- If the width of the public road is more than 20 metres, the building shall be setback at least 2 metres from the road boundary.

In addition, for a building built taller than 9 metre but not over 23 metre high, the wall or balcony must keep distance at least 3 metres from the site boundary.

The provision dimension was used to design the simplified models in CFD simulation. This section will divide the simulation into 2 parts, which are:

- CFD of same aspect ratio of road width and building height
- CFD of same building height and different road width

3.5.2.1 CFD of same ratio of road width to building height

Urban canyon or street canyon affect various local conditions such as wind velocity and air movement. The essential geometrical classification of a street canyon is the ratio of road width (S) to building height (H). The different ratio results in 3 different flow patterns (see Figure 3- 15). Firstly, if the ratio of S/H is over 2.4, this will create isolated roughness flow at the space between the buildings. Secondly, for the ration between 1.4 to 2.4, the wake interference flow occurs at the canyon. Lastly, for the ratio below 1.4, the skimming flow will be created at the canyon.

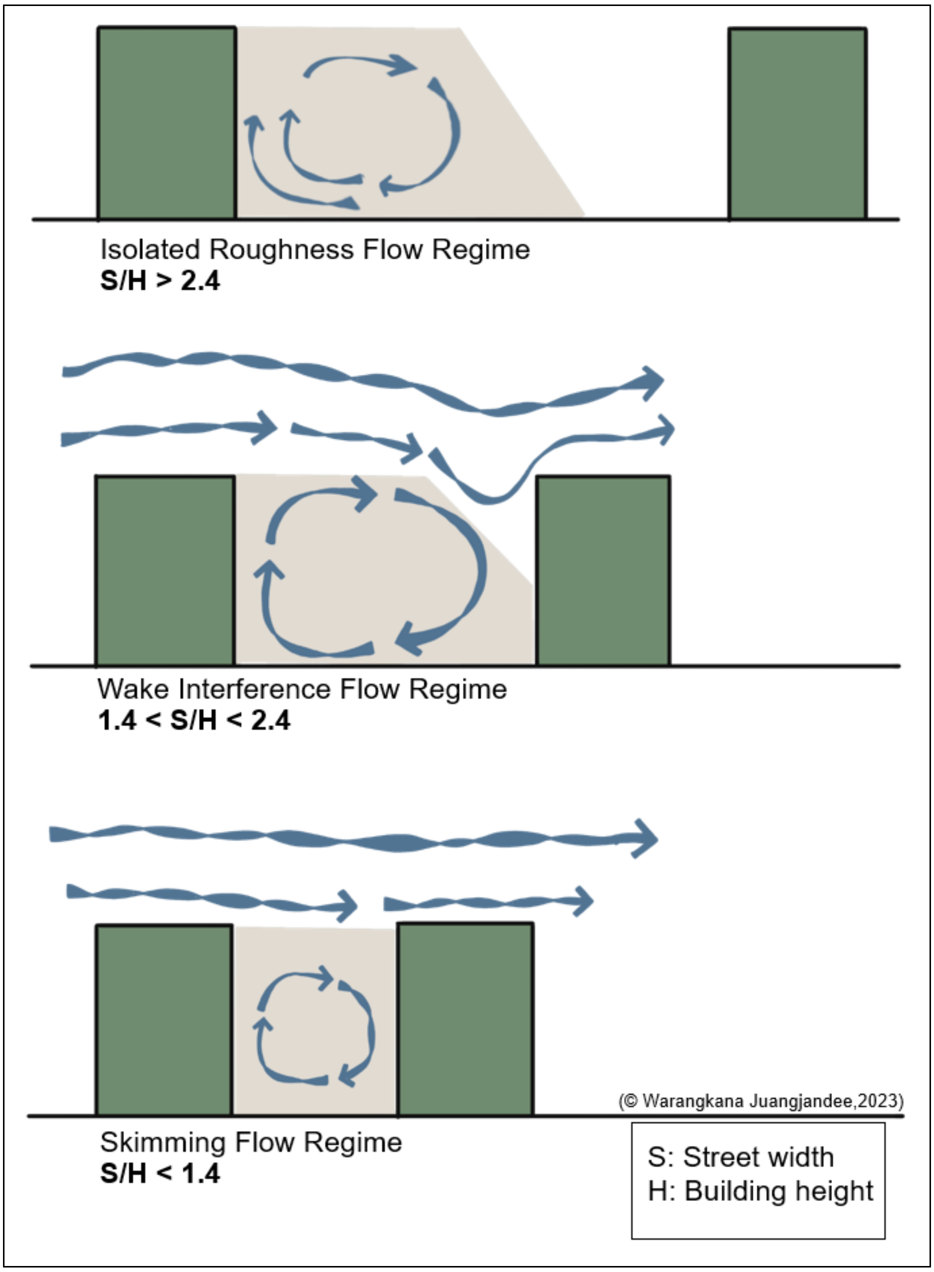


Figure 3- 15 classification of 3 different ratio of road width to building height
(Source: Author adapted data from Oke 2002)

Based on Thailand regulation (MinistryofInterior 2015) determining the minimum building height and setback dimension between different road width and buildings, the S/H ratio between the buildings is between 0.55 to 1.15. All these ratios are below 1.4 and are likely to create skimming flow regime between the buildings. The initial study analysed and compared the air movement at buildings' envelope located along the road for an S/H ratio of 0.55. CFD was used to examine wind speeds of 1 $m.s^{-1}$ and 6 $m.s^{-1}$ because this would demonstrate the air movement of minimum and maximum of the typical wind speed. Wind speeds of 8 $m.s^{-1}$ are rarely occurred in Thailand. (see Figure 3- 16)

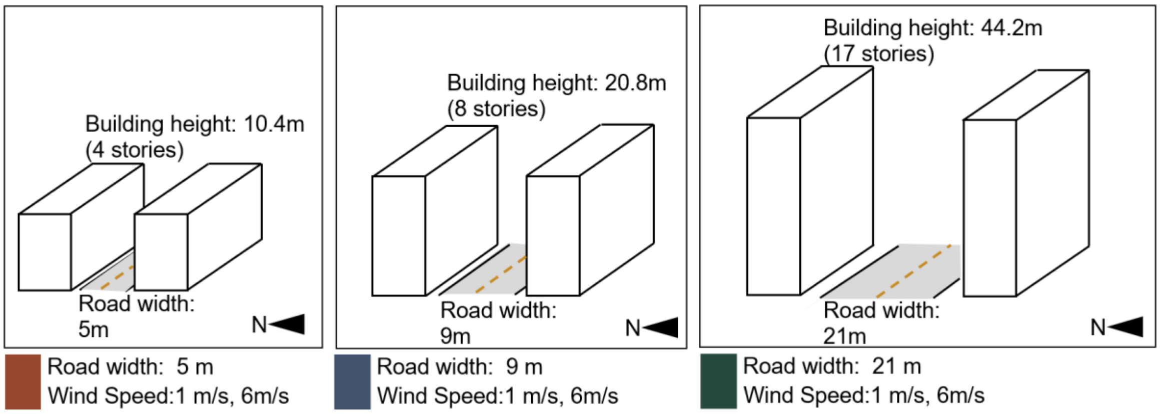


Figure 3- 16 schematic of same ratio (0.55) of road width and building height cases
(Source: Author)

Summer and rainy season have different flow pattern, which are inline flow and staggered flow respectively. Such flow pattern affects air movement and air velocity significantly, so this study would carry out with CFD simulation for 2 seasons, which was summer and rainy season. From initial analyses (Section 6.2), the air movement with the same initial wind speed of the opposite position behaves the same; thus the CFD result of summer can be estimated the winter air movement velocity. (see Table 3- 3)

Table 3- 3 same road width to building height ratio (0.55)

independent variable		cases	
wind direction	summer (south wind), rainy season (south-west wind)	2	24 cases
wind speed	1 m.s^{-1} and 6m.s^{-1}	2	
floor	1st and 7th floor	2	
Road width	5m, 9m and 21 m	3	
dependent variables			
air movement velocity			
controlled variables			
Building size	40.0m (W) x 11.5 m (L) x 20.8m (H)		

3.5.2.2 CFD of varying aspect ratio of building height to road width

CFD simulation was also used to analyse scenarios with same building height but different road width (i.e. varying aspect ratio). This analysis was divided into 2 groups,

i) using a 4 floor building and varying the aspect ratio with 5 m, 9m and 21 m road width (road widths consistent with Thai regulation (MinistryofInterior 2015)

ii) using 8 floor building varying the aspect ratio with 9m and 21 m road width (road widths consistent with Thai regulation (MinistryofInterior 2015)

In each group, the CFD analysis will consider wind speeds of 1 m.s^{-1} and 6 m.s^{-1} (representing the air movement of minimum and maximum of the typical wind speed. (see Figure 3- 17)

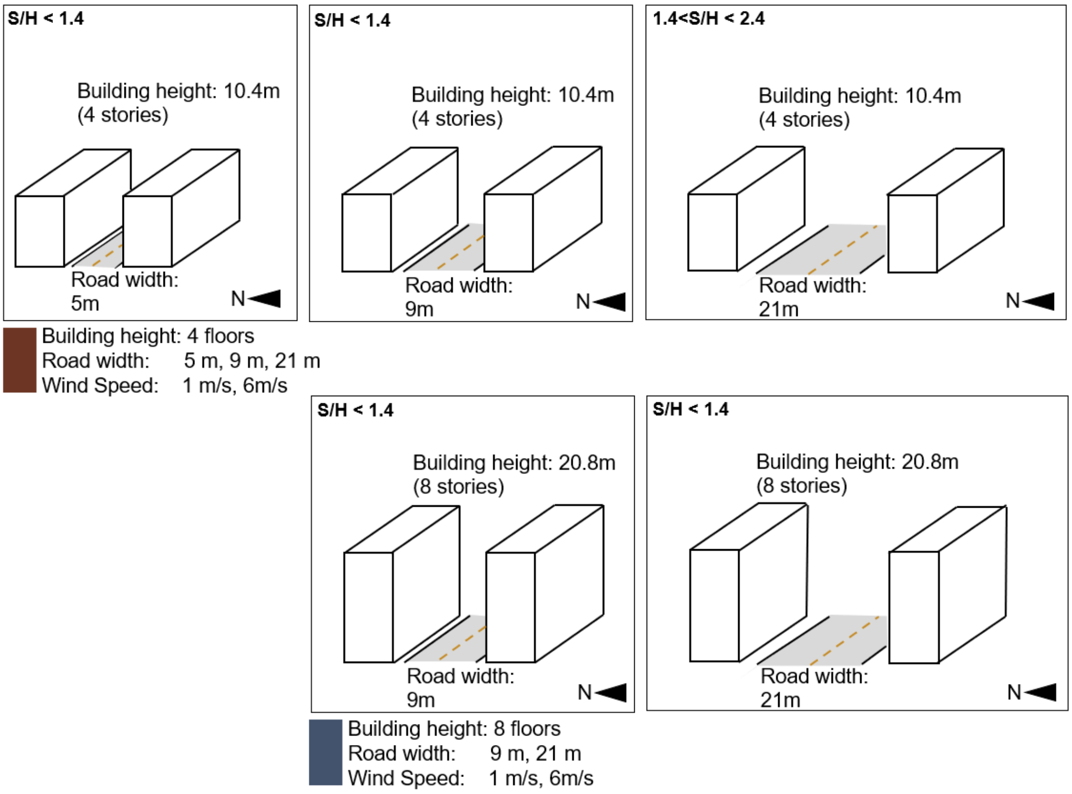


Figure 3- 17 schematic of same building height and different road width cases (Source: Author)

Table 3- 4 varying aspect ratio of building height to road width

independent variable			cases	
4 floors building	wind direction	summer (south wind), rainy season (south-west wind)	2	24 cases
	wind speed	1 m.s^{-1} and 6m.s^{-1}	2	
	floor	1st and 3rd floor	2	
	Road width	5m, 9m and 21 m	3	
8 floors building	wind direction	summer (south wind), rainy season (south-west wind)	2	16 cases
	wind speed	1 m.s^{-1} and 6m.s^{-1}	2	
	floor	1st and 7th floor	2	
	Road width	9m and 21 m	2	
dependent variable				
air movement velocity				
controlled variables				
Building size	40.0m (W) x 11.5 m (L) x 20.8m (H)			

3.5.3 Nearby buildings

In urban area, there are various factors which influence on wind flow pattern, such as building in proximity, vegetation, topography, and surfaces. This analysis focuses on the impact of “layers” of surrounding buildings on the airflow of the case study building. Franke et.al (Franke et al. 2011) suggested that the central area around focus building should represent the actual scenario as much as possible , while further nearby buildings layers may be represented with simple blocks.

The same 8 floor (19.2m) base case building as for previous sections is used for this analysis. The nearby buildings are a mix of 3 floor (8.8 m) shophouse or house buildings and 8 floor (19.2 m) multi-storey buildings.

This section will use CFD simulation to analyse the air movement around the case study building in summer and rainy season. As before the winter, case with north wind will not be simulated as the north wind can be assumed to be the opposite of the south wind, based on CFD simulation of summer season (see Section 6.2). CFD results for different initial wind speeds are found to be proportional to each other (see Section 6.2). Initial wind speed for CFD simulations in this section will be fixed at 4 $m.s^{-1}$ as it is within a range of typical wind speeds.

3.5.3.1 one layer of nearby building

There are 16 different possibilities of focus building and different nearby building height (see Figure 3- 18, Figure 3- 19).

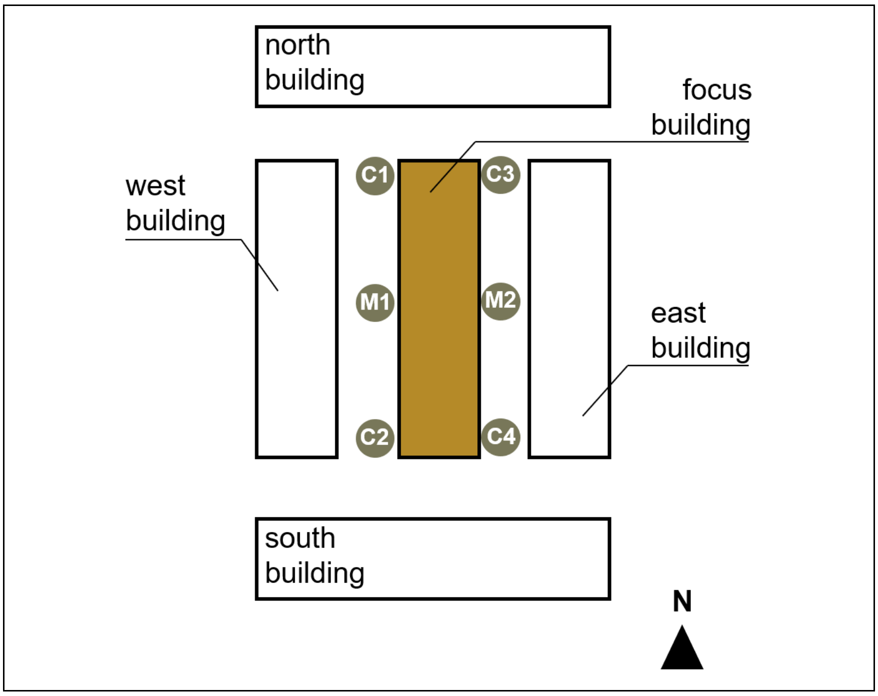


Figure 3- 18 measurement point of air movement on buildings' envelope with one nearby-buildings layer
(Source: Author)

Table 3- 5 one nearby-building layer

independent variable		cases	
wind direction	summer (south wind), rainy season (south-west wind)	2	128 cases
wind speed	4 m.s^{-1}	2	
floor	1st and 7th floor	2	
one nearby-buildings possibility cases	See Figure 3- 19	16	
dependent variables			
air movement velocity			
controlled variables			
focus Building size	40.0m (W) x 11.5 m (L) x 20.8m (H)		

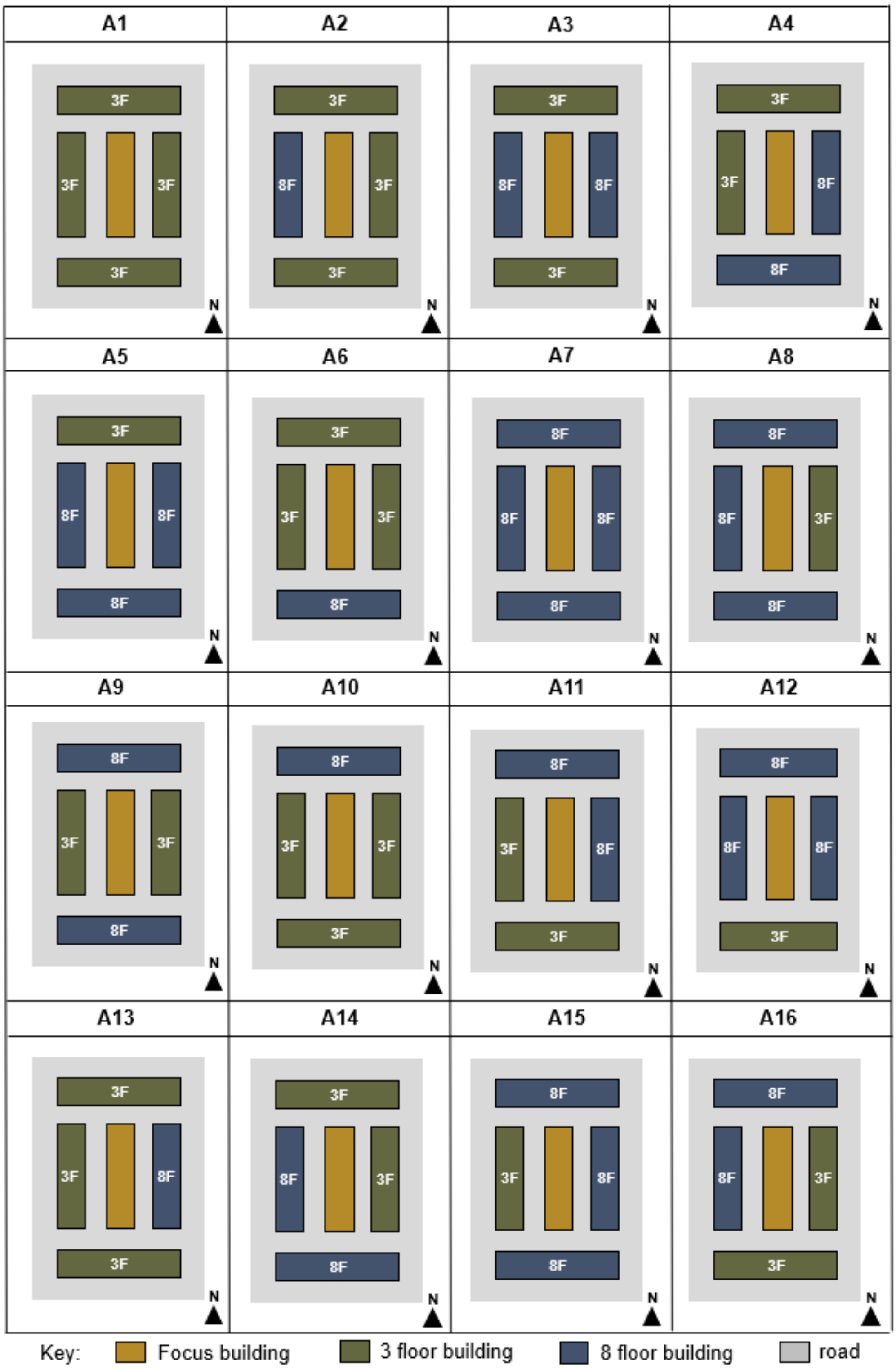


Figure 3- 19 schematic of one nearby-buildings layer cases
(Source: Author)

3.5.3.2 two layers of nearby buildings

These CFD sensitivity experiments will explore air movement at the focus building after extending surrounding building to two-layers. Each nearby buildings' layer contains the same building height, which can raise 4 different possibilities of focus building with different nearby building height (see Figure 3- 21).

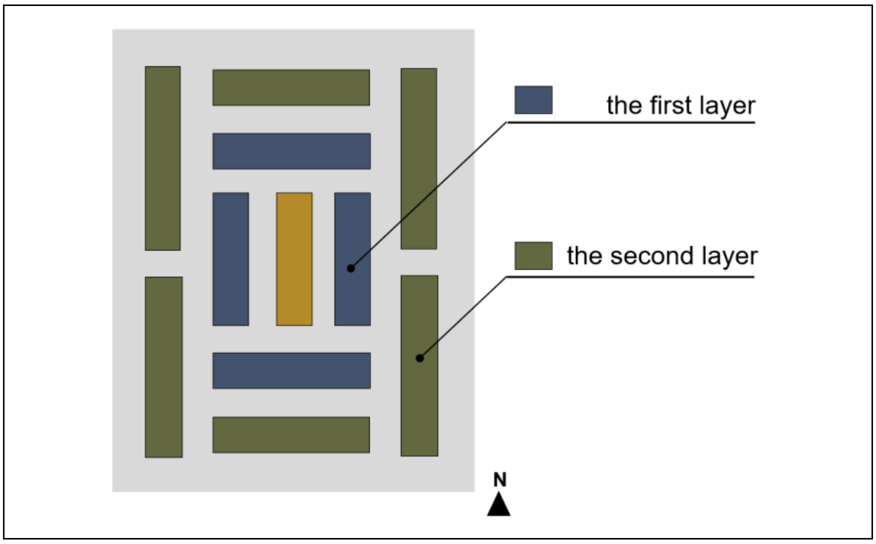


Figure 3- 20 the orientation of two buildings layers from the focus building

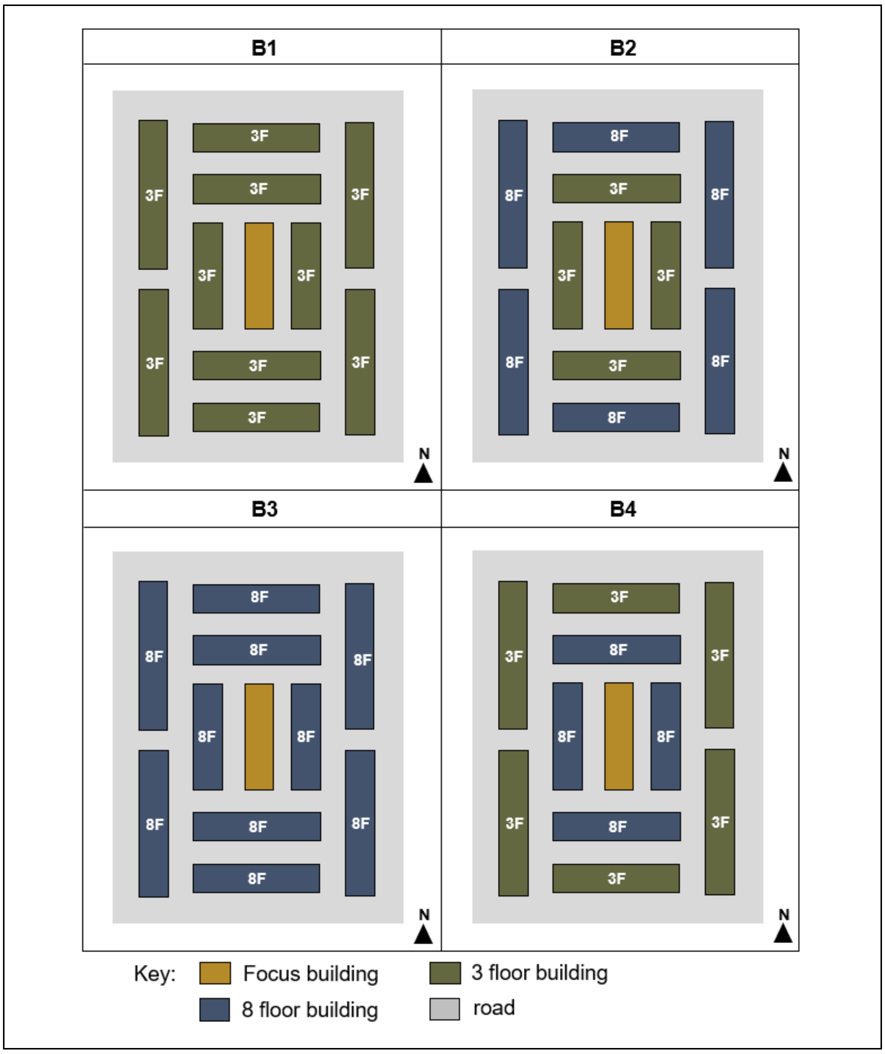


Figure 3- 21 schematic of two nearby-buildings layers cases
(Source: Author)

Table 3- 6 two nearby-buildings layers

independent variable		cases	
wind direction	summer (south wind), rainy season (south-west wind)	2	32 cases
wind speed	4 m.s^{-1}	2	
floor	1st and 7th floor	2	
nearby-buildings	2 layers - See Figure 3- 21 for height scenarios	4	
dependent variables			
air movement velocity			
controlled variables			
focus Building size	40.0m (W) x 11.5 m (L) x 20.8m (H)		

3.5.3.3 three layers of nearby-buildings

These CFD sensitivity experiments will explore air movement at the focus building after extending surrounding building to three layers. Each nearby buildings' layer contains the same height, which can raise 8 different possibilities of focus building with different nearby building height (see Figure 3- 22).

Table 3- 7 three nearby-buildings layers

independent variable		cases	
wind direction	summer (south wind)	1	32 cases
wind speed	4 m.s^{-1}	2	
floor	1st and 7th floor	2	
nearby-buildings	3 layers - See Figure 3- 22 for height scenarios	8	
dependent variables			
air movement velocity			
controlled variables			
focus Building size	40.0m (W) x 11.5 m (L) x 20.8m (H)		

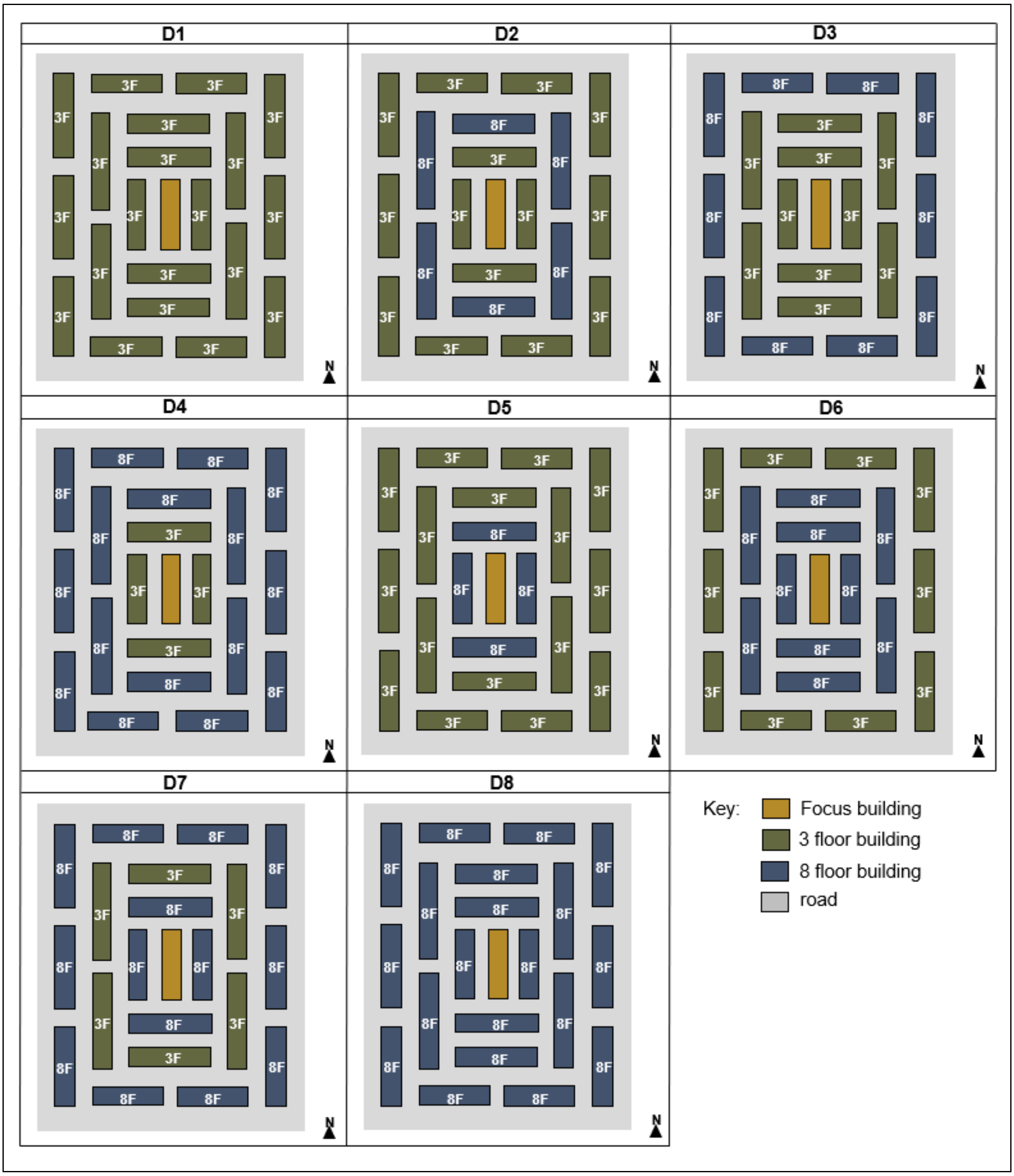


Figure 3- 22 the orientation of three building layers from the focus building (Source: Author)

3.6 CFD sensitivity analysis: indoor (Phase 2)

3.6.1 Validation

CFD model outputs can be validated by related then to monitored data. In this project, the data obtained from physical measurement in one of multi-residential building rooms in Chapter 3.3.3 was used to validate the best starting point for the CFD simulation and determine the accuracy of the CFD models.

The two options of starting point for the CFD simulation are illustrated in Figure 3- 23.

i) Inputting Cp data from MacroFlo (detailed in 3.2.2)
ii) Inputting microclimate boundary condition from Envi-met programme.

Both models used a climate (EPW) file based on.

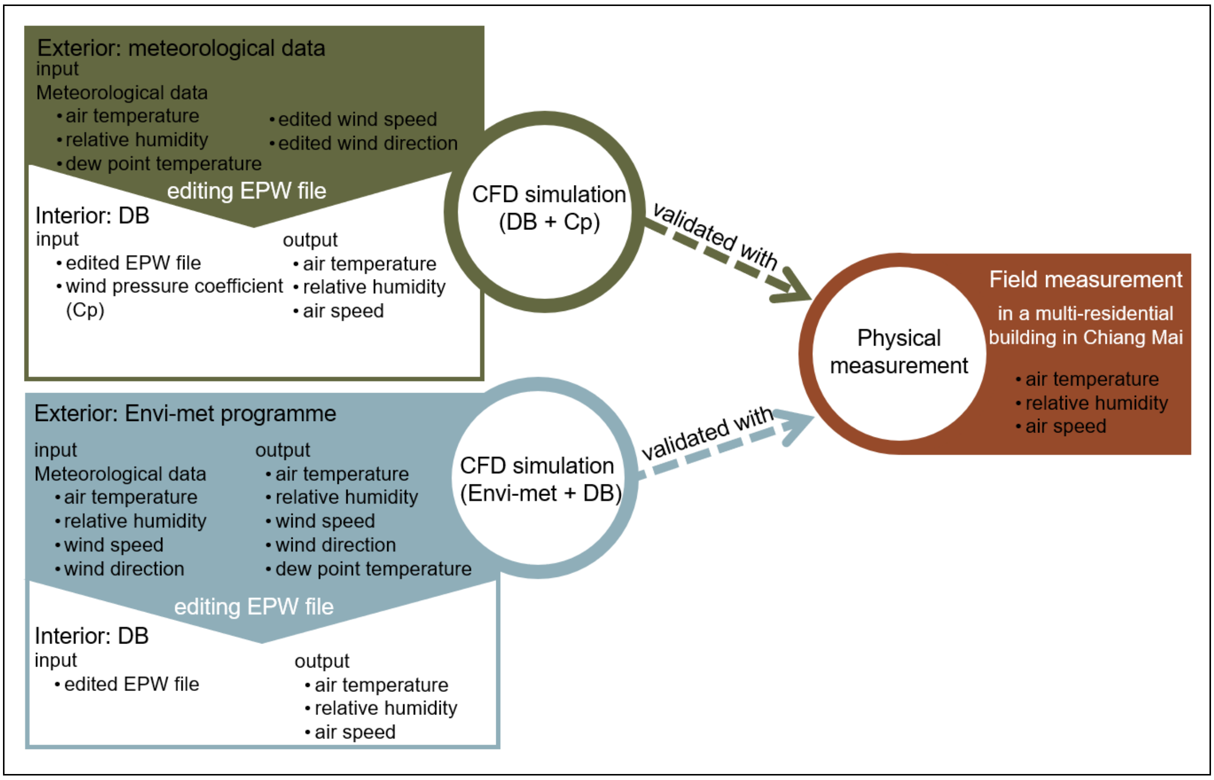


Figure 3- 23 validation procedure
(Source: Author)

The validation procedures and details are as follows:

3.6.1.1 Physical measurement data in multi-residential building

Referring to the physical measurement, data derived from Room AM were selected to validate in this study as the room has single-sided ventilation. The room is a middle room on the third floor of Building A (described in Section 3.3.3). The surrounding buildings are a maximum of 5m away. Figure 3- 24 shows the site of building A, which was constructed with a beam-column structure. The detail of building configuration and materials are described in Table 3- 8.

The model was set with a fine grid size of 0.1 grid spacing and 0.03 grid line merge tolerance. Turbulence model of RANS with k-ε model was employed. EnergyPlus simulation calculated the thermal behaviours of the building and then input the data as the boundary condition for the model.

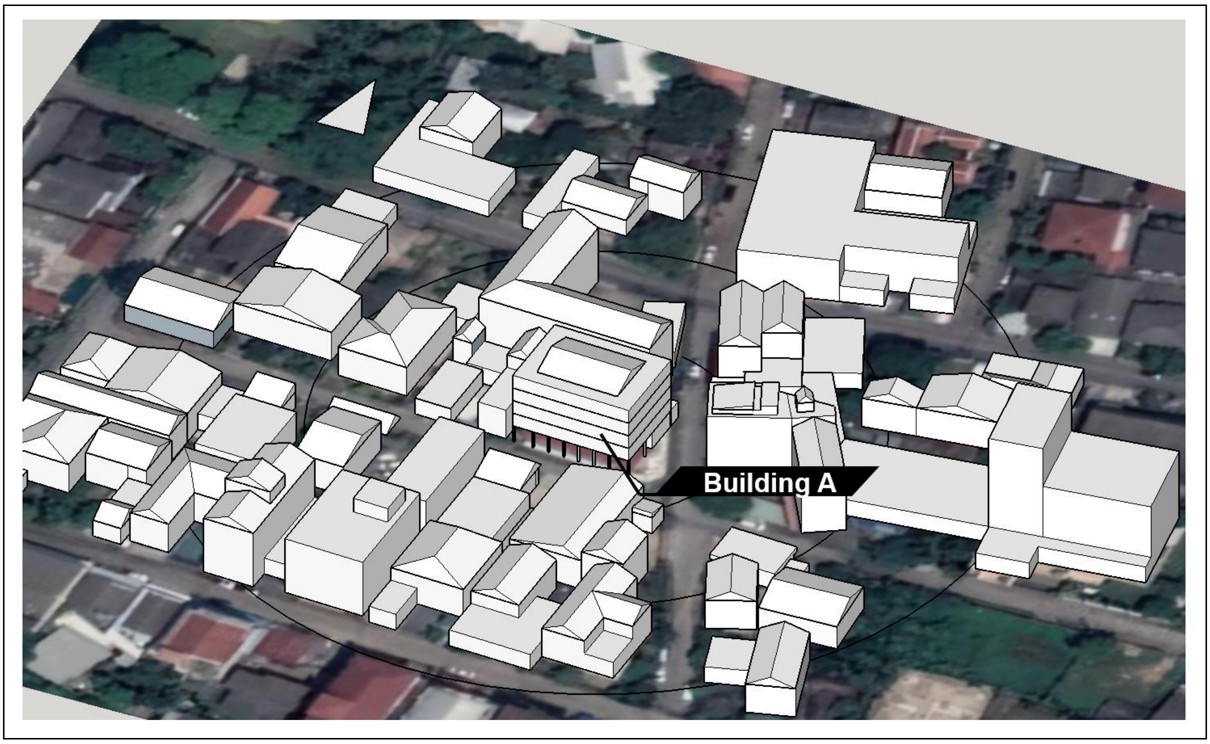


Figure 3- 24 Building A and surrounding environment
(Source: Author)

Table 3- 8 Building A configuration and materials

Building configuration	Corridor	corridor width 1.65 m
	Room size	3.19m (W) x 7.6m (L), floor to floor 2.8 m
	Room plan	type HB
	Room location	middle room
	Room orientation	opening facing the north
	Occupancy	1 person per a unit
	HVAC system	natural ventilation
Materials	Room door	hardwood 100cm (W) x 200cm (L)
	Balcony door	hardwood 75cm (W) x 200cm (L)
	Toilet door	uPVC 75cm (W) x 200cm (L)
	Window	wooden frame with single clear glass (3 mm)
	Wall	concrete (80 mm) with cast concrete (20 mm)
	Ceiling	concrete
	Floor	ceramic tile

3.6.1.2 CFD model setting in DesignBuilder with Cp data

Room AM model was built by inputting building configuration and material data into the programme. The model used hourly weather data derived from OneBuilding 2004-2018 in the period of 16th January to 6th February, which is the same duration as the physical measurement. However, in urban area, wind speed and direction are influenced by many obstructions, such as adjacent buildings. This can cause changes in flow speed and pattern (Ghiaus et al. 2006). In order to be more practical, wind speed was revised to be local wind speed as calculated by Equation 2 and Equation 3 in Section 3.2.2, and wind direction was revised by using CFD Sensitivity Analysis: Outdoor data. In addition, Cp data with exposure type of sheltered high-rise wall of from MacroFlo was input to the model (Appendix A, (IES 2018)).

3.6.1.3 CFD model setting in DesignBuilder with microclimate data from Envi-met

Default template of DesignBuilder has limitations and cannot provide data in relation to microclimate. DesignBuilder uses the engine "EnergyPlus", which cannot model physical terrain feature, such as ground inclination, vegetation and nearby buildings. Therefore, this study analysed the benefits of using a DesignBuilder model based on microclimate data from Envi-met as the boundary condition. Envi-met is a three-dimensional microclimate programme providing CFD simulation for urban environment. Envi-met can establish the microclimate data influenced by detailed site parameters such as detailed as Leaf Area Index (LAI) and Leaf Area Density (LAD) (ENVI-met 2022).

Envi-met was used to model Building A and its surroundings including nearby buildings, street, and trees. Hourly weather data from OneBuilding 2004-2018 in the period of 16th January to 6th February was input into Envi-met model. The boundary domain should have enough space from the target region to avoiding contamination of the solution (Franke et al. 2011). The boundary condition should show the influence of the surrounding on the focus building. In non-uniform urban and unequal buildings, the influence region of focus building should be set at least 3 building layers from the focus building for the convergence. In urban area, inflow, lateral, and top boundaries should have distance at least 5 times the highest building height (5H), while the outflow boundary should be 15H from the regions of focus building (see Figure 3- 25) (Franke et al. 2011; Tong et al. 2016). In this scenario, the influence region was 200 metres wide, 200 metres long, and 17 metres high for the highest building. Therefore, the inflow, lateral, and top boundaries were 85 metres, 255 metres, and 85 metres, respectively. The model was set with a 2m grid size as the short distance between Building A and surrounding buildings. The height and types of trees on the site were set into the model. The materials for Building A were specified as detailed in Table 3-8. Additionally, the Envi-met model incorporated all surrounding environmental features and materials present at the real site. This included nearby building heights and materials, ground materials, vegetation types and heights. Leaf Area Index (LAI) and Leaf Area Density were specified basing on the different types of vegetation in the area. Figure 3- 26 shows CFD domain of the influence region relating to site data in Chiang Mai.

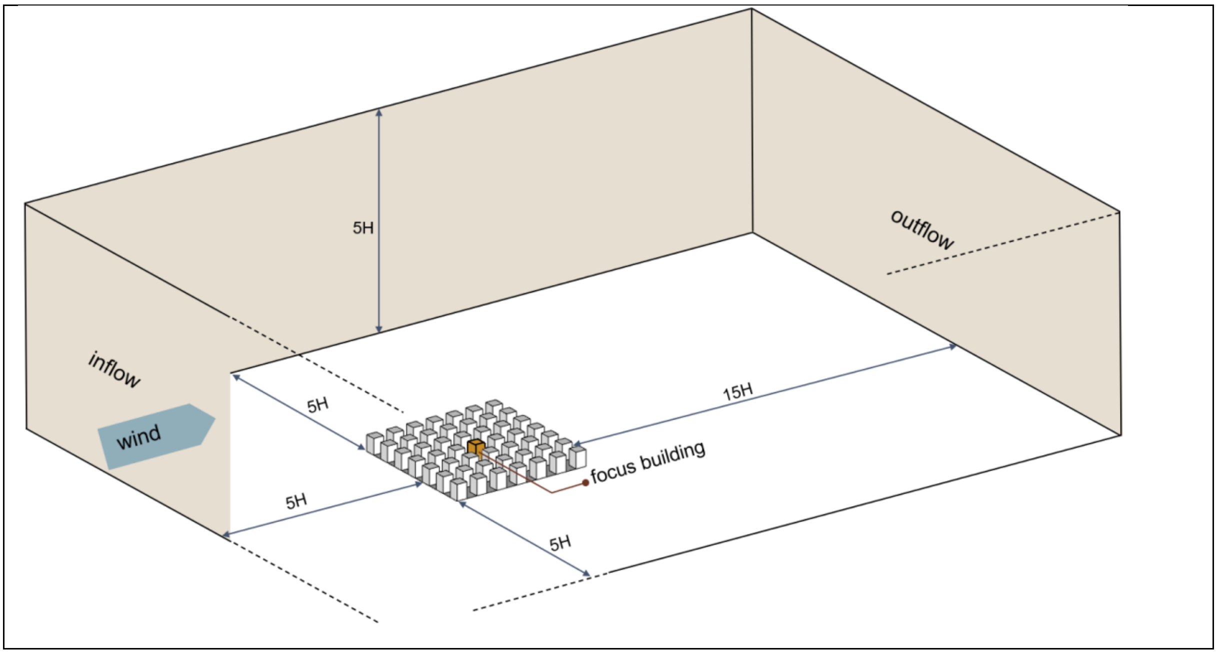


Figure 3- 25 boundary conditions
(Source: Author)

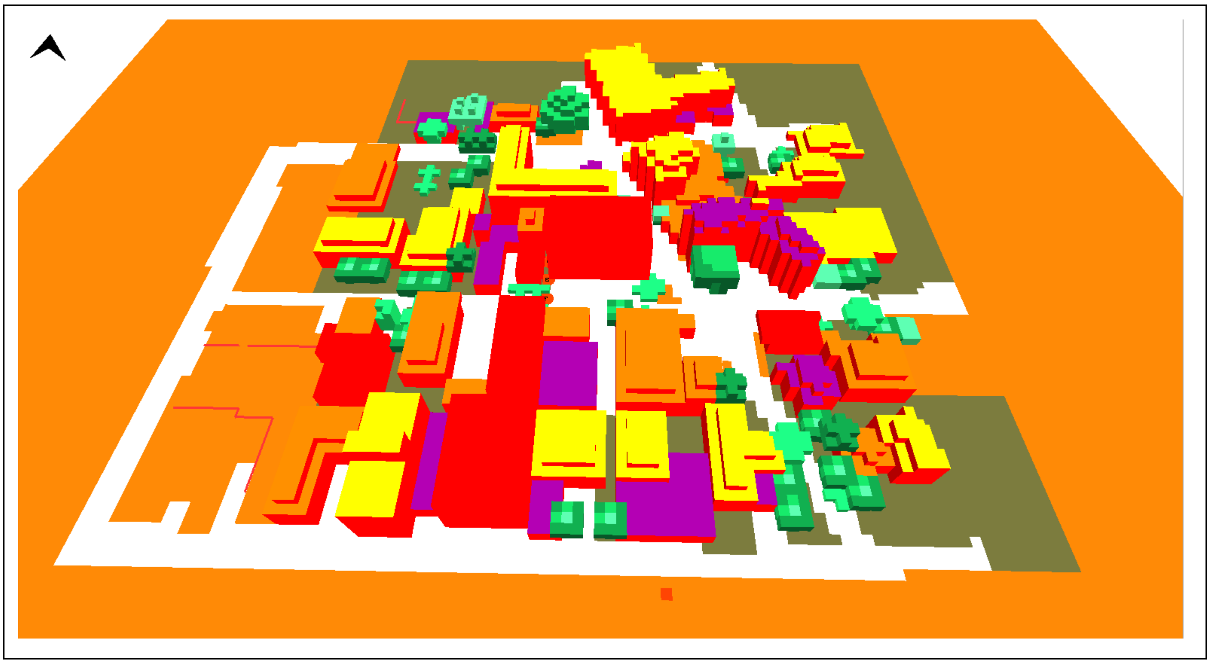


Figure 3- 26 CFD domain of influence region relating to site in Chiang Mai
(Source: Author)

The output data from Envi-met was used for generating EPW file for setting external environment of CFD model's boundary condition in DesignBuilder, such as dry bulb temperature, relative humidity, wind speed and site ground temperature. The material and building configuration of Room AM was developed to reflect to the real site (see Table 3- 8). The model of Room AM was then simulated.

3.6.1.4 Data analysis

The simulated data from DesignBuilder with inputting Cp data (Section 3.6.1.2) and simulated data from DesignBuilder with inputting microclimate boundary condition from Envi-met (Section 3.6.1.3) were compared with monitored data. A Square R calculated from regression analysis can determine the adequacy of simulated model fitting the monitored data. Square R value close to 1 implies as the stronger relationship (Sternstein 1996). Additionally, in field of physical science and engineering, a square R value above 0.7 is generally considered acceptable (Valchanov 2023). Therefore, this study determines the acceptable level of square levels of square R at 0.8. On the other hand, RMSE measures the error of a model by calculating the differences between values simulated model and the monitored data. An RMSE value close to 0 indicates the better the model simulation performance. An RMSE lower than 2.0 is typically defined as indicative of satisfaction prediction accuracy (Moriasi et al. 2007). As a result, this study defines an acceptable criterion for the data of less than 2.0. Regression and RSME method were used evaluate the accuracy of the CFD model (Resulted in Section 7.2).

3.6.2 CFD sensitivity for exploring indoor parameters

To achieve Objective 5 of the research, this study conducted sensitivity analysis of CFD simulation of internal factors on natural ventilation in the base case multi-residential building in Thailand (defined in Section 7.3). The investigation aimed to explore internal factors on the feasibility of ventilation for the multi-residential building's room.

The study criteria were established based on the finding in Chapter 2, including weather data thermal comfort, IEQ standards. The hottest day, rainy season, coldest day weather data was considered as an input data. The hourly annual average temperature, relative humidity and wind speed were determined to be 27.4 °C, 71%RH and 2.35 $m.s^{-1}$, respectively. (see Table 3- 9). The thermal comfort criteria set between

22.3 and 29.3 °C and 20%RH and 80%RH. The acceptable relative humidity for health benefit was between 40%RH and 60%RH. The acceptable ventilation in room was in the range of 0.2 $m.s^{-1}$ to 0.8 $m.s^{-1}$ and the required ventilation rate was 10 $L.s^{-1}$ or 0.01 $m^3.s^{-1}$ (more detailed in Section 2.2).(see Table 3- 10). The wind direction was determined to be parallel to the building orientation, as determined in the finding in Chapter 6.4.

Table 3- 9 climate data

	Average Temp (°C)	Min Temp (°C)	Max Temp (°C)	Average Rh (%RH)	Min Rh (%RH)	Max Rh (%RH)	Average Wind speed ($m.s^{-1}$)
coldest day	20.88	14.00	29.10	64.00	32.00	94.00	2.67
hottest day	32.42	26.00	38.10	46.42	24.00	76.00	1.93
rainy season	27.40	23.00	33.00	80.58	59.00	94.00	2.90
hourly average annual	27.40			70.00			2.35

Table 3- 10 criteria of study

Thermal comfort range	air temperature	22.3 – 29.3 °C
	ventilation	0.2-1.0 $m.s^{-1}$
	%RH	20%RH-80%RH
IEQ	required ventilation rate	10 L/s or 0.01 m^3/s
	acceptable ventilation	0.2-0.8 $m.s^{-1}$
	Relative humidity for health benefits	40-60%RH
summary	air temperature	22.3 – 29.3 °C
	acceptable ventilation	0.2-0.8 $m.s^{-1}$
	Relative humidity for health benefits	40-60%RH
	required ventilation rate	10 L/s or 0.01 m^3/s

The study was divided into three stages for CFD sensitivity of indoor parameters. The first (preliminary) stage, focused on investigating the base case for the study. The second stage used base case from the previous stage to explore room parameters identifying which ones meet the criteria in Table 3- 10. Parameters to be explored included, with and without chimney, and then the inlet and outlet size of room. The third stage focused on investigate chimney parameters related to the thermal behaviour in room and the chimney. This was carried out using a sensitivity analysis of different dimension of chimney inlet and outlet size, chimney width, chimney depth, chimney outlet and different storeys connecting to the chimney. The findings from stage one to three were analysed and proposed design options to improve the indoor environmental condition.

3.6.2.1 Stage 1: defining base case room

This stage established a base case room for internal CFD experiments by considering Thailand building regulations and the result of the occupant perception survey (Section 5.4). According to the minimum requirement of the regulation for the indoor dimension of the Building Control Act, the minimum unit interior area is 20 m^2 (MinistryofInterior 2017) (see Figure 3- 3). An 8-storey residential building with a double-loaded corridor was chosen as the base case because it was a common building type in high residential zones. Therefore, the study determined the minimum room size of 20 m^2 with a 4 m constructional span wide and floor to floor height is 2.60m to be a base case of room size. Typical materials were found from the occupant perception survey and were set for the base case room (See Table 3- 11).

Table 3- 11 material of base case room

Material	
room door	hardwood 100cm (W) x 200cm (L)
balcony door	hardwood 75cm (W) x 200cm (L)
toilet door	uPVC 75cm (W) x 200cm (L)
window	wooden frame with single clear glass (3 mm)
wall	concrete (80 mm) with cast concrete (20 mm)
ceiling	concrete
floor	ceramic tile

Variants on the base case room (Table 3- 12) were analysed using EnergyPlus and CFD to explore their impact on natural ventilation. These include:

- Full Balcony (FB) with WC near corridor and Half Balcony (HB) with WC near balcony
- Opening orientation options facing north and south or facing east and west (see Figure 3- 27)
- Room locations on, including 1st, 4th and 7th floor as well as corner and middle room

The base case for further stages was selected as having poor natural ventilation.

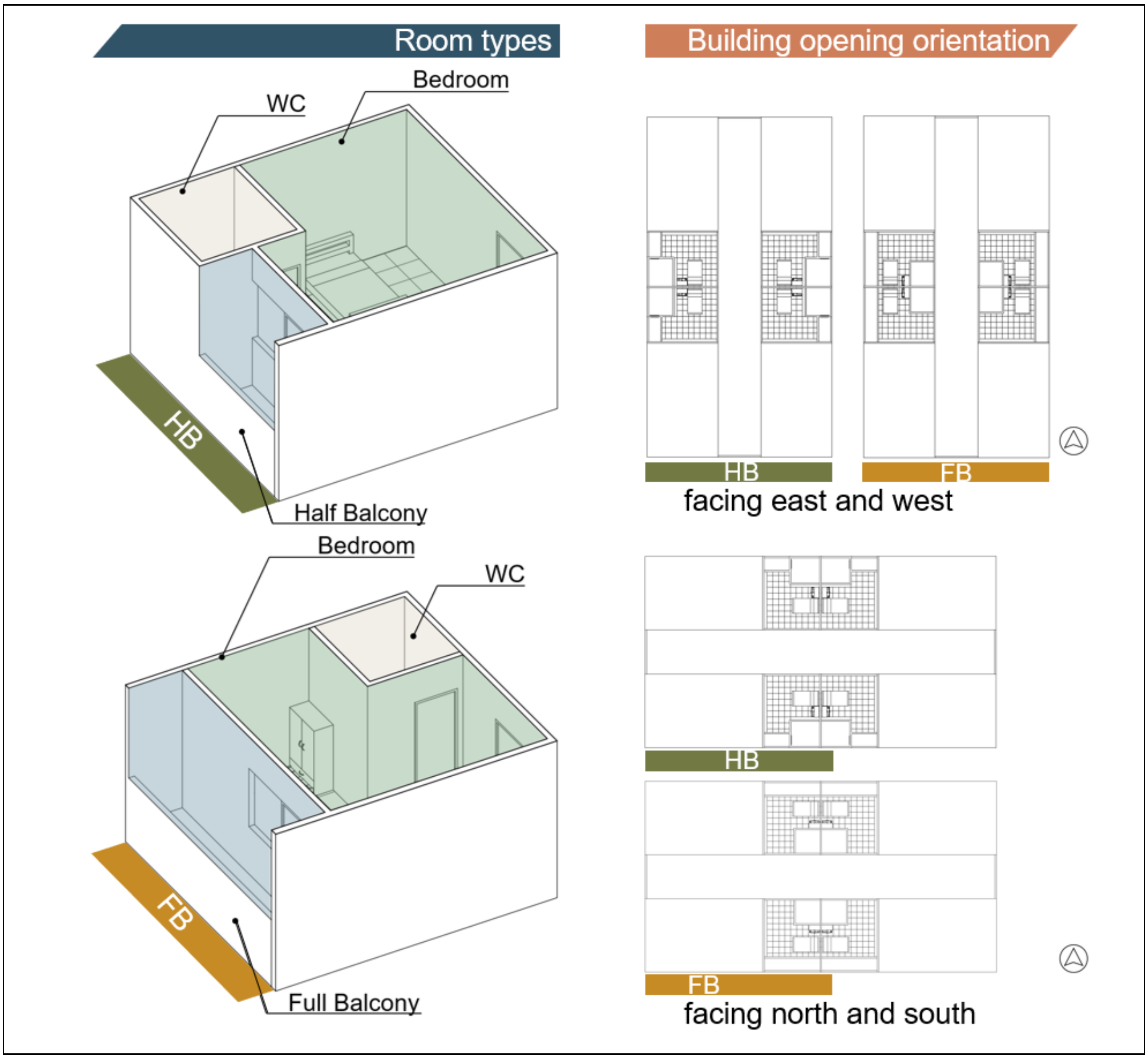


Figure 3- 27 Room types and building opening orientation options
(Source: Author)

Table 3- 12 Exploring base case room by EnergyPlus and CFD simulation

independent variable		**cases**	
room type	Full Balcony (FB) and Half Balcony (HB)	2	EnergyPlus 72 cases CFD 288 cases
building orientation	facing EW, facing NS	2	
floor	1st floor, 4th floor, 7th floor	3	
weather data	hottest day, rainy season, coldest day	3	
room location	middle room, corner room	2	
time	3 AM, 8AM, 12AM, 4PM	4	
dependent variables			
air temperature			
relative humidity			
airflow rate			
controlled variables			
room specification	See Table 3- 11 for materials		
room size	20 sq.m (4m wide x 5m long)		

3.6.2.2 Stage 2: exploring room changes to improve natural ventilation flow

The next stage was to investigate the potential of improving natural ventilation flow and IEQ by introducing a ventilation chimney and changing the ventilation aperture. The related indoor parameters, such as temperature, relative humidity and airflow were simulated using EnergyPlus and CFD simulation.

From stage 1, the HB room type in the middle of corridor was found to be the hardest to ventilate, this was chosen as the base case for this stage (details in Table 3- 13). The naming conventions used for each parameter in the base case room can be found in Figure 3- 28.

Table 3- 13 building configuration by EnergyPlus and CFD simulation

Building configuration	
room size	4m (W) x 5m (L), floor to floor 2.6 m
room plan	type HB
room location	middle room
room orientation	opening facing the north
occupancy	1 person per a unit
HVAC system	natural ventilation

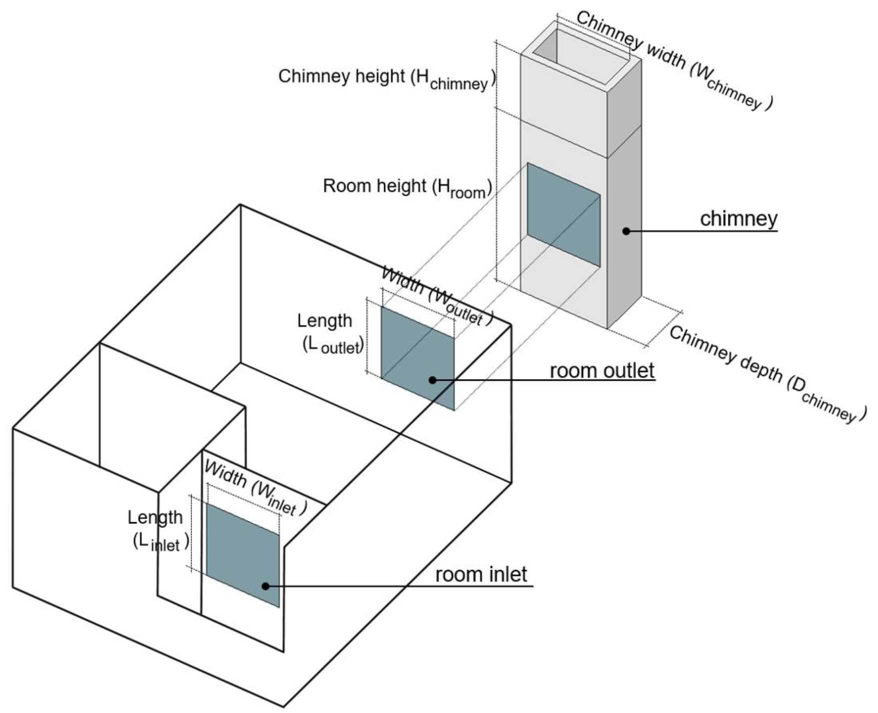


Figure 3- 28 HB Room layout with naming conventions for parameters used in simulation
(Source: Author)

3.6.2.2.1 Room with and without chimney

Initially, the base case room was analysed with and without chimney to determine which improved natural ventilation and thermal comfort. Hourly analysis was carried out on three different weather conditions, which are the highest temperature day, the representative day of rainy season and the lowest temperature day. (see Table 3- 14)

Table 3- 14 Room with and without chimney for by EnergyPlus and CFD simulation

independent variable		cases	
room	room without chimney	2	144 cases
	room with chimney	2	
weather data	hottest day, rainy season, coldest day	3	
Hourly	24 hours	24	
dependent variables			
air temperature			
relative humidity			
air speed			
airflow rate			
controlled variables			
room specification	See Table 3- 11 and Table 3- 13		
chimney geometry	size 1.0m ($W_{chimney}$) x 0.5m ($D_{chimney}$) x 3.0m ($H_{chimney}$)		
room inlet size	inlet 1.0m (W_{inlet}) x 1.1m (L_{inlet})		
room outlet size	outlet size 1.0m (W_{outlet}) x 1.1m (L_{outlet})		

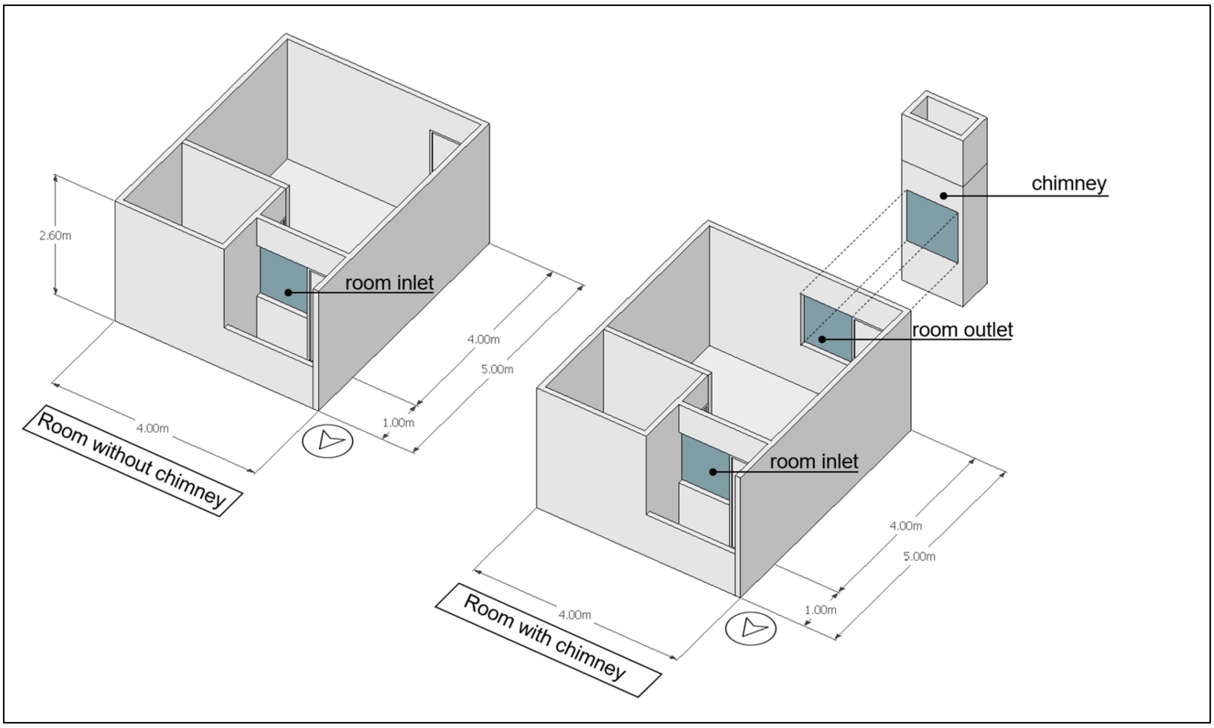


Figure 3- 29 Room with and without chimney
(Source: Author)

3.6.2.2.2 Room inlet and room outlet size

This section studied the impact of room inlet and outlet on natural ventilation and thermal behaviour. Room inlet size was set according to the conventional window size in Thailand (width of 1.0m and length of 0.55m, width of 1.0m and length of 1.1m, width of 1.0m and length of 2.0m). Room outlet size was varied in 10 cm interval. The purpose of this section is to determine the optimal room inlet and outlet for achieving acceptable natural ventilation and thermal comfort. (see Table 3- 15 and Figure 3- 30)

Table 3- 15 Room inlet and room outlet size for by EnergyPlus and CFD simulation

<table>
<tr><th colspan="2">independent variable</th><th colspan="2">cases</th></tr>
<tr><td>room inlet size</td><td>1.0m (W_{inlet}) x 0.55m (L_{inlet}), 1.0m (W_{inlet}) x 1.1m (L_{inlet}),
1.0m (W_{inlet}) x 2.0m (L_{inlet})</td><td>3</td><td rowspan="2">63 cases</td></tr>
<tr><td>room outlet size</td><td>Wide Outlet (W_{outlet} fixed to1.0m): 11 cases
1.0m (W_{outlet}) x 0.1m (L_{outlet}),
1.0m (W_{outlet}) x 0.2m (L_{outlet}),
1.0m (W_{outlet}) x 0.3m (L_{outlet}),
1.0m (W_{outlet}) x 0.4m (L_{outlet}),
1.0m (W_{outlet}) x 0.5m (L_{outlet}),
1.0m (W_{outlet}) x 0.6m (L_{outlet}),
1.0m (W_{outlet}) x 0.7m (L_{outlet}),
1.0m (W_{outlet}) x 0.8m (L_{outlet}),
1.0m (W_{outlet}) x 0.9m (L_{outlet}),
1.0m (W_{outlet}) x 1.0m (L_{outlet})
Narrow Outlet (W_{outlet} varied from 0.1 to 0.5 m): 10 cases
0.1m (W_{outlet}) x 1.0m (L_{outlet}),
0.2m (W_{outlet}) x 1.0m (L_{outlet}),
0.3m (W_{outlet}) x 1.0m (L_{outlet}),
0.4m (W_{outlet}) x 1.0m (L_{outlet}),
0.5m (W_{outlet}) x 1.0m (L_{outlet}),
0.1m (W_{outlet}) x 2.0m (L_{outlet}),
0.2m (W_{outlet}) x 2.0m (L_{outlet}),
0.3m (W_{outlet}) x 2.0m (L_{outlet}),
0.4m (W_{outlet}) x 2.0m (L_{outlet}),
0.5m (W_{outlet}) x 2.0m (L_{outlet})</td><td>21</td></tr>
<tr><th colspan="4">dependent variables</th></tr>
<tr><td colspan="4">vapour pressure</td></tr>
<tr><td colspan="4">air speed</td></tr>
<tr><td colspan="4">airflow rate</td></tr>
<tr><th colspan="4">controlled variables</th></tr>
<tr><td>room specification</td><td colspan="3">See Table 3- 11 and Table 3- 13</td></tr>
<tr><td>weather</td><td colspan="3">average annual weather data see Table 3- 9</td></tr>
<tr><td>chimney geometry</td><td colspan="3">size 1.0m ($W_{chimney}$) x 0.6m ($D_{chimney}$) x 3.0m ($H_{chimney}$)</td></tr>
</table>

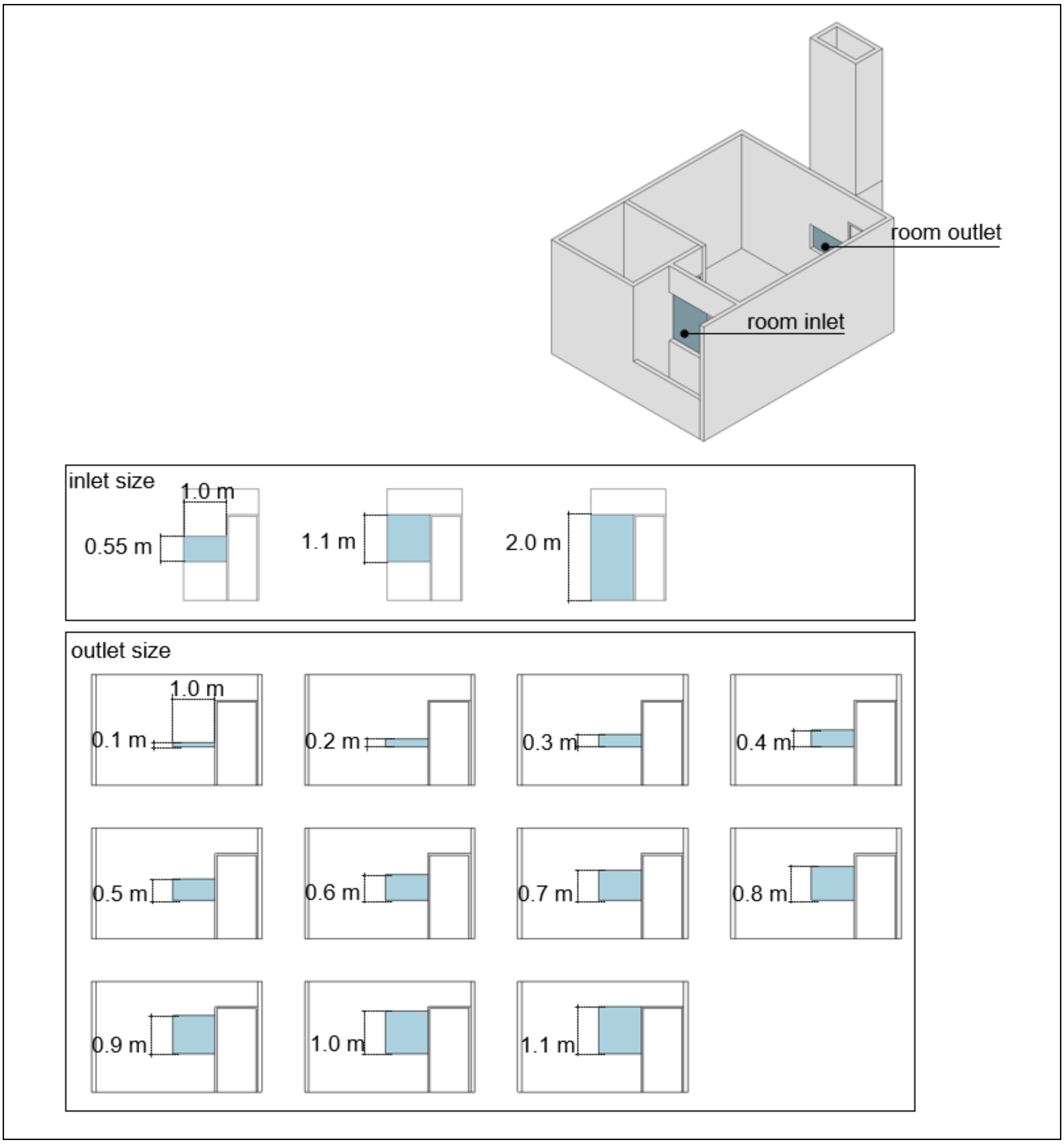


Figure 3- 30 Room inlet and room outlet size
(Source: Author)

3.6.2.3 Stage 3: exploration of chimney parameters impact on natural ventilation

This section aimed to explore various variables relating to the chimney and its connecting to the room in order to determine the optimal chimney design for providing acceptable ventilation and thermal comfort.

3.6.2.3.1 Chimney width and depth

In the exploration of chimney width and depth, the study divided into two parts, which were varying width and depth with fixed chimney outlet and varying width and depth with varied chimney outlet dimension. This study was not only used to establish the optimal chimney dimension but also used to determine the parameters with most influence on natural ventilation between chimney dimension and chimney outlet size. (see Table 3- 16 and Figure 3- 31)

Table 3- 16 Chimney width and depth by EnergyPlus and CFD simulation

<table>
<tr><th colspan="3">independent variable</th><th colspan="2">cases</th></tr>
<tr><td rowspan="2">fixed chimney outlet (0.3m x 0.3m)</td><td>$W_{chimney}$</td><td>0.3m, 0.4, 0.5m, 0.6m</td><td>4</td><td rowspan="2">32 cases</td></tr>
<tr><td>$D_{chimney}$</td><td>0.3m, 0.4, 0.5m, 0.6m, 0.7m, 0.8m, 0.9m, 1.0m</td><td>8</td></tr>
<tr><td rowspan="2">varied chimney outlet</td><td>$W_{chimney}$</td><td>0.3m, 0.4, 0.5m, 0.6m</td><td>4</td><td rowspan="2">40 cases</td></tr>
<tr><td>$D_{chimney}$</td><td>0.1m, 0.2m, 0.3m, 0.4, 0.5m, 0.6m, 0.7m, 0.8m, 0.9m, 1.0m</td><td>10</td></tr>
<tr><th colspan="5">dependent variables</th></tr>
<tr><td colspan="5">vapour pressure</td></tr>
<tr><td colspan="5">airflow rate</td></tr>
<tr><th colspan="5">controlled variables</th></tr>
<tr><td colspan="2">room specification</td><td colspan="3">See Table 3- 11 and Table 3- 13</td></tr>
<tr><td colspan="2">weather</td><td colspan="3">average annual weather data see Table 3- 9</td></tr>
<tr><td colspan="2">chimney height</td><td colspan="3">3 m</td></tr>
<tr><td colspan="2">room inlet size</td><td colspan="3">1.0m (W_{inlet}) x 2.0m (L_{inlet})</td></tr>
<tr><td colspan="2">room outlet size</td><td colspan="3">0.3m (W_{outlet}) x 1.0m (L_{outlet})</td></tr>
</table>

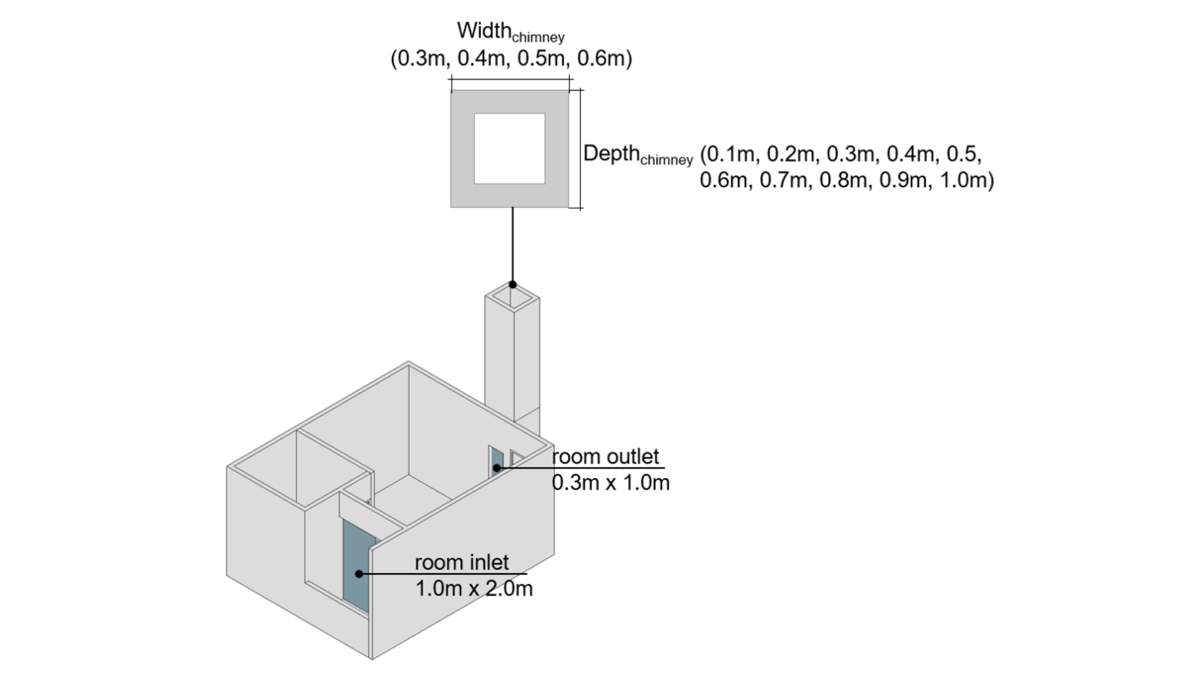


Figure 3- 31 Chimney width and depth
(Source: Author)

3.6.2.3.2 Room outlet location

This section focused on exploring the different locations of room outlet (see Figure 3-32). The outlet locations were divided into three columns and three rows. The columns included left, right and corner. The row of the outlet location was divided into three height level, which were upper, middle and lower outlet. The upper outlet refers to the hight above occupant's head. The middle outlet refers to the occupant's living level. The lower outlet refers to the height of bed. (see Table 3- 17)

Table 3- 17 Room outlet location by EnergyPlus and CFD simulation

independent variable		**cases**	
outlet location (row)	upper (U), middle(M), lower(L)	3	9 cases
outlet location (column)	left (L), central (C), right(R)	3	
dependent variables			
vapour pressure			
airflow rate			
controlled variables			
room specification	See Table 3- 11 and Table 3- 13		
weather	average annual weather data see Table 3- 9		
chimney height	3m		
Room inlet size	1.0m (W_{inlet}) x 2.0m (L_{inlet})		
Room outlet size	0.3m (W_{outlet}) x 1.0m (L_{outlet})		
chimney width and depth	0.3m ($W_{chimney}$) x 0.3m ($D_{chimney}$)		

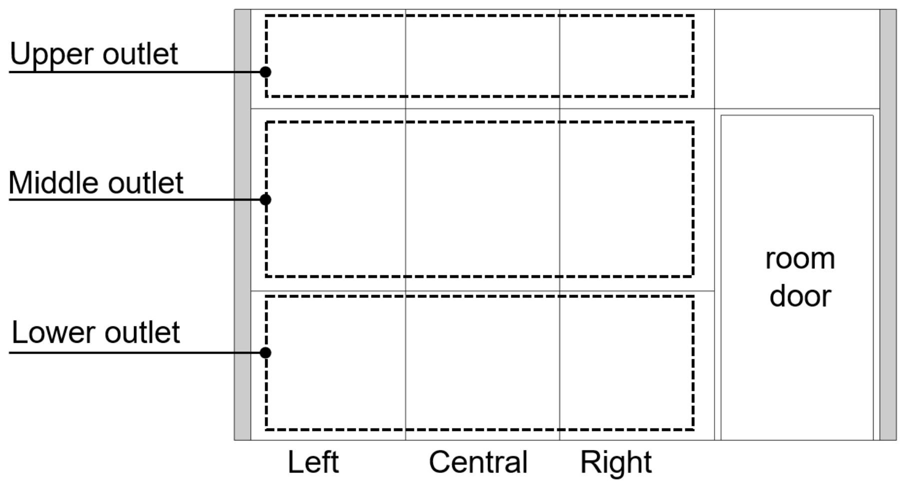


Figure 3- 32 Room outlet location on wall close to corridor
(Source: Author)

3.6.2.3.3 Chimney material

According to the finding Section 2.4.3.1, solar chimney can enhance ventilation flow compared to conventional chimney. This is because solar chimney can generate greater difference between outdoor and indoor air temperature. In addition, insulation is another crucial parameter of solar chimney, as solar heat gain in the chimney can be lost through uninsulated wall (Afonso and Oliveira 2000). Therefore, this study aimed to explore vapour pressure and airflow rate of three chimney types, including chimney, solar chimney without insulation and solar chimney with insulation (see Table 3- 18).

Table 3- 18 Chimney material by EnergyPlus and CFD simulation

independent variable		**cases**
chimney material	chimney	3 cases
	solar chimney without insulation	
	solar chimney with insulation	
dependent variables		
vapour pressure		
airflow rate		
controlled variables		
room specification	See Table 3- 11 and Table 3- 13	
weather	average annual weather data see Table 3- 9	
chimney height	3m	
Room inlet size	1.0m (W_{inlet}) x 2.0m (L_{inlet})	
Room outlet size	0.3m (W_{outlet}) x 1.0m (L_{outlet})	
chimney width and depth	0.3m ($W_{chimney}$) x 0.3m ($D_{chimney}$)	

3.6.2.3.4 Chimney design

3.6.2.3.4.1 Trimmed chimney

Referring to chapter 2.4.3.1, about duct design method, pressure drop in the chimney can be influenced by chimney's internal angle. Internal angle of 45 degrees is recommended as it can minimise turbulence, pressure drop and the risk of blockages. Therefore, this section aimed to investigate ventilation in the room and chimney with different internal angles. (see Table 3- 19 and Figure 3- 33)

Table 3- 19 Trimmed chimney by EnergyPlus and CFD simulation

independent variable		**cases**
chimney design	untrimmed chimney	3 cases
	0 degree trimmed chimney	
	45 degree trimmed chimney	
dependent variables		
ventilation		
controlled variables		
room specification	See Table 3- 11 and Table 3- 13	
weather	average annual weather data see Table 3- 9	
chimney height	3m	
Room inlet size	1.0m (W_{inlet}) x 2.0m (L_{inlet})	
Room outlet size	0.3m (W_{outlet}) x 1.0m (L_{outlet})	
chimney width and depth	0.3m ($W_{chimney}$) x 0.3m ($D_{chimney}$)	

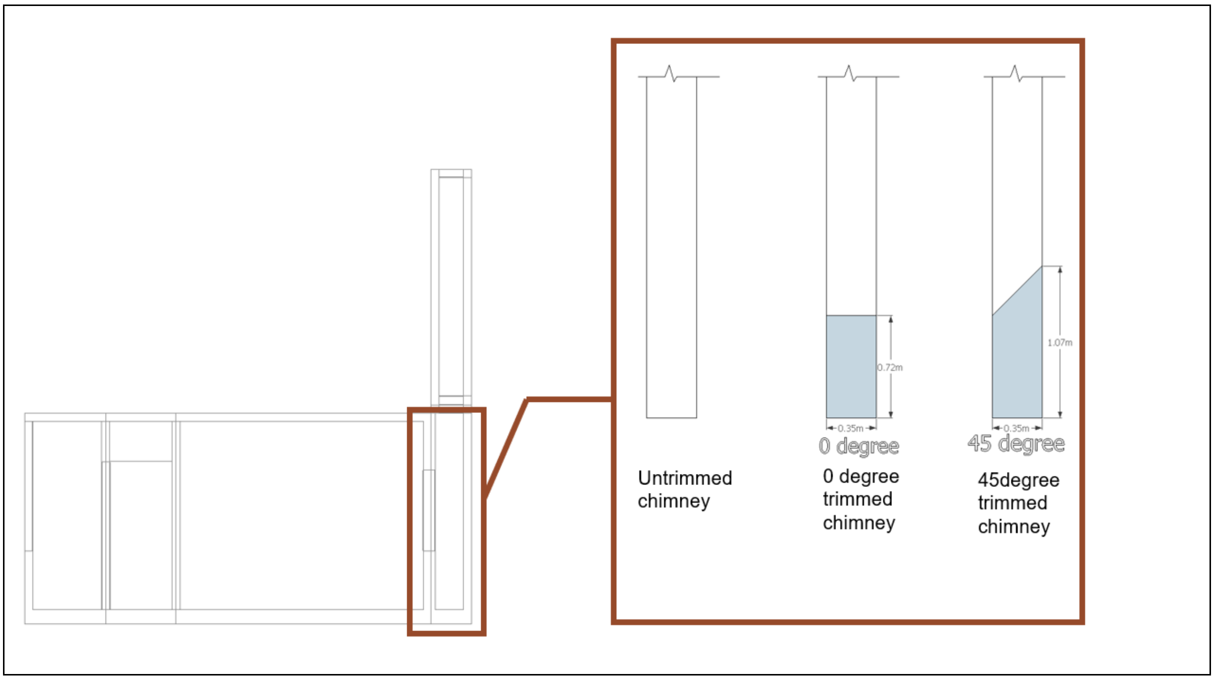


Figure 3- 33 Trimmed chimney
(Source: Author)

3.6.2.3.4.2 Room with and without grille and mosquito wire

In building located in Thailand, it is common to have mosquito wire installed on openings to prevent insects and small pests entering. Grille is another type of opening protection to protect building opening from larger unwanted animals, such as birds. The addition of the obstruction to room aperture has an impact on the discharge coefficient of the opening and can reduce the flow rate. Therefore, this section of the study focuses on investigating ventilation and vapour pressure between the opening with and without grille and mosquito wire (see Figure 3- 34 and Table 3- 20). The dimension of mosquito wire and grille in the model were selected based on common practices in Thailand. For example, mosquito wire holes were set with a width and length of 2 mm. Grille blades of 5 cm were installed at a 45- degree angle with 5 cm space between each blade.

Table 3- 20 Room with and without grille and mosquito wire by EnergyPlus and CFD simulation

independent variable		**cases**
opening material	with grille and mosquito wire	2 cases
	without grille and mosquito wire	
dependent variables		
airflow rate		
vapour pressure		
controlled variables		
room specification	See Table 3- 11 and Table 3- 13	
weather	average annual weather data see Table 3- 9	
chimney height	3m	
Room inlet size	1.0m (W_{inlet}) x 2.0m (L_{inlet})	
Room outlet size	0.3m (W_{outlet}) x 1.0m (L_{outlet})	
chimney width and depth	0.3m ($W_{chimney}$) x 0.3m ($D_{chimney}$)	

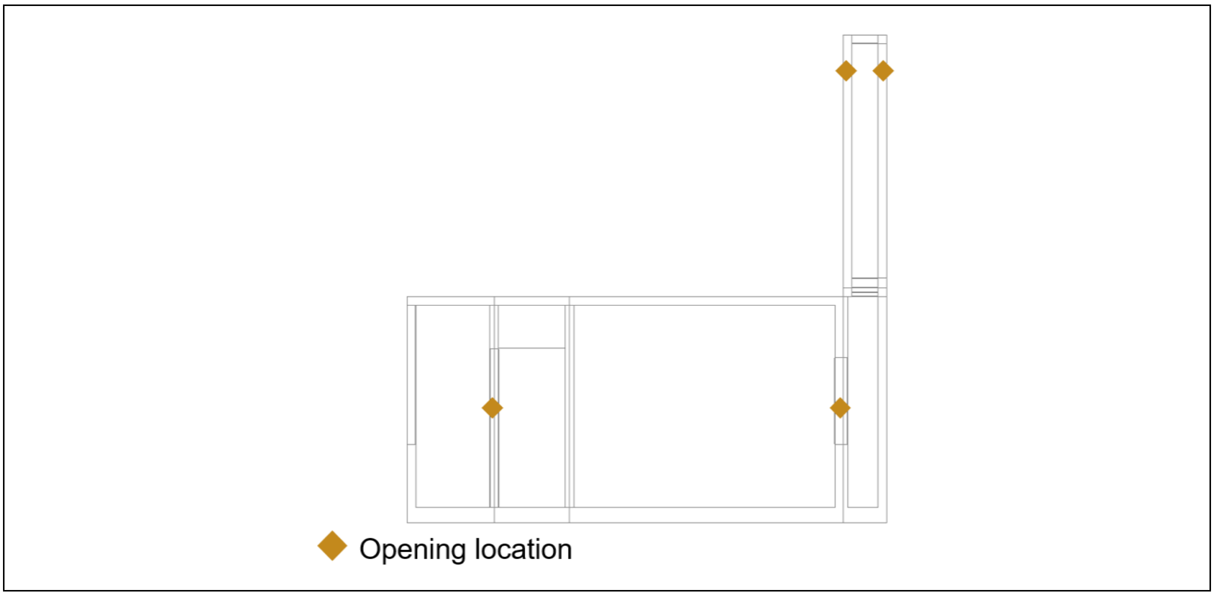


Figure 3- 34 Room with and without grille and mosquito wire
(Source: Author)

3.6.2.3.5 Chimney outlet style

Chimney outlet size and location are one of the influencing factors of thermal performance of chimney. Based on the finding in Section 2.4.3.1, solar chimney is recommended to face south for maximising exposure to sunlight. A top outlet of chimney can provide continuous natural airflow upward and out of the chimney. However, using a top outlet has a limitation as the outlet needs to be designed to prevent water from entering the chimney. In Thailand, roof systems are prone to occasional water leaking during rainy season (Naing et al. 2017). Side outlet is another type of chimney outlet, which helps mitigate water leakage issue.

This section focuses on exploring ventilation and vapour pressure of four different styles and locations of chimney outlet locations. This includes chimney outlet on roof, facing south, facing both the north and the south and multi-chimney facing both the north and south (see Table 3- 21 and Figure 3- 35). In addition, height of the outlet was also investigated in this section. Higher outlet (H) results proportionally in the reduction of solar chimney material area on the wall due to the limitation of the chimney height.

Table 3- 21 Chimney outlet style by EnergyPlus and CFD simulation

independent variable		**cases**
chimney outlet location	on roof (top outlet)	4 cases
	facing the south	
	facing the north and the south	
	multi-chimney facing north and the south	
Height of chimney outlet (H) (multi-chimney facing north and the south)	0.3 m, 0.4 m, 0.5 m, 0.6 m, 0.7 m, 0.8 m, 0.9 m, 1.0 m, 1.1 m, 1.2 m, 1.3 m, 1.4 m, 1.5 m	13 cases
dependent variables		
vapour pressure		
airflow rate		
controlled variables		
room specification	See Table 3- 11 and Table 3- 13	
weather	average annual weather data see Table 3- 9	
chimney height	3m	
Room inlet size	1.0m (W_{inlet}) x 2.0m (L_{inlet})	
Room outlet size	0.3m (W_{outlet}) x 1.0m (L_{outlet})	
chimney width and depth	0.3m ($W_{chimney}$) x 0.3m ($D_{chimney}$)	

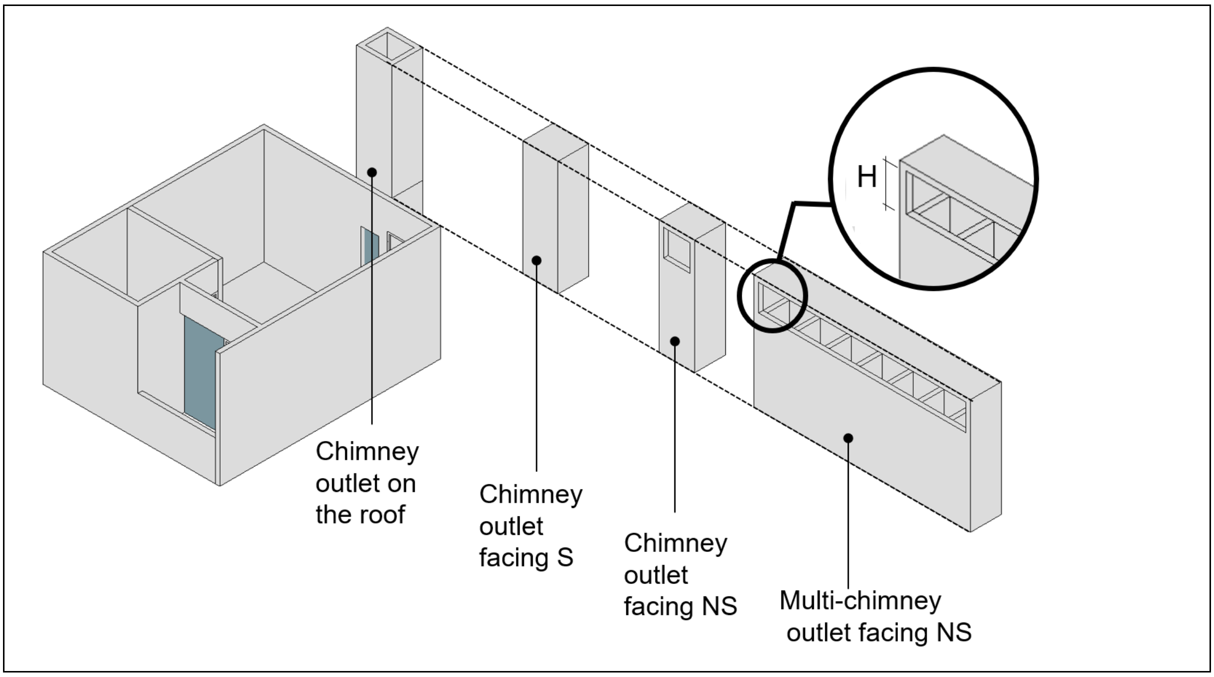


Figure 3- 35 Chimney outlet style
(Source: Author)

3.6.3 Summary

The findings from Stage 1 to Stage 3 of internal sensitivity analysis were summarised the key internal factors on vapour pressure and natural ventilation in apartment blocks in Thailand. The optimal design options were analysed and to establish design proposals for improving indoor environmental quality via passive design strategy. In addition, thermal comfort hours were analysed in relation to different seasons.

3.7 Validating design options for improving internal environment quality within thermally free- running apartments (Phase 3)

To achieve Objective 6 of the research, the aim of this phase is to validate the design options applicability in practice. This was achieved by consulting with Thai built environment professionals (BEPs), e.g., architects, engineers, and academics, who are involved in multi-storey building design and construction projects.

Semi-structured interview was applied as a method to investigate the professionals' thoughts, ideas and perceptions of the proposed design options. The interviews were conducted online in order to encourage professionals involvement.

Ethics approval was confirmed before interview began (see Appendix E). All the participants were informed about project details, data protection and voluntary participation to reduce a risk of any participants experiencing either physical or psychological discomfort.

3.7.1 Participant's criteria

The interview invited BEPs including engineers, architects and academics, who reside in Thailand and have experience in multi-storey building design and construction projects to participate the project. Purposive sampling method was applied for selecting the interviewees. Relevant literature was consulted for the appropriate sample size. Marshall et.al 2013 recommended between 20 and 30 interviews as a sample size for Grounded Theory studies and between 15 and 30 for single-case studies. Galvin 2015 suggested that saturated data can be achieved after between 12 and 30 interviews. Francis et.al 2010, reached data saturation within 14-17 interviews. This research, therefore, set 17 interviews as a minimum sample size, but additional invitations were extended in case non-availability. The aim was to equal representation across three groups of BEPs, architects (33.3%), engineers (33.3%) and academics (33.3%).

In total, there were 21 interviewees, which were 7 people for each group. The architect group included both architects and interior architects. The engineer group comprised of construction engineers and mechanical engineers. The academics group consisted of two professional backgrounds, which are architect-based and engineer-based academics. The academics were from diverse institutions. Most of them have research background about ventilation system in building in Thailand context.

3.7.2 Interview design

The interview questions were designed based on semi-structured interview method. The research developed interview questions from broad to specific questions. Follow up questions were designed to probe deeper into the topic for clarifying and validating information purpose. The interview questions were divided into two parts. Part one established context of the expert's experience and knowledge in relation to current multi-storey residential building and passive design. Part two focused on specific questions about passive strategies and design options to improve natural ventilation in thermally free-running multi-residential buildings in Thailand. Prior to interviewing BEPs, a pilot study was tested and the questions' developed to ensure reliability and internal validity.

3.7.2.1 Part one of interview questions

This part aimed to explore opinion, experience, and knowledge of the BEPs about multi-storey residential building and passive design in Thailand context. Open-ended questions were employed in this part to obtain the opinion of the BEPs. The questions in this part allowed the interviewees to express their thoughts and demonstrate their understanding. Interview questions are in Table 3- 22.

Table 3- 22 part one of interview questions

topic	questions
1.1 General question	What is your built profession? (architect, engineer, academics)
1.2 Issue of indoor environmental quality	What (if any) indoor environmental quality problems exist in free-running multi-storey residential buildings in Thailand? What design solutions do you think could be implemented to solve these issues(s)?
1.3 Natural ventilation	Do you think natural ventilation is important in thermally free running building in Thailand? If yes - what benefits do you think natural ventilation brings? If no - are there specific issues that you associate with natural ventilation?

3.7.2.2 Part two of interview questions

In this part, specific questions about passive cooling strategies and design options were employed. Participants were solicited to provide their opinions on how to implement passive cooling in multi-residential building in Thailand. BEPs were inquired to define significant factors related to building and construction projects for each design option illustrated and provide suggestions for future buildings (see Table 3- 22). A combination of open and close -ended question were used in this part. The interview question about improving natural ventilation in building encouraged the participants to suggest solutions and locate the area for improving natural ventilation of multi-storey residential building (in Figure 3- 37). The questions about BEPs' opinions on options solicited the participants to provide perspectives on the potential of natural ventilation in multi-storey floor plan. Building model and CFD simulation result for each option were provided (see Appendix F). The questions were formulated based on optimal options derived from the finding of CFD internal sensitivity analysis.

Table 3- 23 part two of interview questions

topic	questions
2.1 Improve natural ventilation in building	a. What feature in Figure 3- 36 can be developed to improve ventilation in a thermally free running multi-residential building in Thailand b. What feature in Figure 3- 37 can be developed to improve ventilation in a thermally free running multi-residential building in Thailand
2.2 Solar chimney	a. What opportunities and obstructions do you see in integrating solar chimney with multi-residential building in relation to natural ventilation, building design, energy, and construction? b. For obstruction, what additional system should be used to assist solar chimney in relation to natural ventilation, building design, energy, and construction?
2.3 Professionals' opinions on options	Please give your opinions on the options in relation to the potential of natural ventilation options in thermally free-running apartment dwellings in Thailand climate condition. 2.3.1 Different balcony type a) Room with solid wall balcony b) Room with railing balcony 2.3.2 Room inlet size a) Room with window size 1.0 x 1.1 m b) Room with window size 1.0 x 2.0 m 2.3.3 Room with and without chimney a) Room without chimney b) Room with chimney 2.3.4 Chimney design a) One chimney connected to multi-rooms b) One chimney connected to only one rooms 2.3.5 Room outlet design a) Room with horizon room outlet b) Room with vertical room outlet

(a) whole floor plan of multi-residential

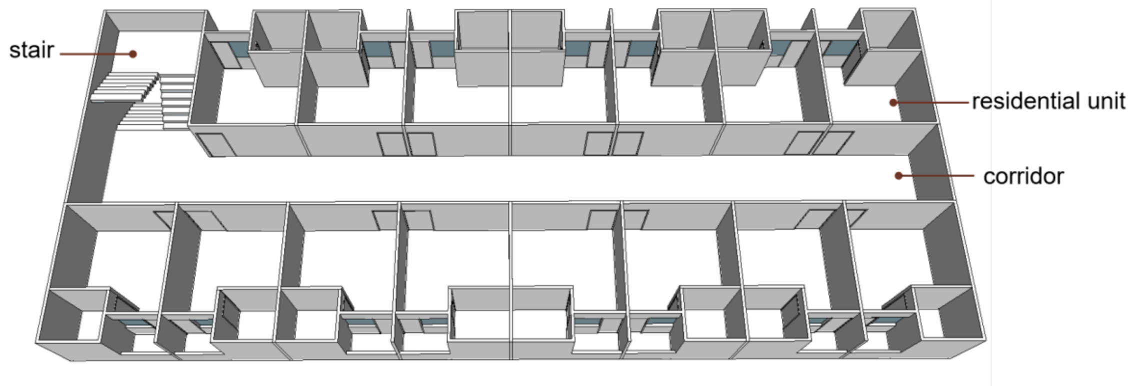


Figure 3- 36 whole floor plan of multi-residential
(Source: Author)

(b) a plan of one room in multi-residential building

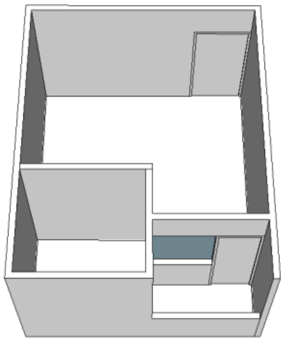


Figure 3- 37 floor plan of one room multi-residential building
(Source: Author)

3.7.3 Data analysis

Thematic analysis was utilised to identify, analyse and demonstrate pattern of professionals' opinions. Thematic analysis is a qualitative method which is commonly used to describe and categorise themes of data (Braun and Clarke 2006). Thematic analysis can be used to interpret various aspects of participants' opinions, for example, construction, passive design strategy, aesthetic and socio-cultural context influencing their response. In addition, inductive approach in thematic analysis was used to reveal unexpected information and then refine theme for a deep understanding of the data. The study utilised NVIVO 12 to support coding and analyse of interview data.

The five steps of coding in Thematic analysis were applied to the research (Castleberry and Nolen 2018; Williams and Moser 2019)

- Initial coding involves capturing main ideas, concepts or themes that emerge from the data. This is a primary exploration to identify patterns to generate set of descriptive codes, which provides a foundation for the next step of coding.
- Open coding is a more in-depth exploration, which aim to develop coding achieved from initial coding step. Open coding is approaching the thematic fragments and systematically organising data collection.
- Axial coding involves further refining and categorising the completion achieved from open coding in order to prepare data for focus coding.
- Focused coding is to develop coherence by connecting and combining by connecting and combining topics in order to find significant connections between individuals. The individuals were sought out for profound connections.

- Selective coding is used to identify the core themes that encapsulate the main points of data. This coding generates cohesive narrative to reflect the main themes.

3.7.4 Design options

Referring to the findings presented in Chapter 8, both the original room and the optimal case will be evaluated thermal behaviour difference using EnergyPlus and CFD simulation. This section focuses on examining vapour pressure and ventilation pattern of these across different weather seasons (resulted in Chapter 9)

Table 3- 24 design options by EnergyPlus and CFD simulation

<table>
<tr><td colspan="2">independent variable</td><td colspan="2">cases</td></tr>
<tr><td>balcony</td><td>original room, optimal case</td><td>2</td><td rowspan="4">36 cases</td></tr>
<tr><td>Room floor</td><td>1^{st} floor room, 4^{th} floor room,7^{th} floor room</td><td>3</td></tr>
<tr><td>Room inlet size</td><td>1.0m (W_{inlet}) x 1.1m (L_{inlet})
1.0m (W_{inlet}) x 2.0m (L_{inlet})</td><td>2</td></tr>
<tr><td>weather data</td><td>hottest day, rainy season, coldest day</td><td>3</td></tr>
<tr><td colspan="4">dependent variables</td></tr>
<tr><td colspan="4">vapour pressure</td></tr>
<tr><td colspan="4">airflow rate</td></tr>
<tr><td colspan="4">controlled variables</td></tr>
<tr><td>room specification</td><td colspan="3">See Table 3- 11 and Table 3- 13</td></tr>
<tr><td>Room outlet size</td><td colspan="3">0.3m (W_{outlet}) x 1.0m (L_{outlet})</td></tr>
<tr><td>chimney width and depth</td><td colspan="3">0.3m ($W_{chimney}$) x 0.3m ($D_{chimney}$)</td></tr>
</table>

3.8 Summary Methodology

Research methods of this study were carried out in three parts to achieve the research objectives. In the initial part, physical measurements were made to evaluate the current indoor environment conditions. This was carried out in relation to a survey to establish the perceptions of occupants experiencing these environment conditions. The monitoring data from the initial phase was also used to establish boundary conditions for CFD sensitivity model of outdoor (external) conditions in Phase 2. In addition, the monitoring data was used to validate the internal CFD model and building simulation model. These models were used to explore outdoor and indoor factors affecting natural ventilation and thermal behaviour of the building. CFD and building simulation were performed to analyse airflow and thermal behaviour of building. Part 3 investigated design options for improving indoor environmental quality. This part involved engaging with built professionals in Thailand for validating the proposed design. The summary of method flow chart is in Figure 3- 38.

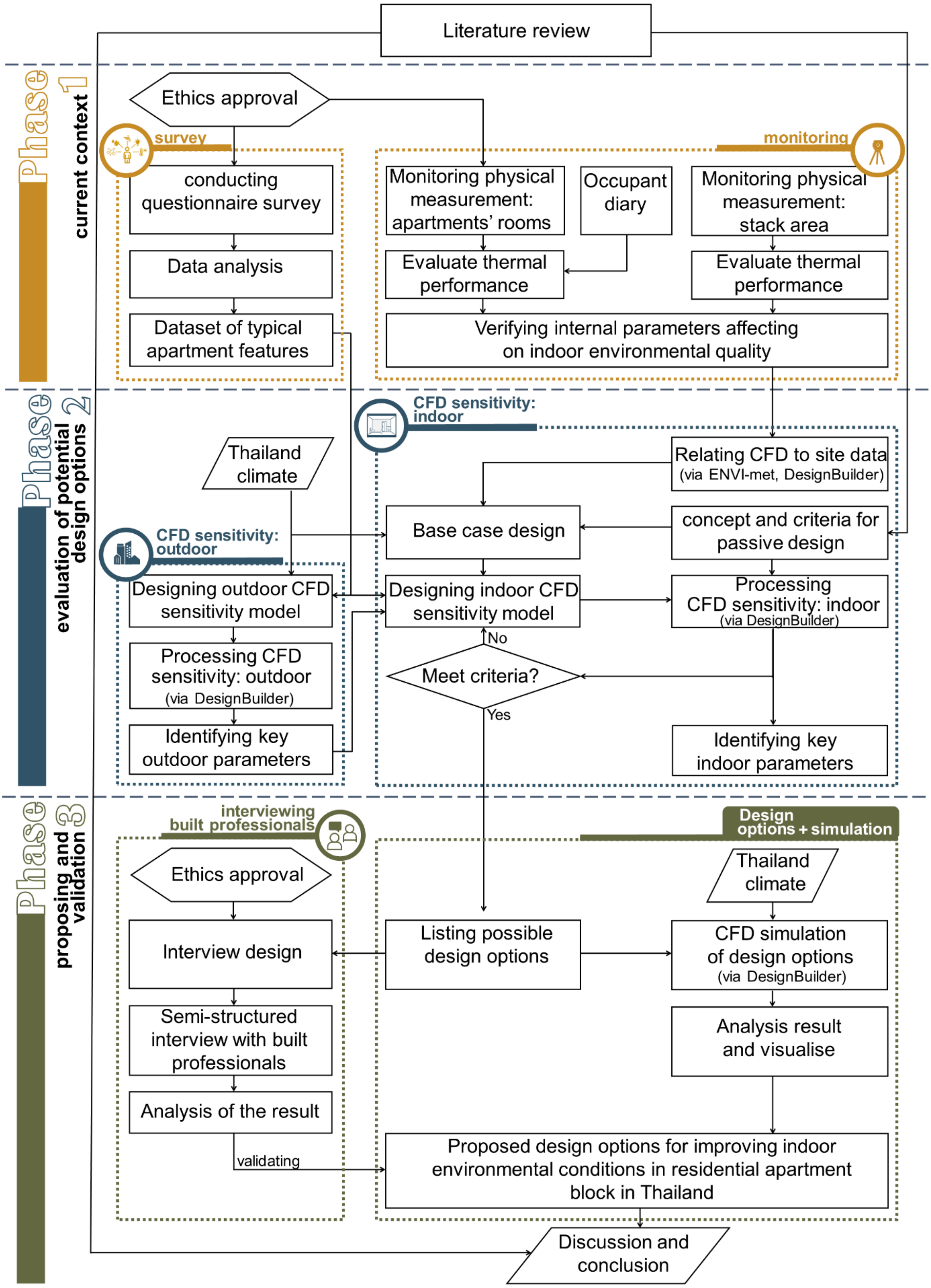


Figure 3- 38 workflow chart
(Source: Author)

4 Monitoring Physical Measurement Result

4.1 Introduction

This chapter presents the findings from monitored physical measurement conducted to explore actual environment conditions in multi-residential building in Thailand, in order to achieve objective 1 of the research. The physical measurements can evaluate current situation particularly, building's IEQ performance in relation to temperature, relative humidity, and air velocity, which can provide insights into internal parameters affecting occupants.

The methodology for monitoring physical measurement were detailed in Section 3.3. Monitored data encompassed air temperature, relative humidity and air velocity. This study divided physical measurement into two parts, which are stack area and apartments' rooms. Monitoring in the stack area was conducted in the stairwell of a 5-storey building, as the stairwell exhibited some of the parameters of the stack chimney. In apartments' rooms, the physical measurements were conducted in four participants' rooms, in multi-storey buildings in Chiang Mai.

The monitoring physical measurement results in this chapter are divided into two parts, which are Stack area results (Section 4.2) and Apartments' rooms results (Section 4.3).

4.2 Stack area results

The results are divided into 3 cases regarding the three different scenarios, which are:

- Case 1: only the window at the half landing between the 1st floor and the 2nd floor (W2) was opened (Section 4.2.1)
- Case 2: only the top window (W4) was opened (Section 4.2.2)
- Case 3: both W2 and W4 were opened (Section 4.2.3)

Figure 4- 1 model of a multi-storey building for collecting stack temperature, relative humidity, and air velocity
(Source: Author)

4.2.1 Case1: only the window at the half landing between the 1st floor and the 2nd floor (W2) was opened

4.2.1.1 Air Temperature

The outside temperature was decreasing during the nighttime and reached the lowest of 20.7°C at 7.24 am. The temperature during the daytime increased and reached its peak at 29.05°C at 3.39 pm. Nevertheless, the indoor temperature was more stable in comparison to the outside temperature. The higher position had a higher temperature, however, the temperature of location A steadily paralleled to the other locations only in the daytime(8.00am-4.00pm). When approaching the nighttime the temperature of location A was similar location B's temperature (see Figure 4- 2). The average temperature at location A, B, C and D was 21.66°C, 22.13°C, 23.00°C and 24.05°C, respectively. The minimum temperature at this stack area was between 21.00°C and 23.22°C, which was location A, whereas the maximum temperature was a range from 22.28°C to 25.29 °C, which was location D. The standard deviation (S.D.) of the temperature at each different height had a similar value which was between 0.38 and 0.57. This means the temperature data at each indoor location was clustered around the mean temperature. However, the outdoor temperature data had more spread out than the internal temperature, which was approximately 2.44.

4.2.1.2 Relative humidity

Overall relative humidity was inversely proportional to temperature. The outdoor relative humidity gradually increased during the nighttime and reached a peak at 6.30 am. with 73.04%RH. Then it plunged to 44.95%RH at 3.27 pm. The outdoor relative humidity fluctuated more compared to the indoor relative humidity. Additionally, the standard deviation (S.D.) of the outdoor humidity data had approximately 7.32 higher than the S.D. value of the indoor area. The lower positions showed higher relative humidity; for example, location A had higher relative humidity than location B (see Figure 4- 3). The average relative humidity of location A, B, C and D was 65.77%RH, 63.44%RH, 60.57%RH, and 57.58%RH, respectively. The minimum relative humidity of all internal locations was between 52.94%RH and 65.07%RH, while the maximum humidity was from 59.76 %RH to 67.12%RH.

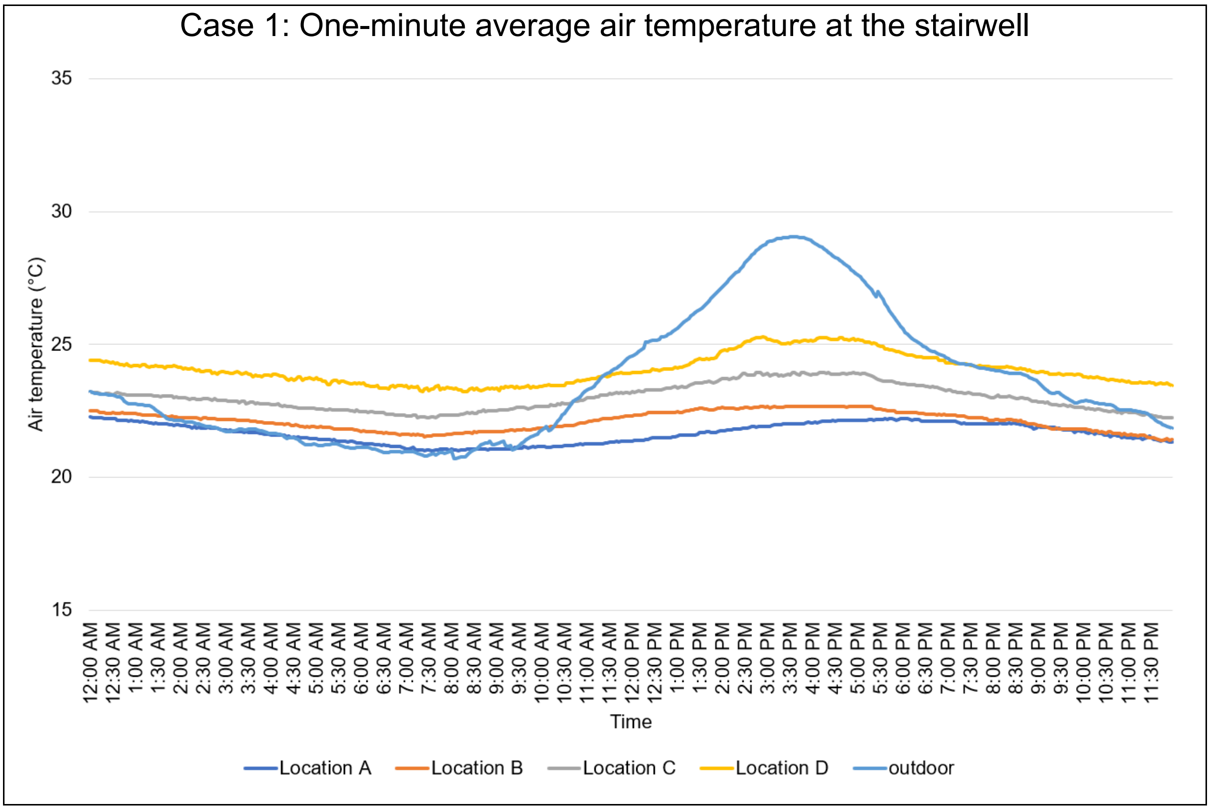


Figure 4- 2 One-minute average air temperature at the stairwell (case 1)

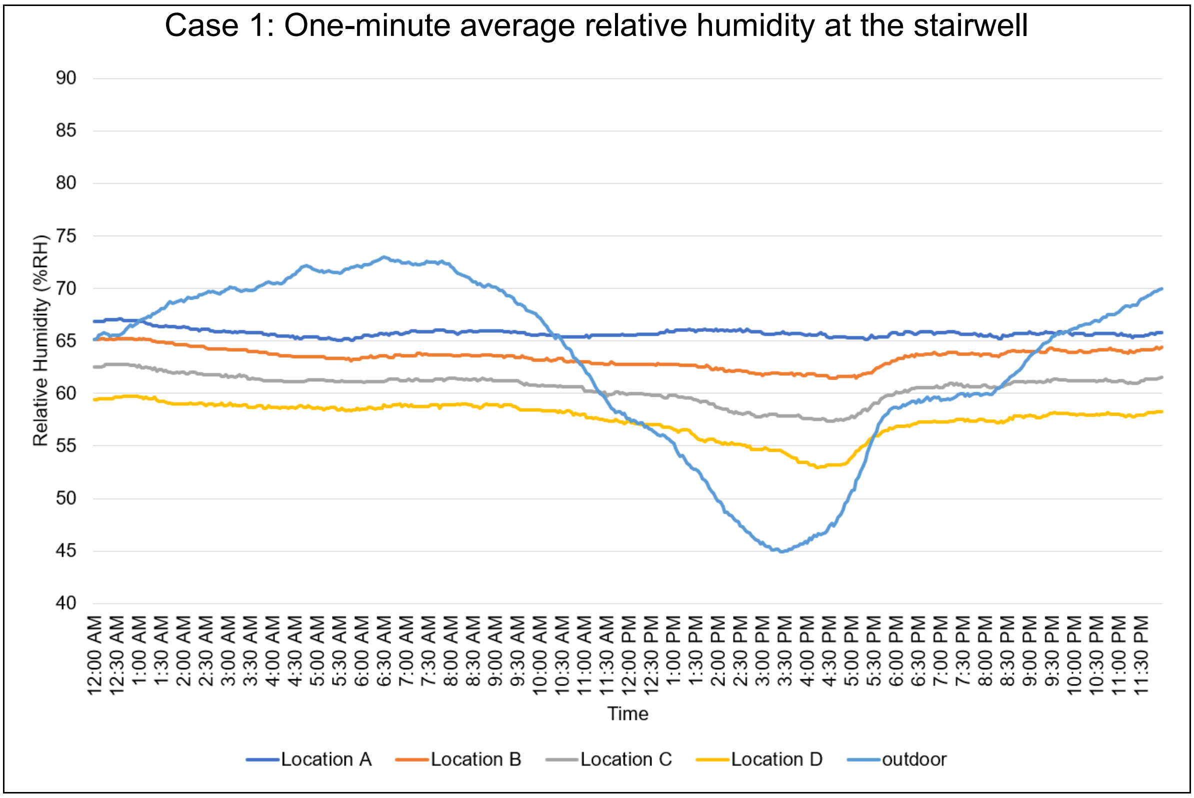


Figure 4- 3 One-minute average relative humidity at the stairwell (case 1)

4.2.1.3 Air movement

The air velocity of all sensors was almost 0 $m.s^{-1}$. Empirically, without outlet opening, there was no effective air velocity through the sensors.

4.2.2 Case 2: only the top window (W4) was opened

4.2.2.1 Air Temperature

The outdoor temperature decreased slightly from 23.43°C at 12.00 am to 21.00°C at 7.48 am. The temperature then reached a peak at 29.80°C at 3.30 pm, finally dropped again. The outdoor temperature fluctuated more than the indoor temperature. Besides, it can consider from the standard deviation value. The standard deviation of outdoor temperature was 2.60, while the standard deviation of indoor temperature was between 0.39 and 0.57. The average temperature of location A, B, C, and D was 21.97 °C, 22.35°C, 23.4°C and 24.33°C, respectively. The range of minimum stack area's temperature was between 21.18°C and 23.40°C, while the maximum was between 22.54°C and 25.58°C. The higher location related to higher temperature parallelly, such as location D had a higher temperature than location D. However, the temperature of location A steadily paralleled to the other locations only in the daytime

(8.00 am-4.00 pm), whereas the temperature during nighttime was gravitating toward location B's temperature (see Figure 4- 4).

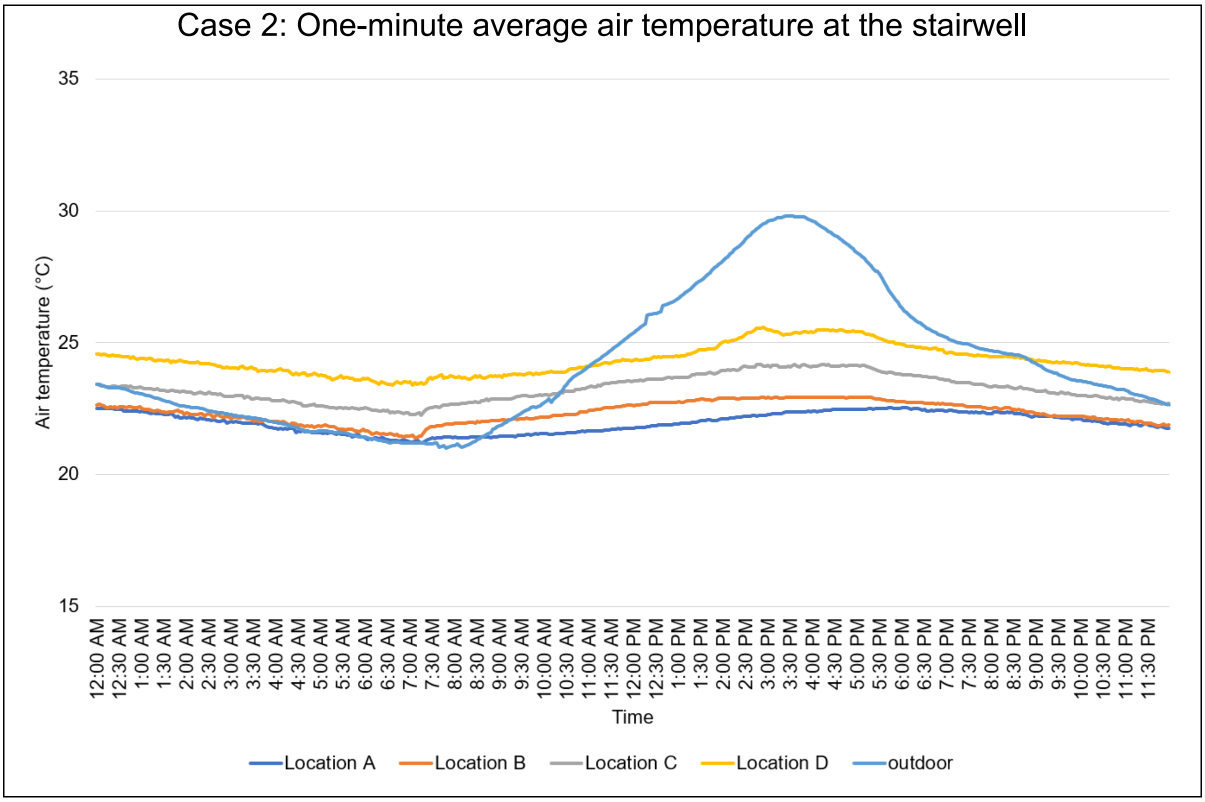


Figure 4- 4 One-minute average air temperature at the stairwell (case 2)

4.2.2.2 Relative humidity

Relative humidity inversely relates to temperature. The outdoor relative humidity rose slightly during nighttime and then reached a high point at 6.30 am with 73.98%RH. The relative humidity declined significantly during daytime and had the lowest at 3.27 pm. Since then, the relative humidity was noticeable increasing. Most of the indoor relative humidity remained stable. The relative humidity of lower location had a higher humidity, e.g., location A had the highest relative humidity in comparison to other locations. The average relative humidity of location A, B, C, and D were 67.90 %RH, 65.65%RH, 62.61%RH and 59.45%RH, respectively.

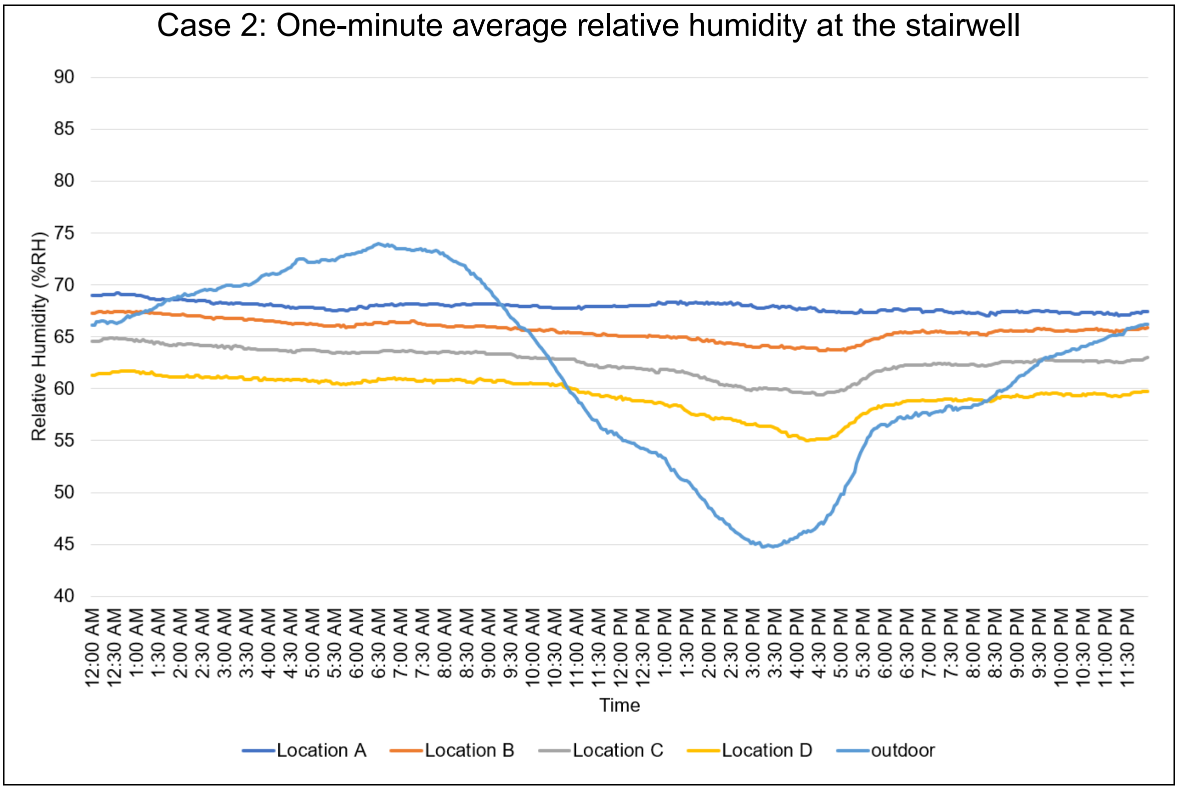


Figure 4- 5 One-minute average relative humidity at the stairwell (case 2)

4.2.2.3 Air movement

The air velocity of all sensors was almost 0 $m.s^{-1}$. Empirically, without outlet opening, there was no effective air velocity through the sensors.

4.2.3 Case 3: both W2 and W4 were opened.

4.2.3.1 Air Temperature

During the nighttime, the outdoor temperature fell to a low point at 6.30 am with 19.29°C. The temperature recovered and reached a peak at 3.33 pm with 29.90 °C, and then the trend was downward again. At location B, C and D, the indoor temperature also declined during nighttime and reached a peak during the daytime, then started to fall again. Such locations' temperature showed a significant relationship with the outdoor temperature. Additionally, the temperature at location B, C and D had a parallel trend to each other, which the higher location had a higher temperature. However, location A's temperature had less fluctuation comparing to other locations' temperature. The temperature trend of this location was clinging toward the outdoor temperature only after midnight (12.00 am – 7.30 am), while the trend showed a significant difference during daytime (from 8.30 am to 7.30 pm) (see Figure 4- 6).

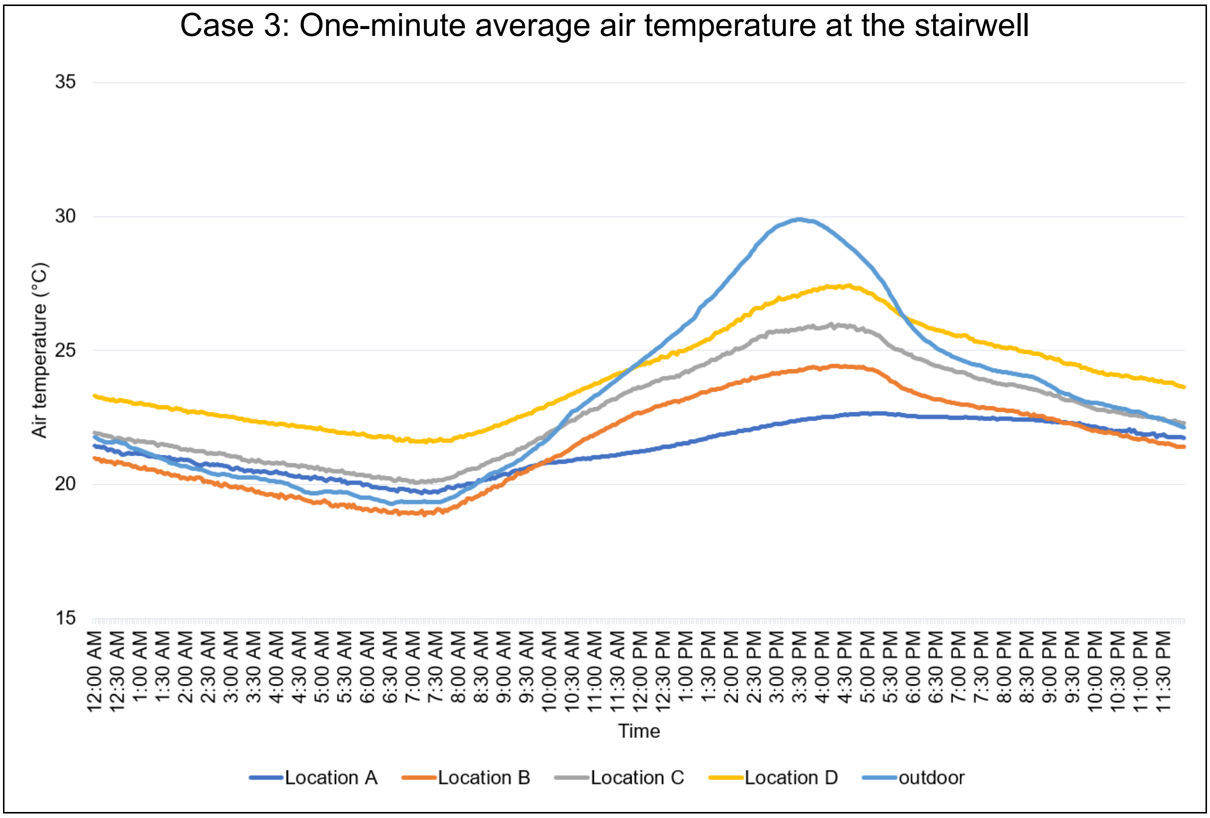


Figure 4- 6 One-minute average air temperature at the stairwell (case 3)

4.2.3.2 Relative humidity

The outdoor relative humidity had the highest fluctuation than the indoor relative humidity. The average outdoor relative humidity during nighttime was 66.72%RH, while the relative humidity during the daytime was 59.51%RH. The overall trend of the indoor relative humidity was considerably associated with the outdoor trend; however the indoor relative humidity had less oscillation than the outdoor. The higher sensor's location had a lower relative humidity, e.g., location D had less relative humidity than location B. Except for location A during 12.00 am and 7.54 am, the amount of relative humidity of this location had similar to location B at the same period. (see Figure 4- 7)

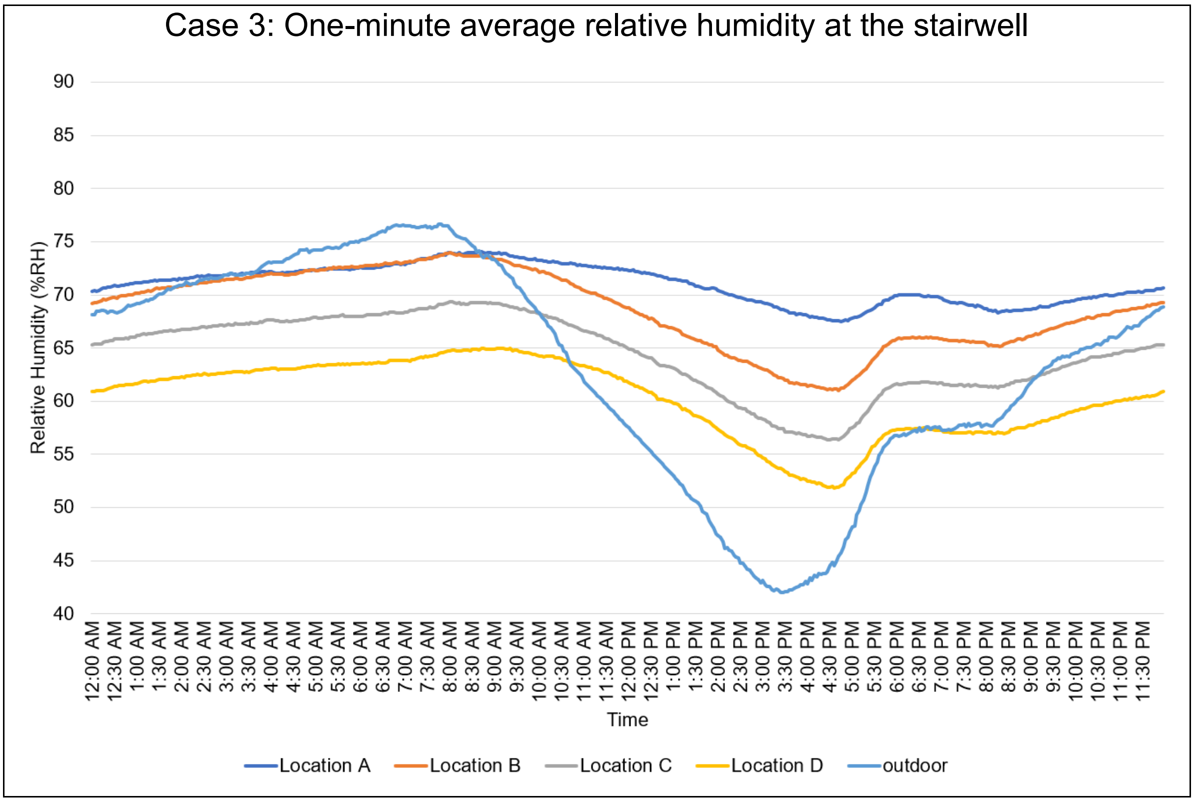


Figure 4- 7 One-minute average relative humidity at the stairwell (case 3)

4.2.3.3 Air movement

Both locations supposed to have the same amount of air speed due to the same size between the inlet and outlet. However, the air velocity at location B was greater than location D. From the site observation, the air roses within the building through the vertical flow passage. The air velocity might be scattered from the texture of the gap between the stairs' flights, the stair shape, and the handrails. The side effect from such obstacles would lead such two sensors' locations to have different air speed.

At location B, the average air velocity can be measured at 0.10 m. s^{-1}. During the nighttime (00.00 am -6.00 am), the air velocity at this location was between 0.07m. s^{-1} and 0.12 m. s^{-1}. Subsequently, the air velocity kept decreasing until reaching its lowest at 0.05 m. s^{-1} at 10.00 am and increasing to its peak at 0.24 m. s^{-1}. Since 3.00 pm, the air velocity declined dramatically then levelled off for a period, then the air velocity after 8.30 pm started gradually rising.

At location D, the average air velocity was 0.02 m. s^{-1}. The air velocity between 12.00 am and 10.24 am had fluctuated vary from 0.01 m. s^{-1} to 0.02 m. $s^{-1}$and continuously increased from 11.12 am until reaching its peak at 0.05 m. s^{-1} around 2.45 pm. The air velocity during the rest of the day remained steady. (see Figure 4- 8).

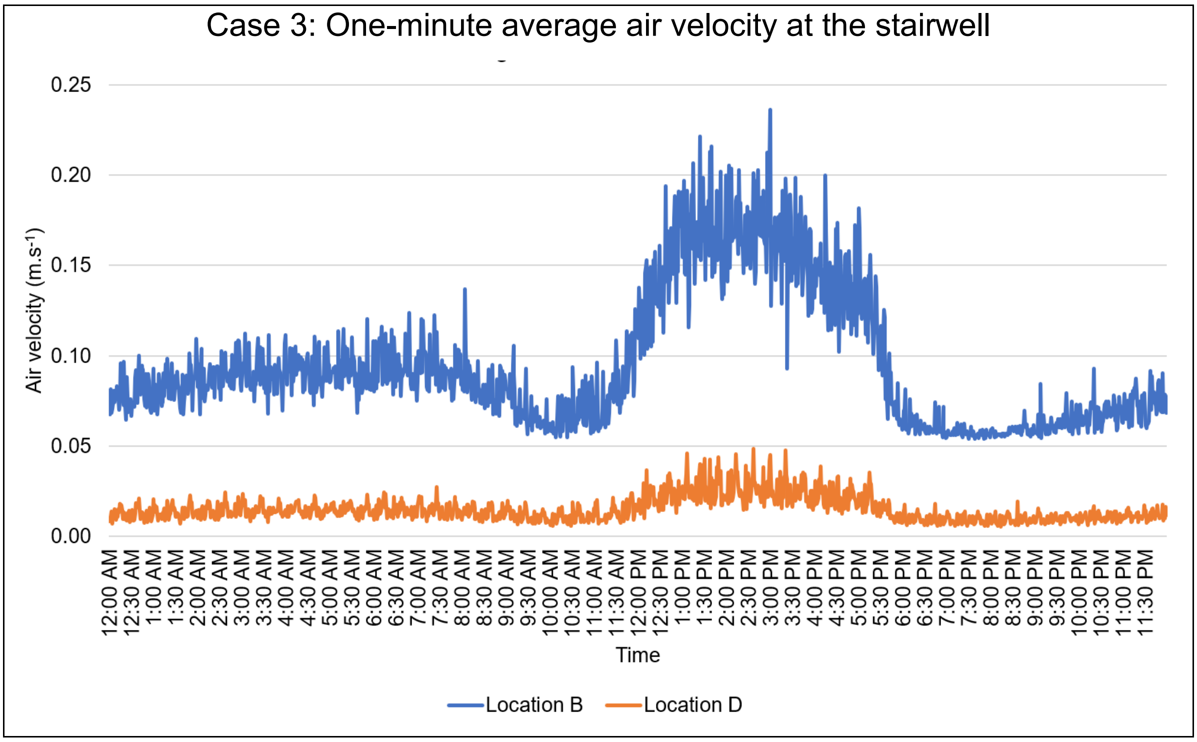


Figure 4- 8 One-minute average air velocity at the stairwell (case 3)

4.2.4 Summary

The outdoor air temperature relates inversely proportional to outdoor relative humidity.

In case 1 and 2, only one window was opened. The trend of indoor air temperature and relative humidity relatively stable paralleling to each other, except the air temperature of location A during the nighttime. The higher air temperature sensor's location appeared the higher amount of air temperature, while the higher location of relative humidity's sensor influenced on achieving lower relative humidity. Overall, the air velocity in these cases appeared 0 m. s^{-1}.

In case3, the trend of both indoor air temperature and relative humidity significantly related to the trend of outdoor air temperature and relative humidity greater than the other two cases. The higher temperature sensor' position likewise showed higher air temperature, whereas the higher relative humidity sensor's location indicated lower relative humidity. The air velocity trend on the lower floor indicated higher velocity.

4.3 Apartments' rooms

4.3.1 Weather during the physical measurement

The physical measurement was carried out from 16th January to 6th February, considered as winter in Thailand. Figure 4- 9 and Figure 4- 10 show the comparison between average meteorological weather data in each season obtained from the Thai Meteorological Department and on-site outdoor measurement. The hourly average meteorological air temperature in winter is the lowest compared to other seasons, between 18.51° and 30.17°C, where the winter relative humidity is between 41.49%RH and 85.95%RH (ThaiMeteorologicalDepartment 2021). The on-site outdoor weather slightly differs in temperature and relative humidity comparing to meteorological winter data, which the difference was around 0.7°C for temperature and 1.3 %RH for relative humidity.

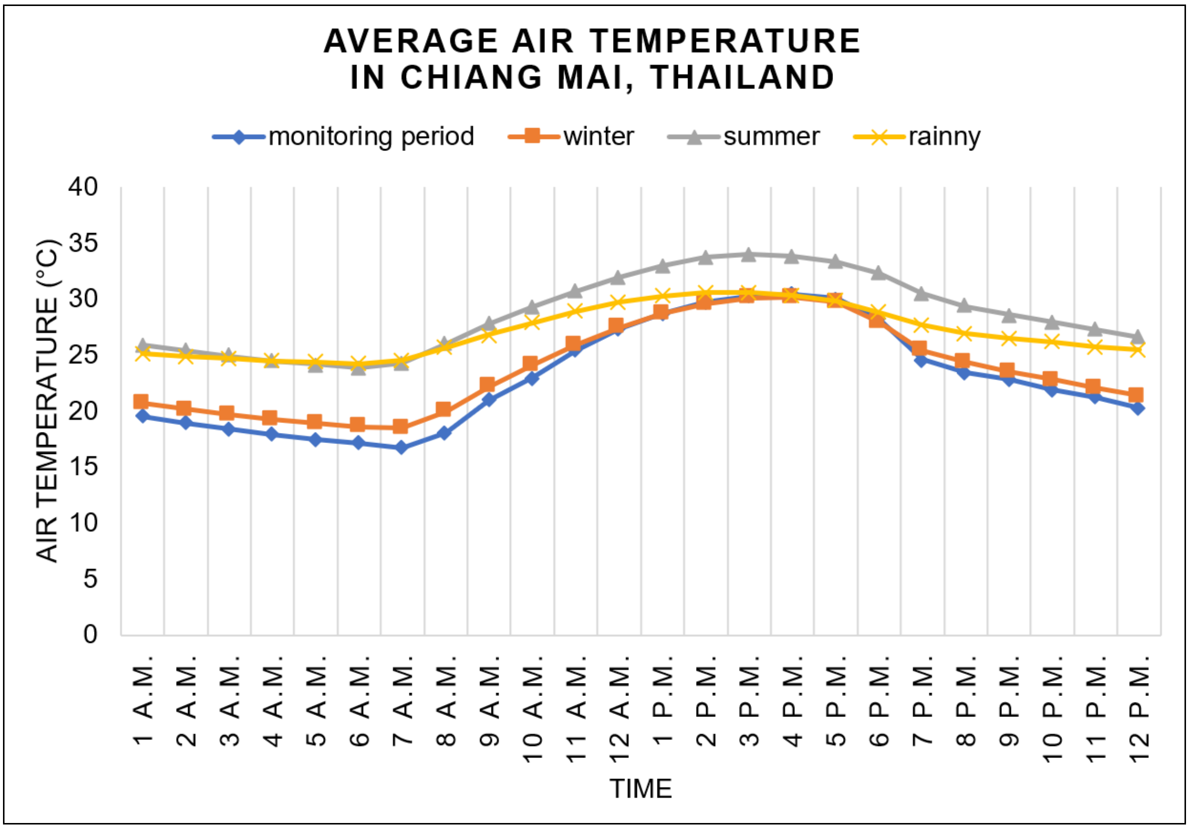


Figure 4- 9 Hourly average outdoor air temperature in each season and physical monitoring period, Chiang Mai, Thailand
(Source: The Meteorological Department 2021)

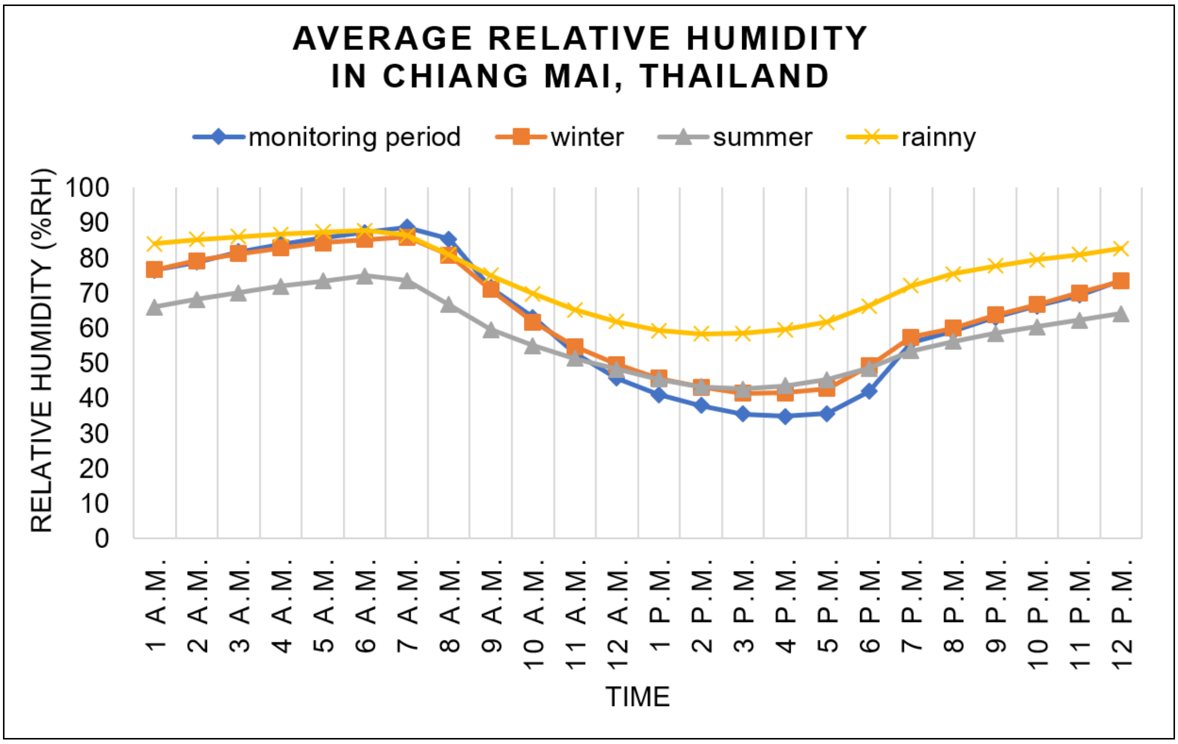


Figure 4- 10 Hourly average outdoor relative humidity in each season and physical monitoring period, Chiang Mai, Thailand
(Source: The Meteorological Department 2021)

The on-site outdoor air temperature varied between 17°C and 31.08 °C, while the relative humidity ranged from 29.10%RH to 87.79%RH. On day 13 and 14 of monitoring, there was raining in Chiang Mai which enhanced the outdoor relative humidity reaching the maximum humidity. The outdoor air temperature and relative humidity during the monitoring period was 55.90% in the thermal comfort zone (see Figure 4- 11), which was 27.48% of the diurnal and 28.42% of the nocturnal outdoor temperature and relative humidity in the comfort zone.

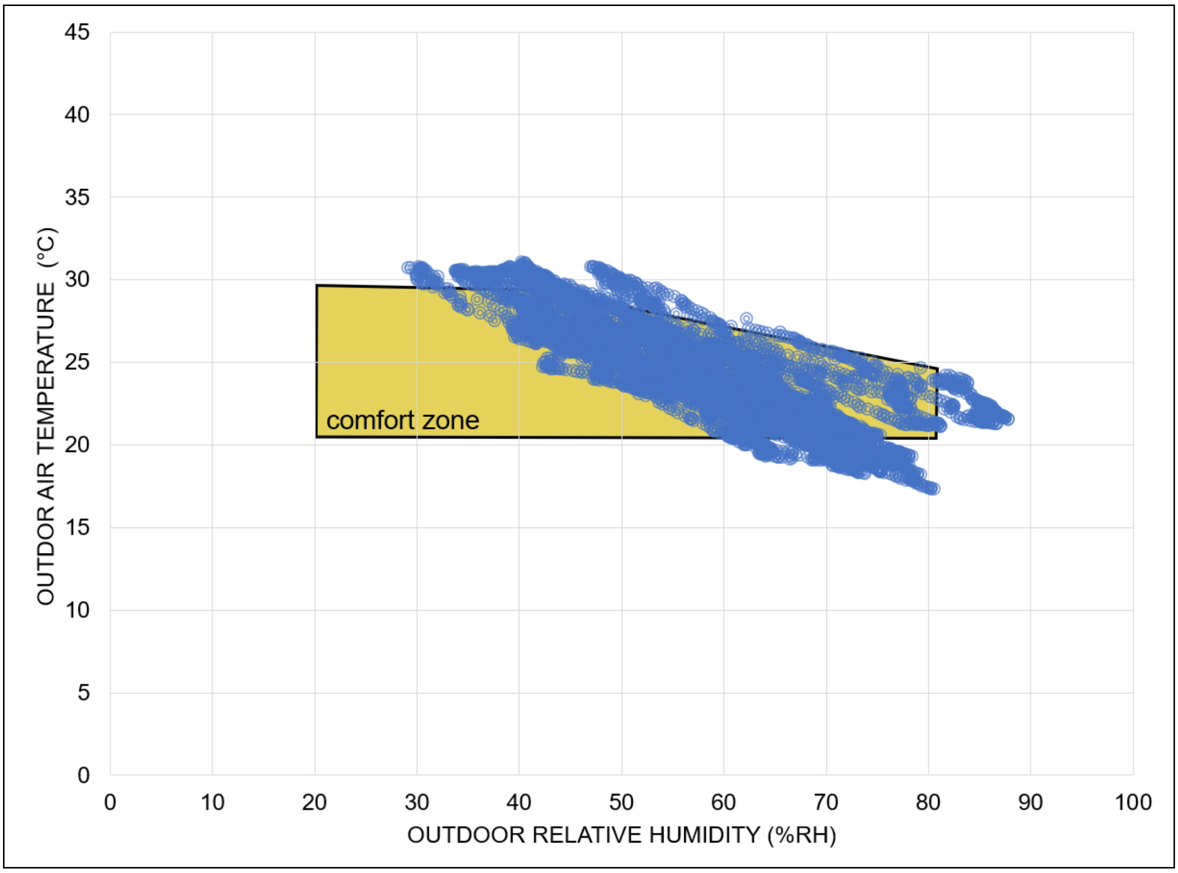


Figure 4- 11 Relationship between outdoor air temperature and outdoor relative humidity during the monitoring period
(Source: Author)

4.3.2 Building conditions

4.3.2.1 Building environment

Four rooms under study were located in two multi-storey buildings, each in proximity to another multi-storey building. The buildings are approximately 4 km from each other and are situated in the city municipality. Both multi-residential buildings are in Chiang Mai city centre, however, differ in the surrounding area.

Building A is mostly surrounded by hardscape elements, such as other buildings and concrete structures, which account for more than 90% of its surroundings. In contrast, Building B had a larger surrounding area of softscape features, including trees and gardens. These different environments likely to contribute variations in water vapor pressure within the rooms of each building, as the presence of softscape or hardscape can significantly influence local microclimates and indoor atmospheric conditions (Holmer and Eliasson 1999; Kuttler et al. 2007; Giridharan and Emmanuel 2018).

4.3.2.2 Materials

Both building A and B were built with column-beam structure with masonry wall (see Table 4- 1).

Table 4- 1 Materials in participants' rooms

		Room AC	Room AM	Room BC	Room BM
Building		A	A	B	B
Building height (floor)		5	5	8	8
Floor level		1st floor	1st floor	3rd floor	3rd floor
Room location		corner	middle	corner	middle
WC location		close to balcony	close to balcony	close to corridor	close to corridor
Window-to Wall Ratio (WWR)		16.86%	21.72%	21.26%	43.08%
Materials	wall	masonry	masonry	masonry	masonry
	floor	tile	tile	tile	tile
	glazing	single pane	single pane	single pane	single pane
	ceiling	gypsum board	gypsum board	gypsum board	gypsum board
	room door	wood	wood	wood	wood
	WC door	plastic	plastic	wood	wood

4.3.3 Result

4.3.3.1 Water Vapour Pressure

The temperature and relative humidity derived from monitoring equipment will be converse to be vapour pressure. This is because partial vapour pressure is a direct measurement of the amount of water vapour in the air (Cengel and Ghajar 2015). Evaluating water vapour pressure provides additional data into the behaviours of moisture in the air. Water vapour pressure measures the quantity of moisture in the air directly, whereas temperature and humidity only offer indirect measurements (Anderson 1936).

Relative humidity (ψ) = $e/e_s \times 100$ (equation 1)

Where ψ = relative humidity

e = the partial water vapour (Pa)

e_s = saturation vapour pressure (Pa)

The relationship between saturation vapour pressure and temperature is by Clausius-Clapeyron equation:

$$e_s \approx e_0 \times \exp\left(\frac{L}{R_v} \times \left(\frac{1}{T_0} - \frac{1}{T}\right)\right) \qquad \text{(equation 2)}$$

Where e_s = saturation vapour pressure (Pa)

R_v = 461 J·K^{-1}·kg^{-1}

T_0 = 273.15 K

T = actual temperature (°C) + 273.15

e_0 = 0.6113 kPa

L a latent-heat parameter. For liquid water, the latent heat of vaporisation is L= L_v = 2.5·10^6 J·kg^{-1}, Lv/Rv = 5,423 K

Mixing Ratio (mass of water vapour per mass of dry gas) is calculated by:

$$X = B \times \frac{e}{\rho - e} \qquad \text{(equation 3)}$$

Where x = mixing ratio (g.kg^{-1})

e = the partial water vapour (Pa)

ρ = total pressure (Pa)

B = Molecular weight of water/ Molecular weight of gas (B_{air} = 621.97 g.kg^{-1})

4.3.3.1.1 Results

Figure 4- 12 shows water vapour the whole period of monitoring. Water vapour of room AM, room AC and the outdoor ranged from 1.3 kPa to 2.5 kPa, while the water vapour in room BM and BC can reach 2.7kPa. The average water vapour in the buildings B's rooms was around 2.1 kPa, which was higher approximately 20 % of the average of buildings A's rooms. The lowest water vapour in each day of all rooms occurred during the nighttime, around 7.00 pm. The highest water vapour of all rooms exhibits between day 13 and day 14, which is due to the rain took place in both sites. In each day, the vapour pressure mostly dropped to the lowest during the afternoon (between 2.00PM-3.00PM).

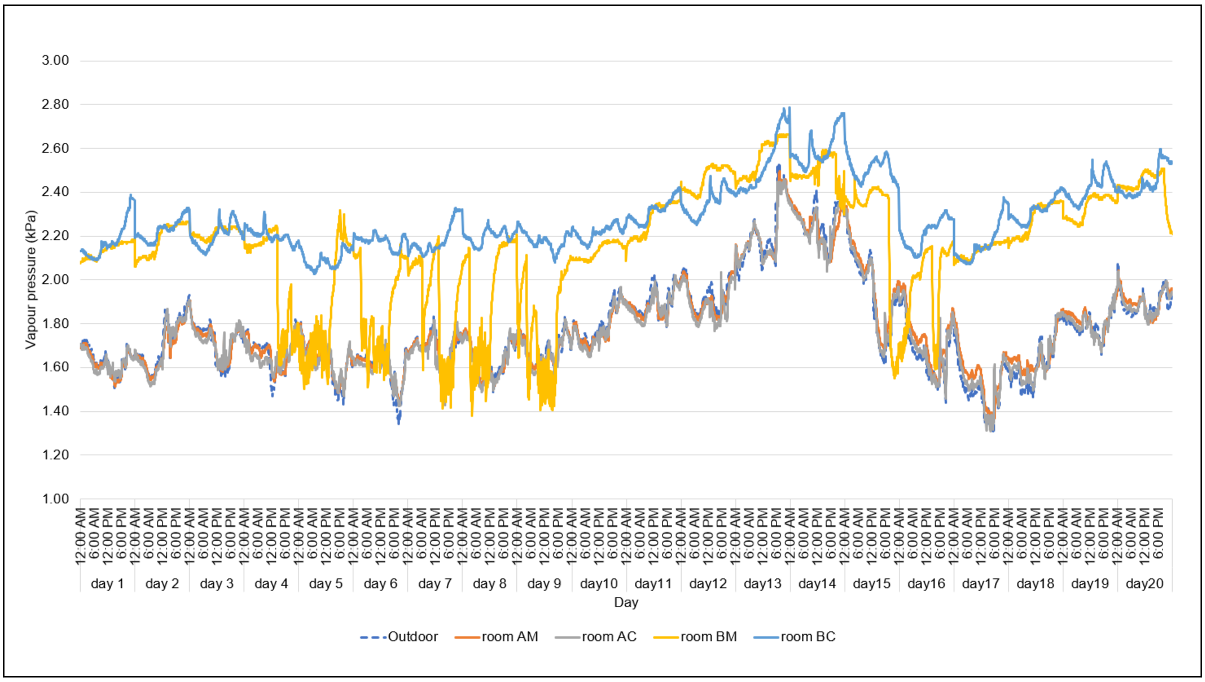


Figure 4- 12 Vapour pressure of outdoor and indoor participants' rooms
(Source: Author)

In detail, Day 17 can show vapour pressure difference in relation to room opening, which be categorised into 4 periods (see Figure 4- 13). **Period A** is a period of sleeping time. All rooms opened the maximum number of their room opening; however, room BC and BM closed the curtains during this period. Room AC had the lowest vapour pressure comparing to the other rooms. The vapour pressure in Room AC and AM remained steady. **Period B** is a period of a morning routine. After taking a shower, Room AC and AM spent 10 and 20 mins respectively to reduce the water vapour produced, while room BC and BM need more than 35 mins to reduce it. **Period C** is an unoccupied period. Occupants in Building A' rooms went out while left all openings open, whereas the participants building B leave the rooms and closed their openings. The vapour pressure in room AC and AM remained stable. **Period D** is a period of the evening. Room BC hung clothes for drying in the rooms resulting in vapour pressure grew strikingly, while room BM was still unoccupied with all openings closed. Both Room AM and AC continuously open their opening. The vapour pressure in Room AC changed relative to the outdoor vapour pressure more than room AM.

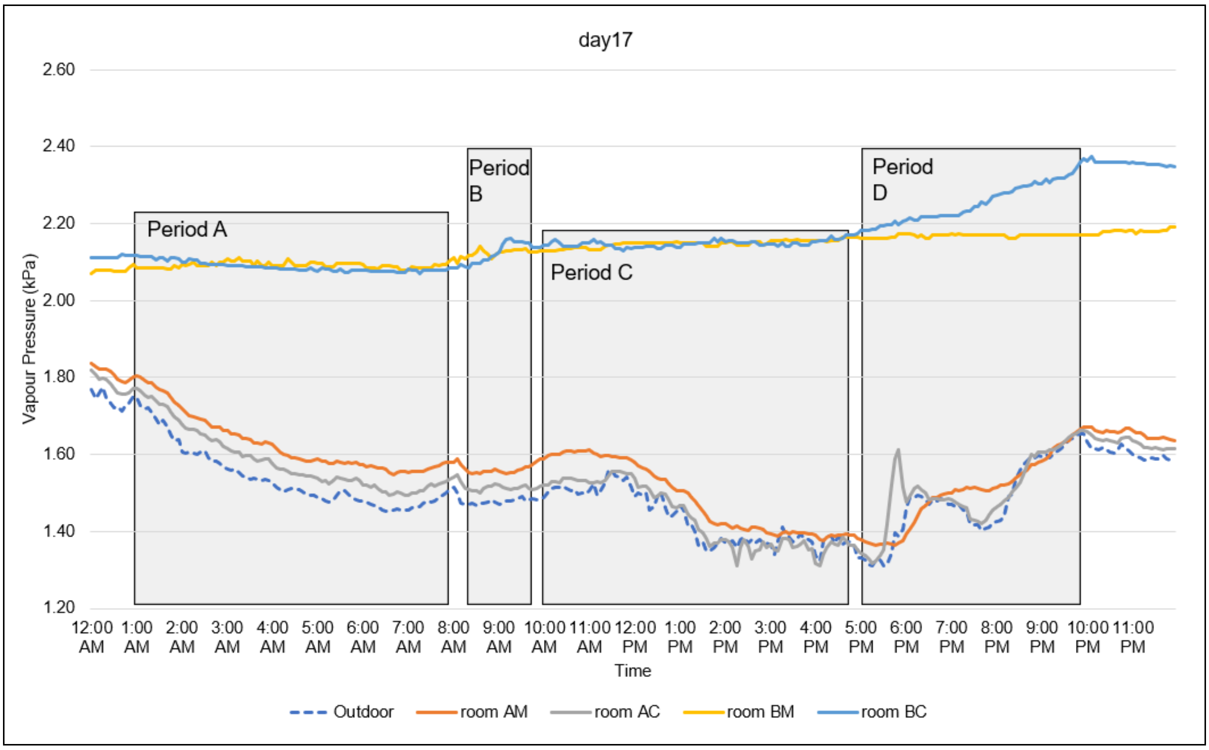


Figure 4- 13 Vapour pressure of outdoor and indoor participants' rooms on Day 17
(Source: Author)

In the detail of Day 13, there was raining between 6.30 PM and 7.30 PM. The data can be divided into 2 periods: Period A – before raining and Period B-during raining (see Figure 4- 14). In **Period A**, the vapour pressure in all rooms rose around 0.45 kPa comparing to the same period in no raining day. In **Period B**, room AC, AM and BC opened their openings during the whole period of rain, while room BM closed the opening. During 30 mins before raining, the mixing ratio of room AC and AM increased around 1 $g.kg^{-1}$, while room BC spent one hour increasing the same amount of mixing ratio. Room BM closing the opening during that time, the mixing ratio rose just 0.25 $g.kg^{-1}$.

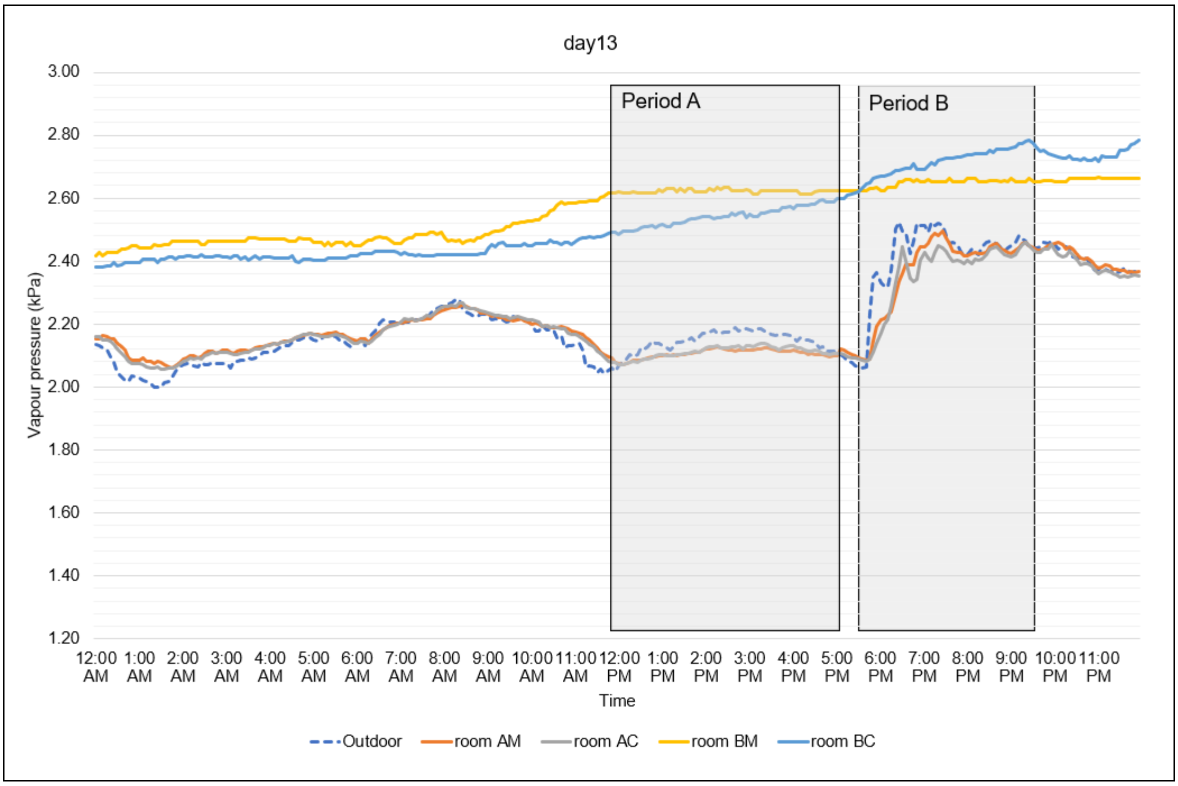


Figure 4- 14 Vapour pressure of outdoor and indoor participants' rooms on Day 13
(Source: Author)

The data in Day 15 can be categorised into three periods (see Figure 4- 15). **Period A** shows that all participants occupied their spaces at the same time. The vapour pressure between outdoor and Room AC was similar for the whole period, while the vapour pressure in Room AM was a bit higher than Room AC. Room BC and BM opened sliding doors at the balcony, but their windows near the balconies were shut. In addition, room BC closed curtains at both window and sliding door, while room BM kept the curtain open. Room BC had the highest vapour pressure even there are two adjacent openings. In this period, room BC and BM's mixing ratio was higher, approximately 4 $g.kg^{-1}$, than Room AC and AM. In **Period B**, the measurement equipment in Room AC was reached by the sun causing the graph to have a peak shape. Room BM went out and shut all openings resulting from the vapour in the room remained stable. **In Period C,** Room BM turned on the air conditioner at 7.25 PM, bringing the vapour pressure dropped sharply. Room AC also turned on the fan; then the vapour pressure gradually reduced.

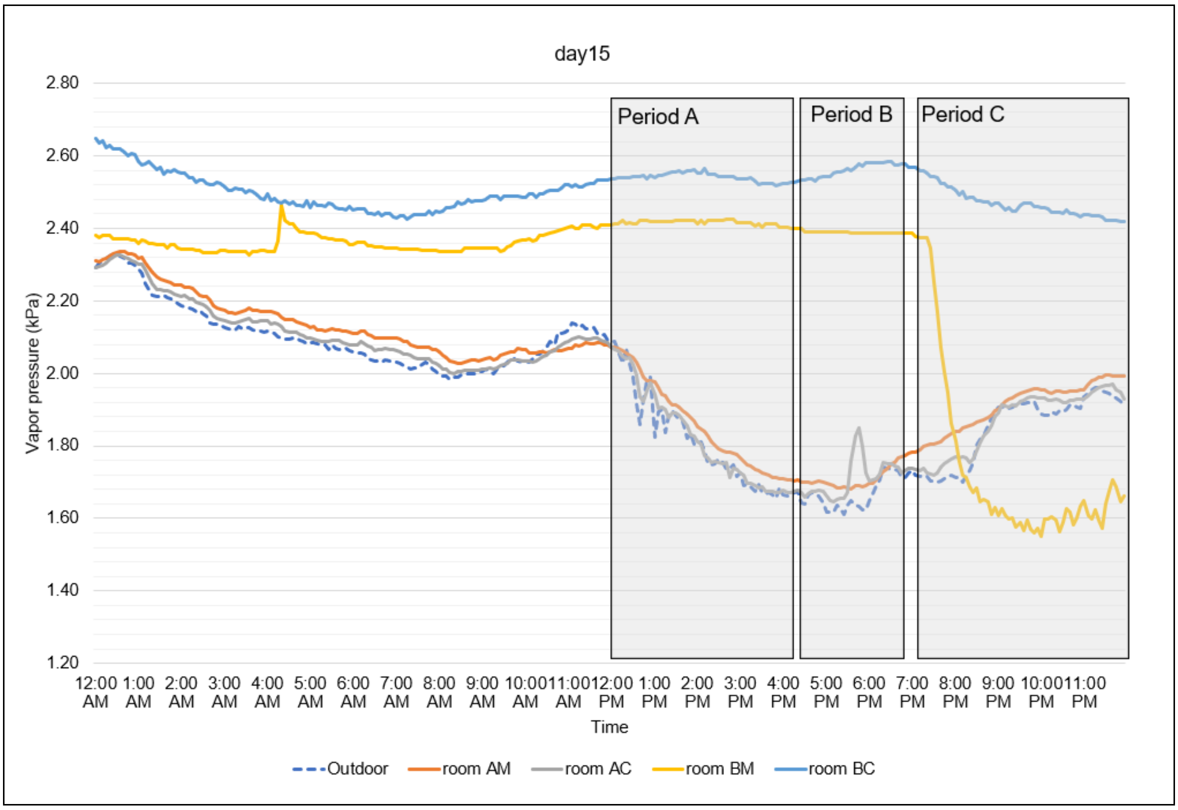


Figure 4- 15 Vapour pressure of outdoor and indoor participants' rooms on Day 15
(Source: Author)

4.3.3.2 Thermal comfort

Bioclimatic chart was used to determine the comfort zoom. The upper and lower limit of temperature in comfort zone were 22.3°C and 29.3°C (De Dear and Brager 2002) (see Section 2.2), while relative humidity comfort for free running building was from 20%RH to 80%RH. When the relative humidity is greater than 60% with a porous material, bioaerosols growth will occur(ASHRAE 2009). However, relative humidity levels less than 25% will associated with increased respiratory issues (Peden and Reed 2010). Referring to Section 2.2, relative humidity between 40%Rh and 60%Rh were recommended to minimise bioaerosols' growth in household (Sterling et al. 1985).

Room AC's temperature and relative humidity are within comfort conditions 78.21% of the monitored period. However, if the relative humidity range is restricted to 30-60% to minimise bioaerosol growth, the percentage dropped by 46.39% (Figure 4- 16).

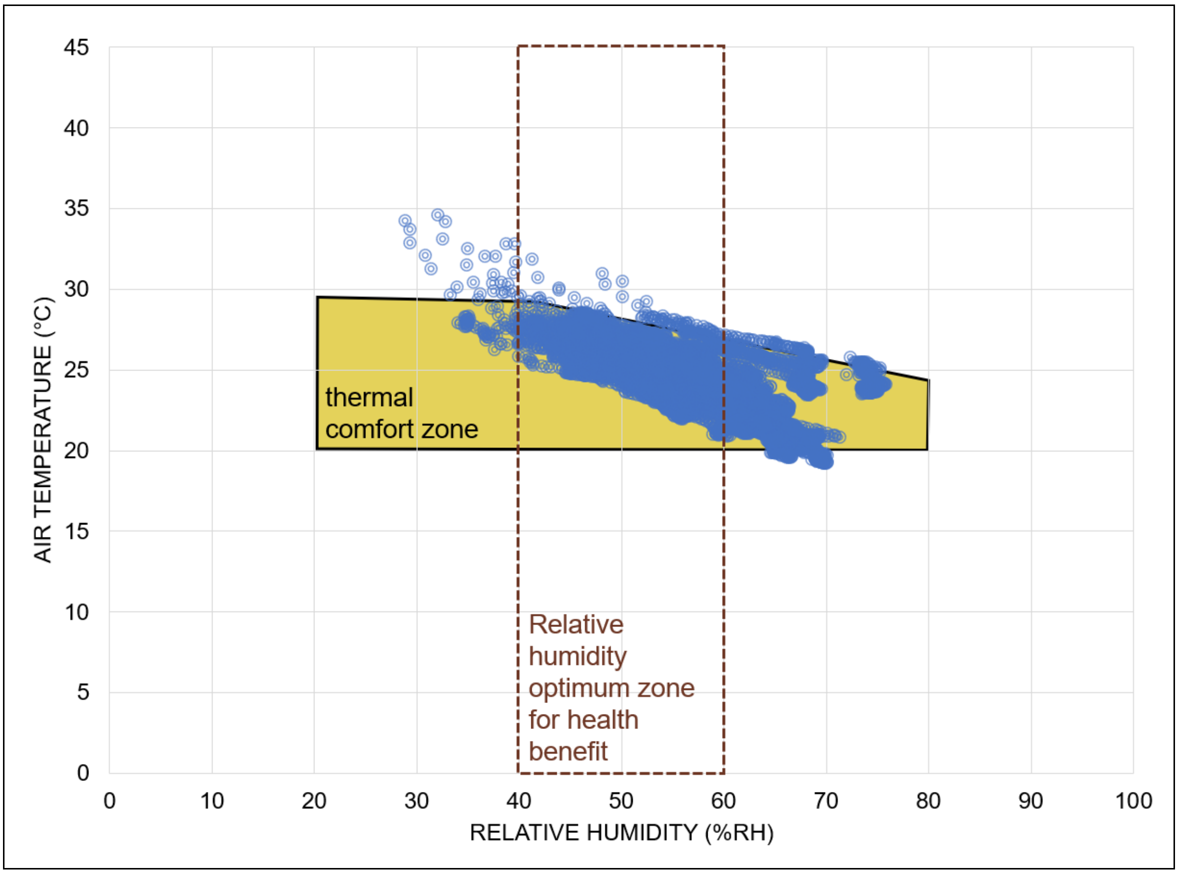


Figure 4- 16 Relationship between Thermal Comfort zone and relative humidity optimum zone for health benefit in room AC
(Source: Author)

The Room AM's temperature and relative humidity was 75.10% in thermal comfort conditions; however the percentage reduced to 37.85% when the relative humidity meet the recommendation relative humidity for reducing bioaerosol criteria (see Figure 4- 17).

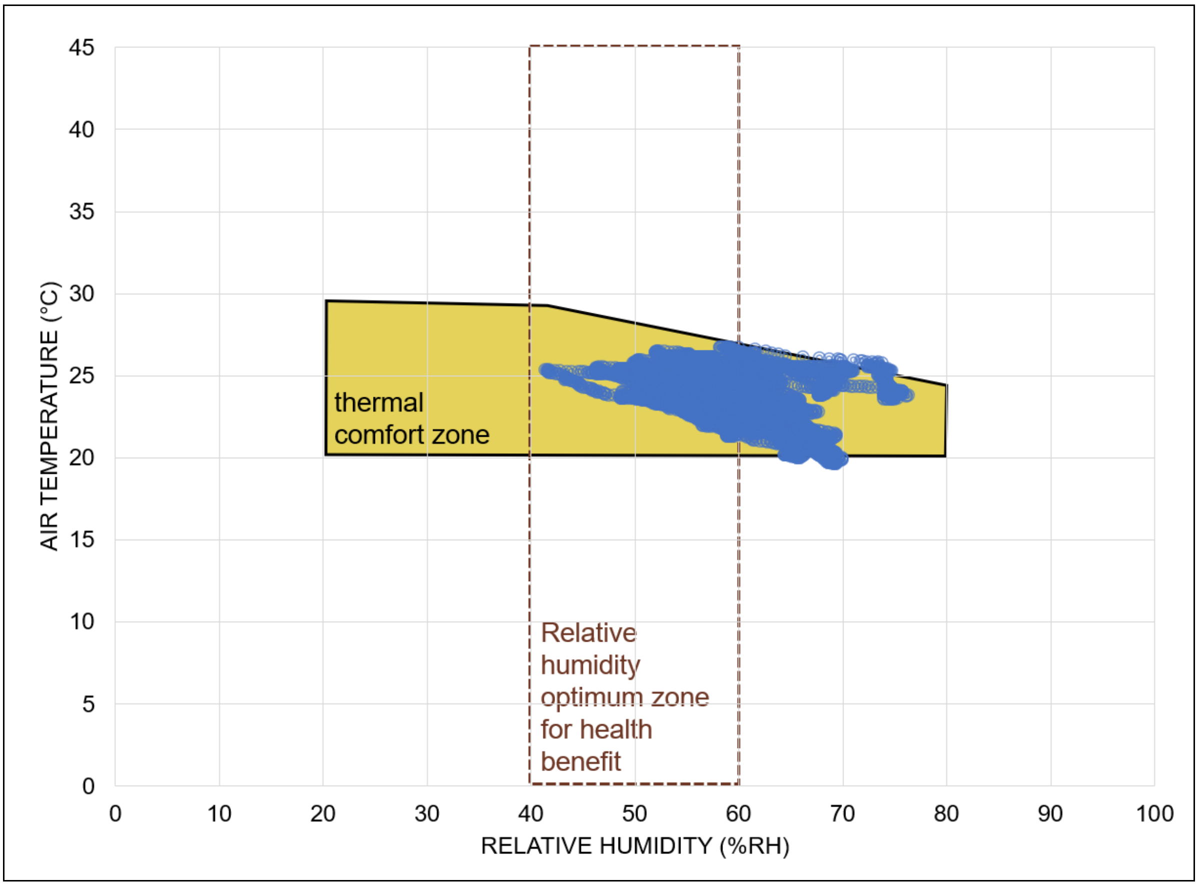


Figure 4- 17 Relationship between Thermal Comfort zone and relative humidity optimum zone for health benefit in room AM
(Source: Author)

In room BC, Only 30.23% of the temperature and relative humidity during the physical measurement were in the thermal comfort zone. Unfortunately, no period of time could reach the thermal comfort zone and the optimum relative humidity recommendation (see Figure 4- 18).

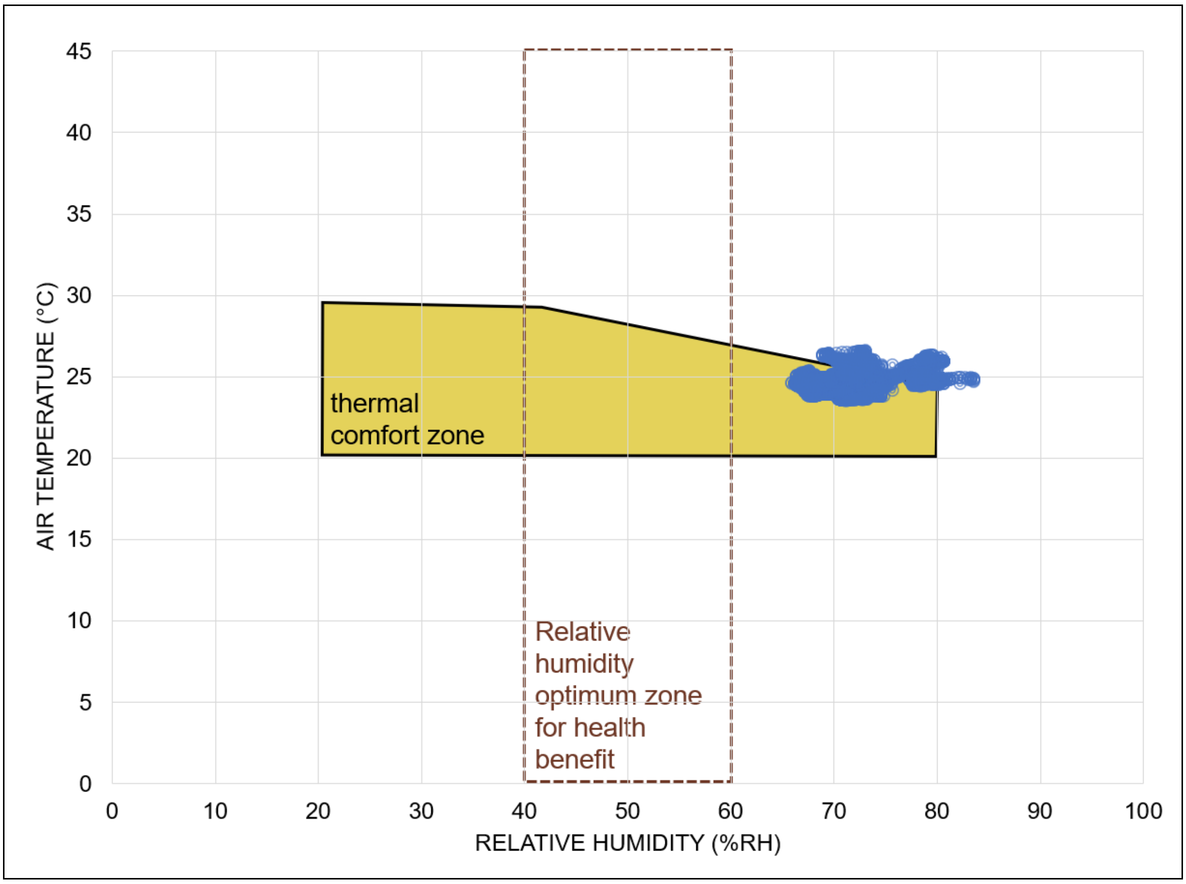


Figure 4- 18 Relationship between Thermal Comfort zone and relative humidity optimum zone for health benefit in room BC
(Source: Author)

Room BM with no air conditioner could be in thermal comfort zone 68.02%, while during air conditioning operation, the room was 85.85% in the thermal comfort zone. However, the room had only 0.16% in the range of thermal comfort zone and the relative humidity recommendation (see Figure 4- 19).

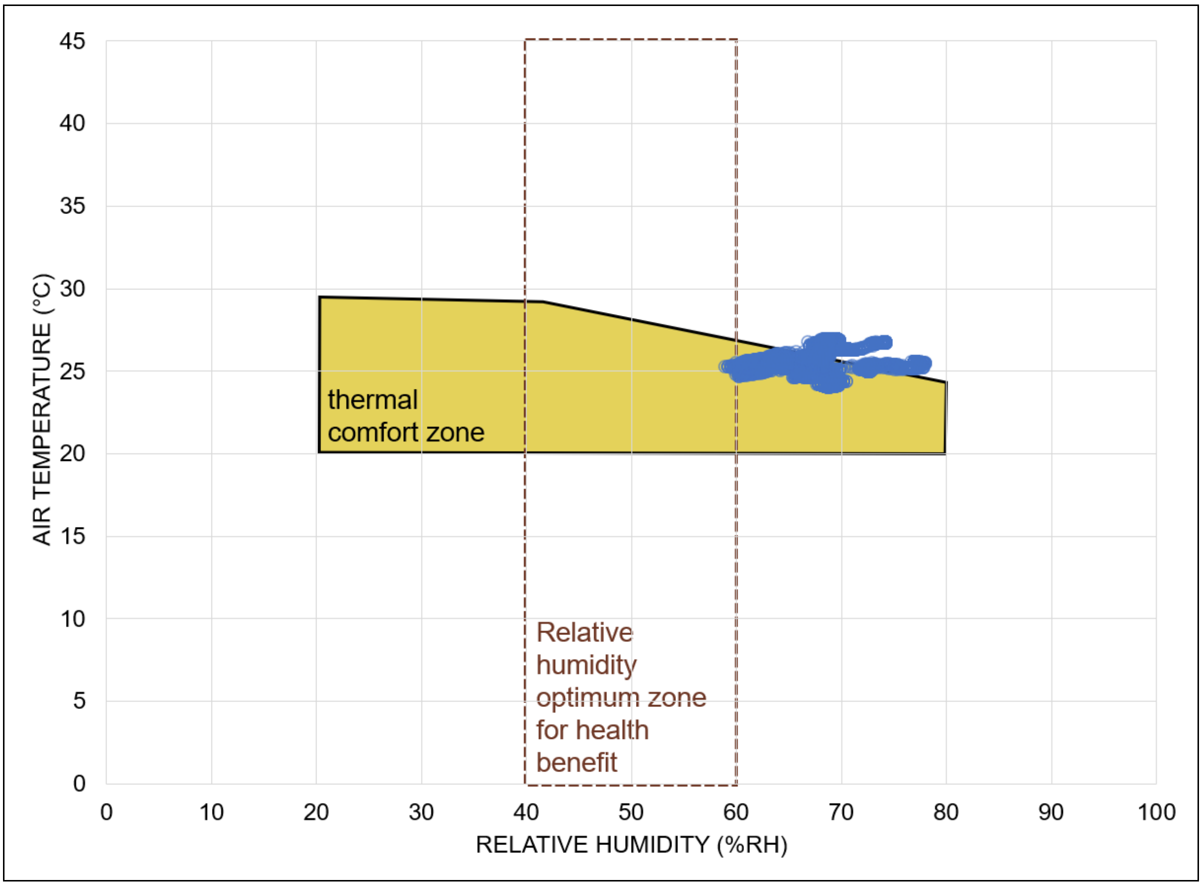


Figure 4- 19 Relationship between Thermal Comfort zone and relative humidity optimum zone for health benefit in room BM
(Source: Author)

Whereas some parts of monitoring values can reach the thermal comfort, the mould and mites' emergence in a building is associated with the relative humidity level. The average relative humidity of all rooms in each day were greater than 50% which can increase indoor dust mite levels. In addition, low ventilation rates may thus increase the prevalence of allergic (Heseltine and Rosen 2009).

4.3.3.3 Air movement

The details of monitoring are addressed in Section 3.3.3.

Air velocity was monitored in building A at room AC and AM. The comparison of air velocity in such two rooms can consider to be three cases (see Figure 4- 20 and Table 4- 2)

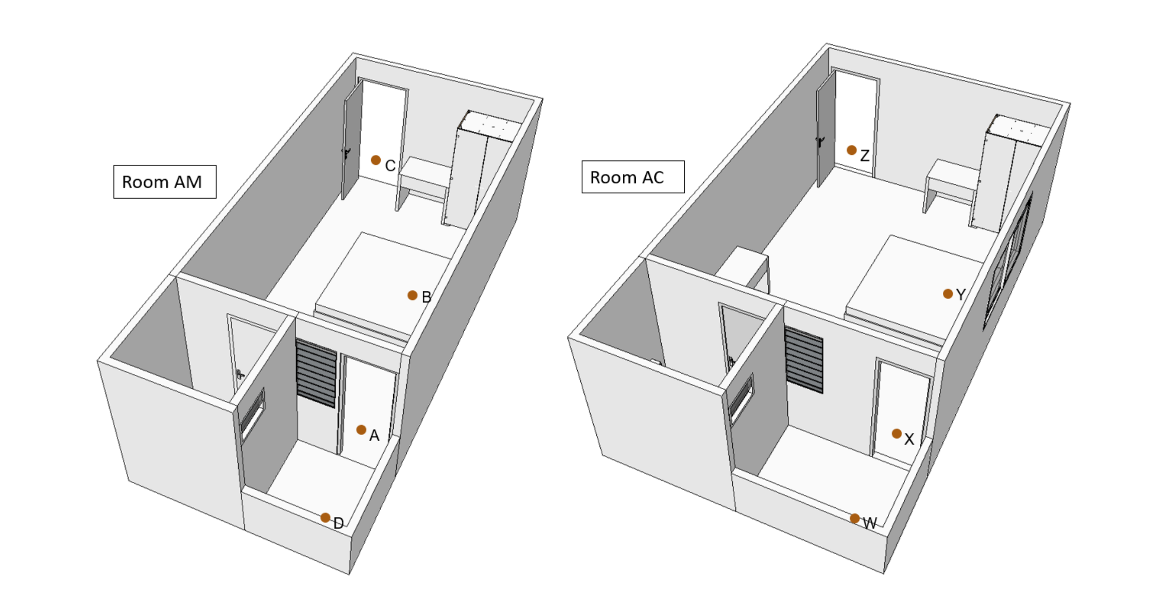


Figure 4- 20 Location of air velocity monitoring in Room AM and AC
(Source: Author)

Table 4- 2 Location of air velocity monitoring and conditions

	condition		monitoring location							
			room AC				room AM			
	room AC	room AM	W	X	Y	Z	A	B	C	D
Case 1	room door (Z) shut window (Y) open	room door (C) shut	●	●	●		●	●		●
Case 2	open all openings	open all openings	●	●	●	●	●	●	●	●
Case 3	room door (Z) and window (Y) shut	room door (C) shut	●	●	●		●	●		●

In case 1, Room AC has more ventilation than Room AM because Room AC has two adjacent opening while room AM has only one opening. According to Dekay,2014 (DeKay and Brown 2013), a single opening will get 12-23% of the exterior velocity, while two openings on adjacent walls will acquire 37-51% of the exterior wind velocity. The difference between room AC and AM is that room AC opened the window at the side wall, while room AM does not have that window. The average air velocity at Room AM's balcony door is approximately 10.76% of the air velocity at the building façade, whereas the average air velocity at Room AC's balcony door can reach 60% of the air velocity at balcony edge. Figure 4- 21 show that Room AC's balcony air velocity is higher in almost double room AM's balcony. The air velocity at the balcony door of room AC is higher, around ten times the air velocity at this location in room AM.

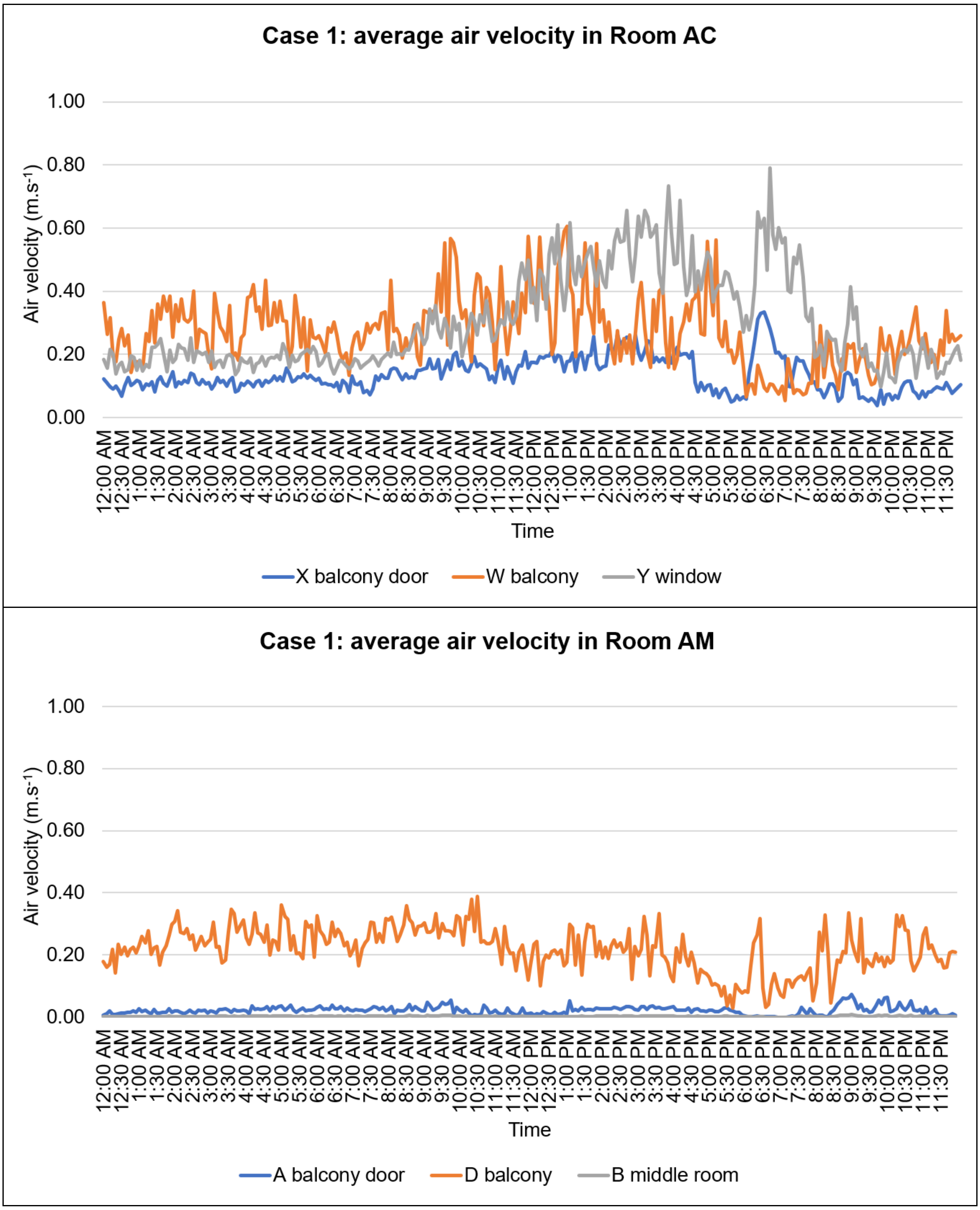


Figure 4- 21 Case1: average air velocity in room AC and AM
(Source: Author)

In case 2, both room AC and AM opened their room doors; however, only room AC opened the opening the extra window on the side wall. Figure 4- 22 shows the air velocity data available from 9 AM to 5 PM. The air velocity at the room AM's door is approximately 5.6 % lower than the air velocity at the balcony edge. The average air velocity at room AC's door is almost the same value as the balcony's door. (see Figure 4- 22)

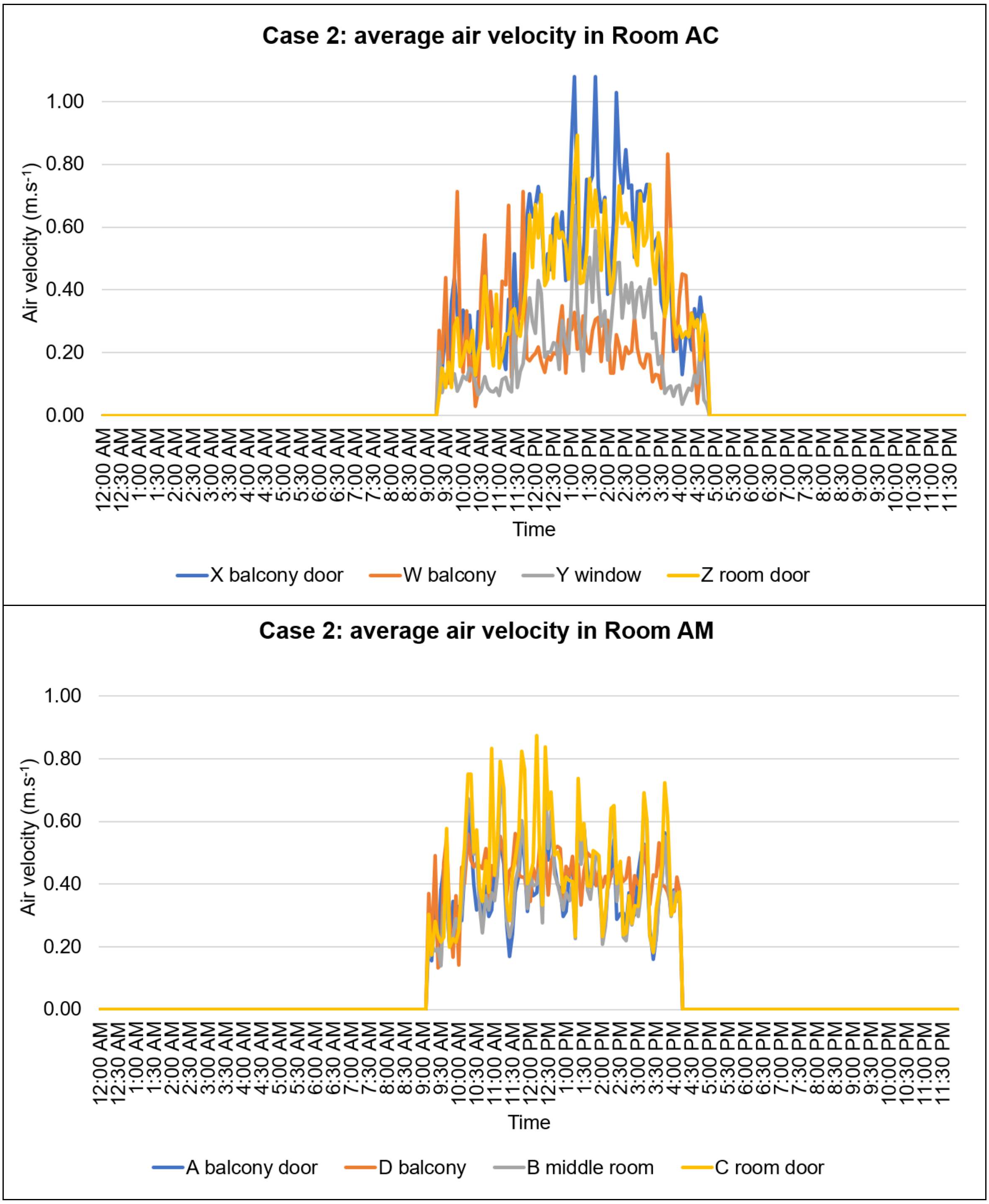


Figure 4- 22 Case2: average air velocity in room AC and AM
(Source: Author)

In case 3, The air velocity at the balcony of room AC is approximately 40% higher than that at the AM's balcony. The air velocity in the middle of both room AC and AM was nearly 0 $m.s^{-1}$; however, the average air velocity of room AC is higher, around 40% of the air velocity at this location in room AM (see Figure 4- 23).

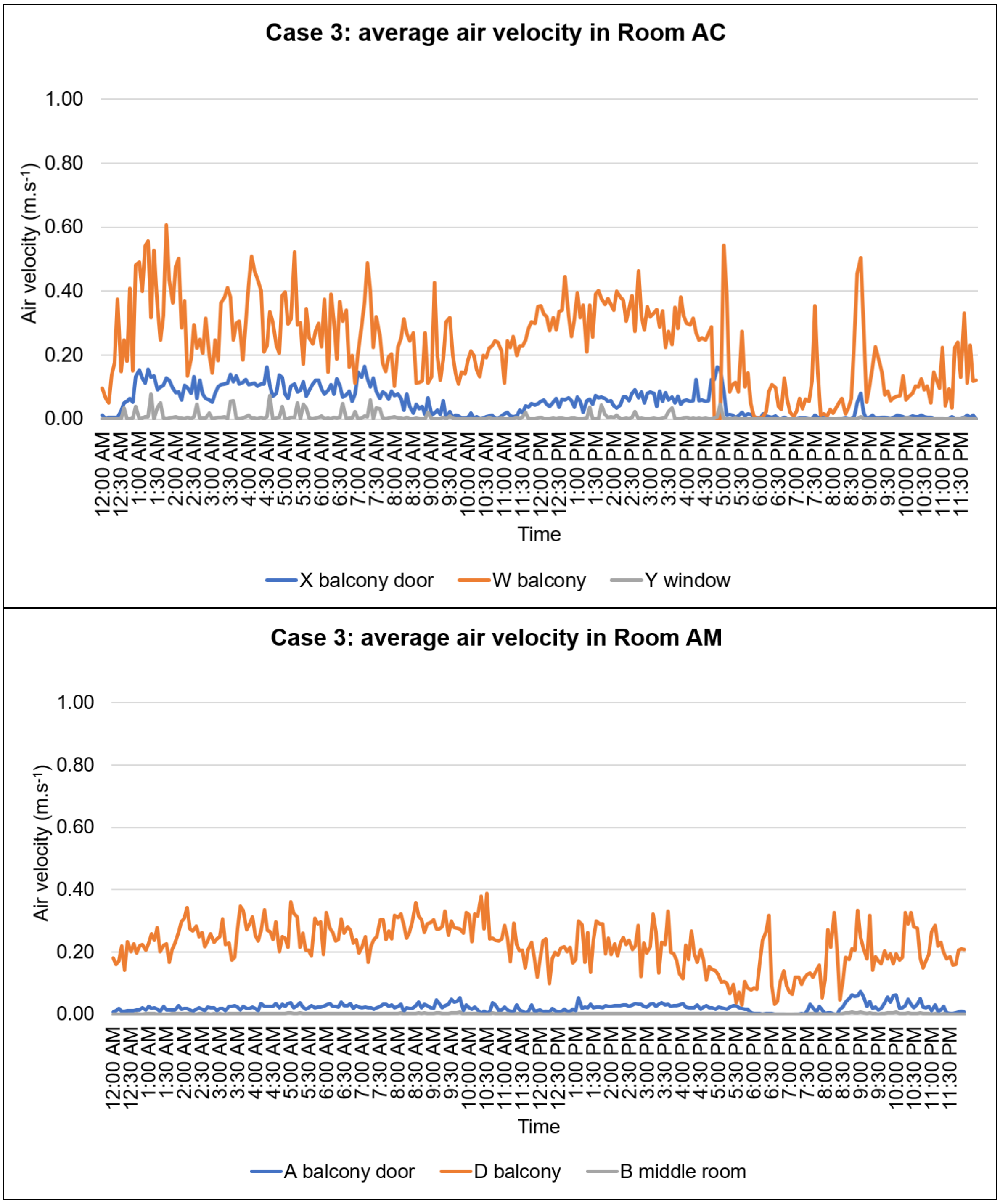


Figure 4- 23 Case3: average air velocity in room AC and AM
(Source: Author)

4.4 Summary Monitoring Physical Measurement

In the **stack area** of the building, the findings reveal that higher elevations are associated with higher indoor temperatures, whereas areas at lower elevations experience higher indoor relative humidity. This pattern is due to lower elevation being overshadowed by buildings in proximity. Additionally, it was observed that relative humidity tends to be inversely proportional to air temperature. The study also found that in the stack area with only single opening, both indoor temperature and relative humidity showed minimal fluctuation compared to the outdoor. Air velocity in this scenario is nearly 0 $m.s^{-1}$. However, in the scenario of two openings in the stack area, indoor temperature and relative humidity are more significantly correlated to outdoor temperature and relative humidity. Additionally, air velocity in this scenario ranged between 0.02-0.05 $m.s^{-1}$. The monitored stack area results demonstrate that stack ventilation can improve ventilation within a building.

The results from monitored physical measurements in four **apartments' rooms** within two multi-residential buildings revealed three primary factors influencing water vapour pressure and thermal comfort within the rooms, including building environment, room layout and occupant activity.

- **Building environment**: Building Environment: The study revealed that while water vapour pressure in a room is influenced by outdoor conditions, the building's location and surrounding environment are also important factors. Both multi-residential buildings were located Chiang Mai city centre, one surrounded by hardscape and the other with more softscape. This difference in outdoor environments had a major impact on water vapour pressure.
- **Room layout**: The layout of a room was another key factor affecting water vapour pressure. Room layout with WC located further inside exhibited higher vapour pressure due to challenges in ventilation and moisture release compared to other layouts.
- **Occupant activity**: Occupant activities had a significant impact on indoor water vapour pressure. For instance, opening a window caused more fluctuation in vapour pressure, while rooms with open windows but closed curtains had higher vapour levels. Humidity-generating activities like bathing, cooking, and drying clothes led to a significant rise in vapour pressure.

The results provide data regarding the actual occupants' rooms in relation to the occupants' activities. This data can reveal insight to cause -and -effect relationships within the building. The findings indicate that actual residential units examined inadequate air velocity for elevate temperature to achieve thermal comfort as it was lower than 0.2 m. s^{-1}.

5 Occupant perception survey result

5.1 Introduction

This chapter provides the results and analysis of the occupant perception survey to achieve Objectives 2 and 3 of the research. Objective 2 focuses on characterising typology and identifying key features of typical buildings in Thailand. Meanwhile, Objective 3 aims to establish a relationship between key features of the typical buildings and occupants' perceptions, particularly their indoor environmental quality (IEQ).

Chiang Mai is selected as a case study. The research used a questionnaire survey to investigate the typical characteristics of apartment blocks in Thailand and explore the satisfaction level of their residents with the indoor environment of their apartments. 482 completed surveys were obtained.

The methodology for the survey was detailed in Section 3.4. The obtained data were analysed via SPSS 27.0. The analysis used descriptive analysis to evaluate general information and inferential methods, including correlation coefficients and multiple regression understand the relationship between key features of typical buildings in Thailand and occupants' perceptions regarding their IEQ.

This chapter is divided into five main sections: Reliability of survey (Section 5.2), Demographic analysis of survey participants (Section 5.3), Physical environment (Section 5.4), Relationship between IEQ (Section 5.5) and Summary (Section 5.6)

5.2 Reliability of survey

Internal consistency is a form of reliability. Basically, it is a measure of how positive and strong covariate with each variable. Cronbach's alpha coefficient is one of internal consistency estimators, which was used to estimate the internal consistency of the occupants' indoor quality scale and comfort in this survey. The value of the alpha above 0.60 can be accepted as an indicator of good reliability (Gliem and Gliem 2003).

All the Cronbach's alpha results in Table 5- 1 were calculated using the reliability command in SPSS.

Table 5- 1 Reliability of occupants' indoor quality scale and comfort satisfaction questionnaires

Indoor environment quality and satisfaction		Cronbach' s Alpha	N of item
ventilation and humidity	stale/ fresh air ventilation dry/ wet air mould relative humidity satisfactory room ventilation satisfactory	0.914	6
natural lighting	natural lighting natural lighting for work natural lighting satisfactory	0.901	3
air temperature	air temperature in winter air temperature in summer air temperature satisfactory	0.683	3
comfort satisfaction	All satisfactory questions	0.793	9

In this study, the alpha coefficients were all higher than 0.60, which can be interpreted as good internal consistency and strong correlation in questionnaire items. The Cronbach's alpha of ventilation and humidity levels and satisfaction concerning such levels was 0.914 indicating excellent reliability.

5.3 Demographic Analysis of Survey Participants

The participants' demographic characteristics are shown in Figure 5- 1. 50.8% of the respondents were female, 44.6% were male, 3.9% preferred not to answer, and 0.6% were other. The occupation of participants inquired via open-ended question can be categorised into four groups: employed group relating to construction and building, non-construction entrepreneur and employee, students, and others. The majority of respondents (60.8%) were students, 36.5% were non-construction entrepreneur and employee, 2.5% were construction and building workers, and 0.2% were other. For ownership, most of the participants were tenants (95%), while 5% were owners. In terms of occupied periods, the participants commonly spent time in their rooms between 8 to 12 hours during weekday and 12 to 16 hours during the weekend.

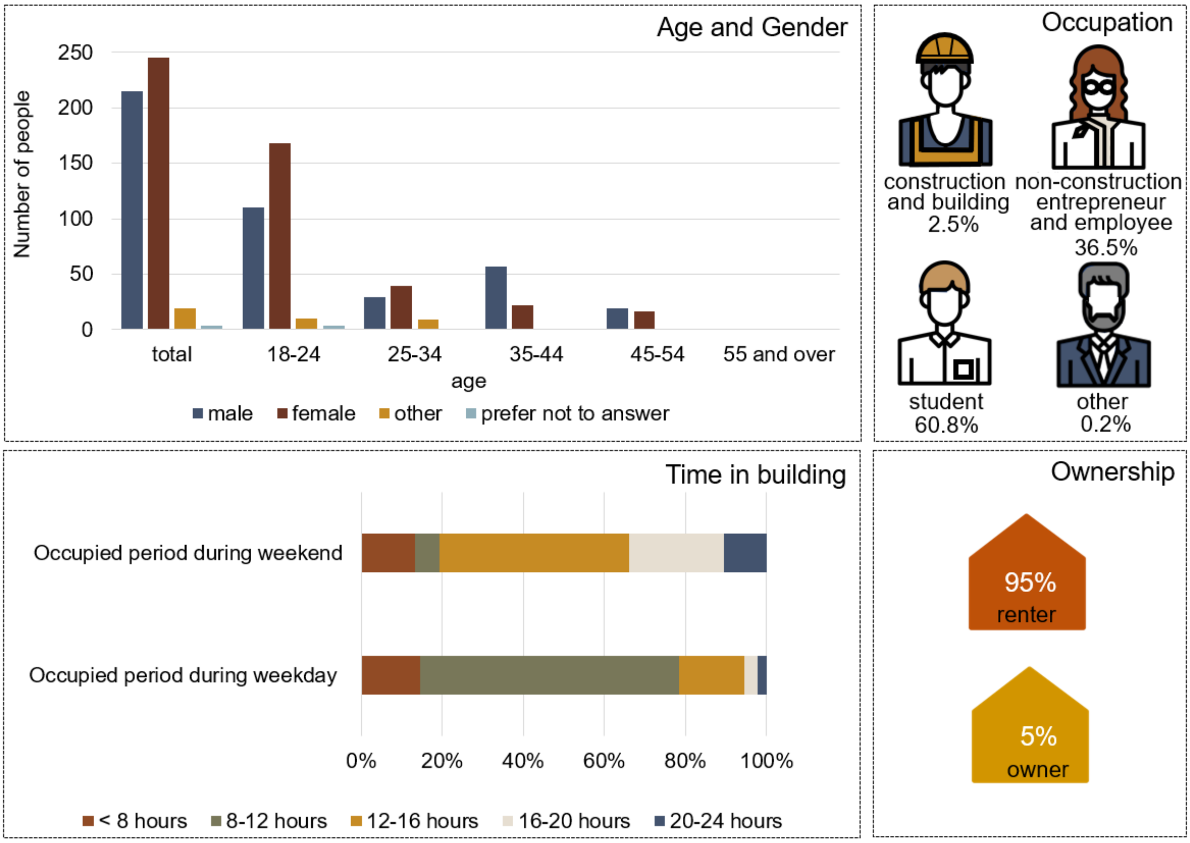


Figure 5- 1 Summary of the demographic characteristics of participants
(Source: Author)

5.4 Physical environment

Figure 5- 2 illustrates the participants' physical environment distribution, such as building height and floor of occupation, building plan and room location, the distance to the nearest building and room orientation. Most of the participants lived in a seven floor building, while approximately 19% of the participants each lived in a four to six floor. Across the building heights, occupants tended to live on the 1st, 2nd and 3rd floor. Approximately two third of participants lived in buildings located 0-6 metres away from the nearest nearby building. Almost half of the participants' room openings faced north. For building plan and room location, over 90% of the respondents lived in double-loaded corridor buildings and over 70% of their rooms' locations were in the middle of the building.

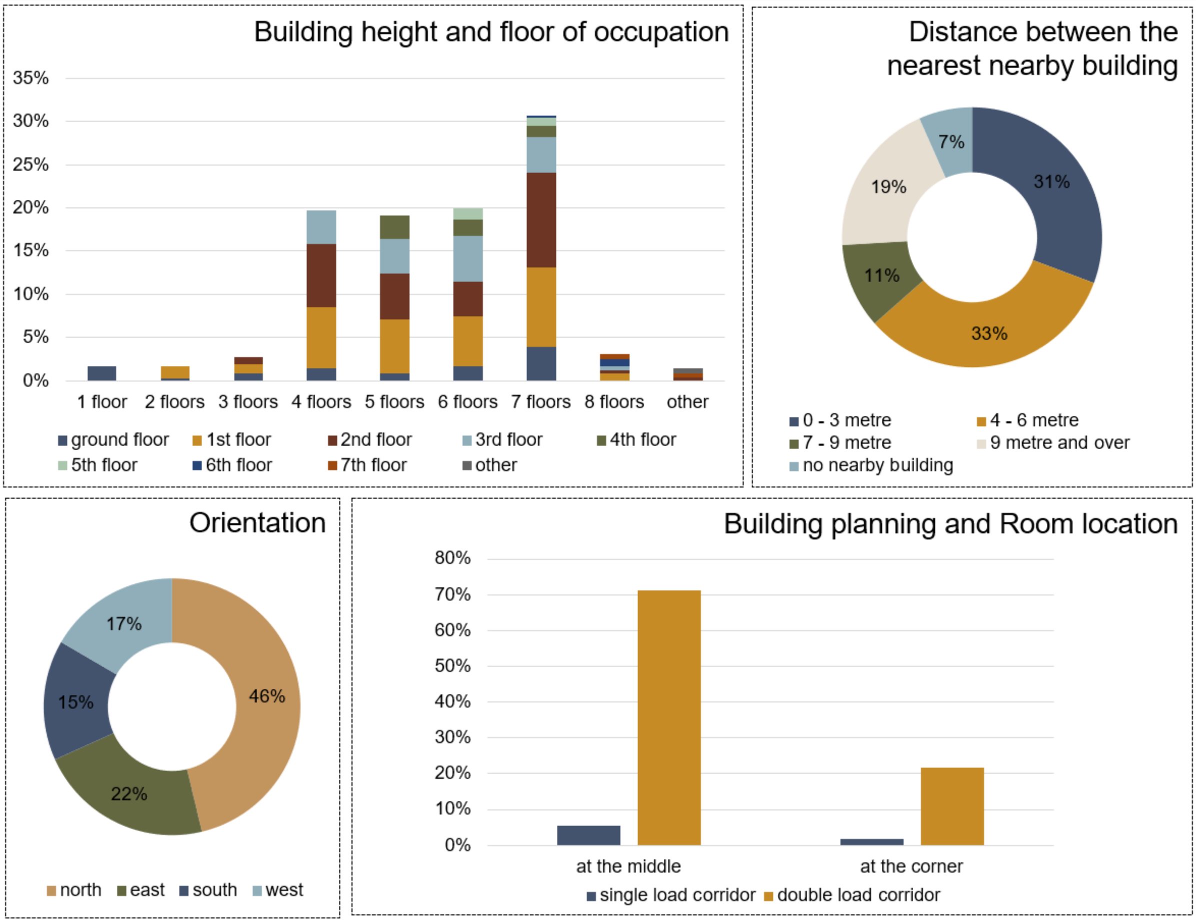


Figure 5- 2 physical environment
(Source: Author)

The majority of rooms comprised of one bedroom, one toilet and one balcony. Three typical room types were defined in relation to location of WC. The proportion of people living in these room types (along with room sizes) is shown in Figure 5- 3. Over half of the respondents lived in room sizes ranging from 21 to 30 sq.m. For room size range 8-20 sq.m and 21-30 sq.m, there is an even distribution of participants' room types in each size band. For example, the 21-30 sq.m. size range has 24.9% Type A, 37.2% Type B and 36.5% Type C.

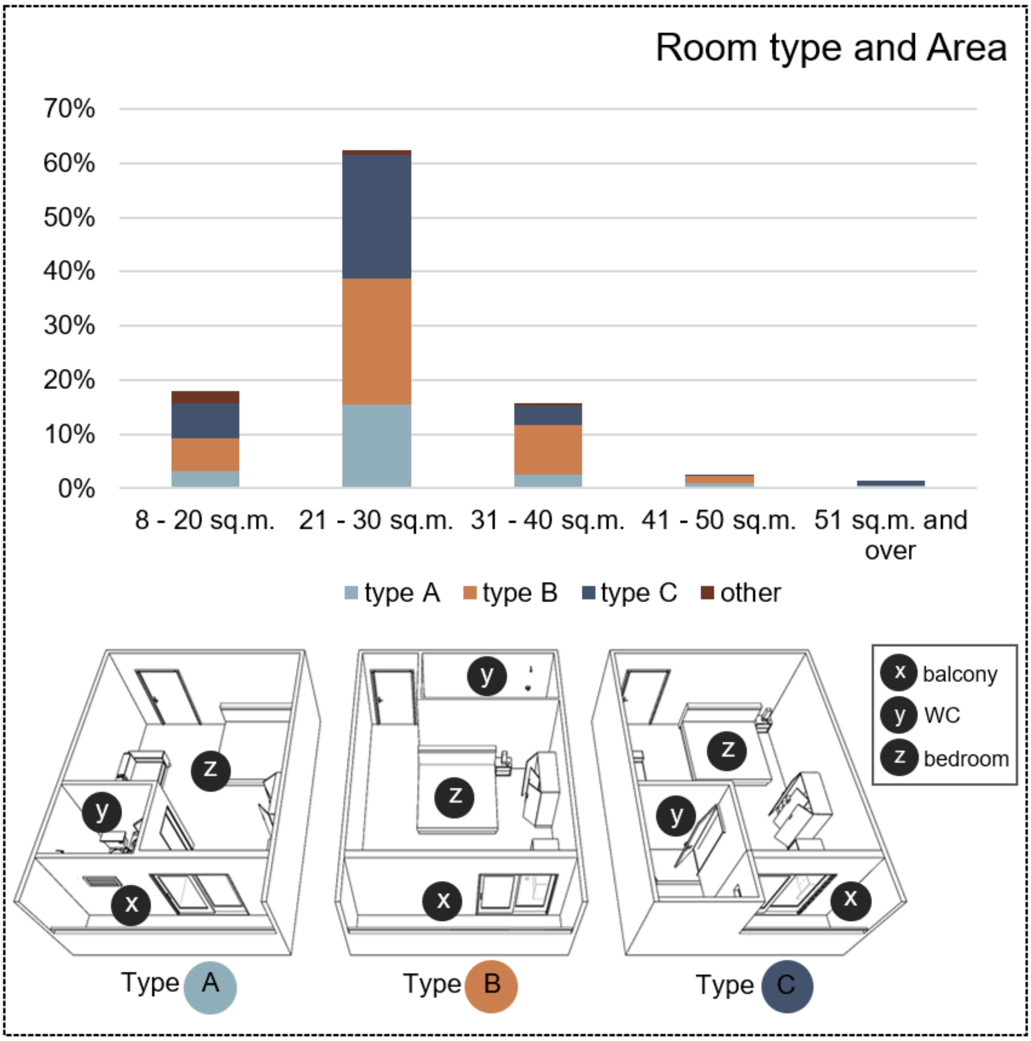


Figure 5- 3 Room type and area
(Source: Author)

The results identifying the typical physical environment features of buildings will used to define as a typical base case for CFD model in Chapter 7. This base case includes double-loaded corridor, middle room, and room layout.

Figure 5- 4 shows the distribution of responses on room materials. This figure shows that 94.1% and 69.2% of the participants had wood for room doors and furniture, respectively. Over half of the respondents' rooms had concrete as a material of wall and ceiling. 80.9% of the responders occupied rooms that had tile as a flooring material. Plastic was a toilet door material of around 56% of the respondents.

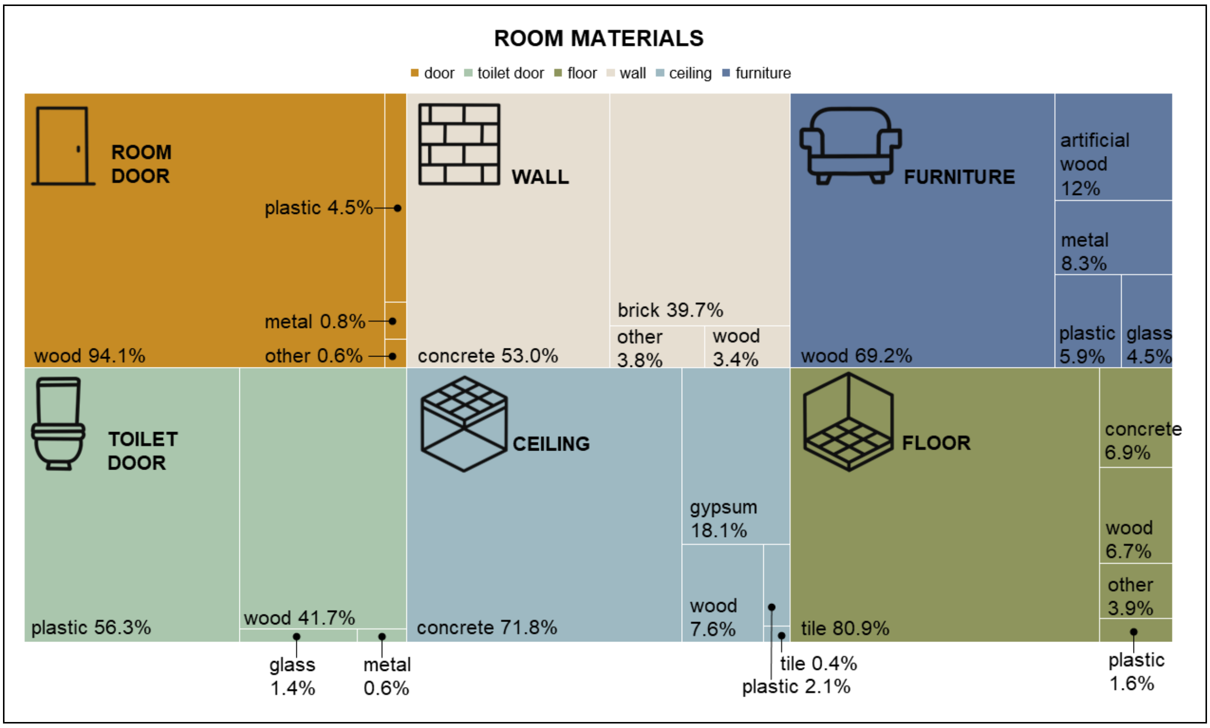


Figure 5- 4 Treemap of occupants' room materials
(Source: Author)

The most common materials were used as the base case input for the simulation model to predict the typicall scenario of a multi-storey building in Thailand (Chapter 7) and also for the design options (Chapter 8).

Moisture can be generated in residence from occupant not only via internal occupant's body but also by various household activities such as cooking, clothes hanging, clothes washing etc. Type, duration and frequency of household activities can produce different rates of moisture generation in room (Yik et al. 2004; Zemitis et al. 2016), for example, 1,500 grams per day for drying clothes indoor, 500 grams per day for washing clothes, 2,000-3,000 grams per day for cooking and 100-200s gram per sq.m for floor mopping (Institution 2011).

This section shows the responses relating to each of these household activities, which will be used to estimate the relationship coefficient with indoor environmental quality perception in the next step.

Figure 5- 5 shows the proportion of each human behaviour characteristics, such as cleaning, clothes washing, cooking and clothes drying.

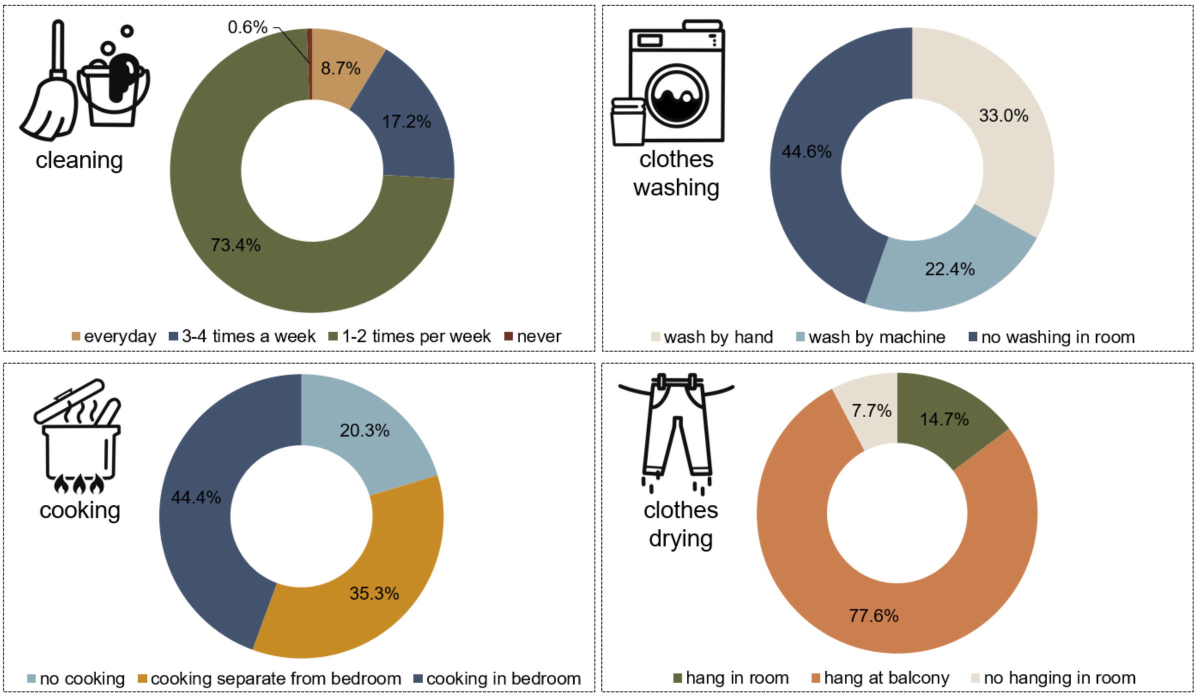


Figure 5- 5 Human behaviour characteristics
(Source: Author)

73.4% of the participants cleaned the room 1-2 times a week. The percentage of no washing in the room, clothes washing by hand and washing by machine were 44.6%, 33% and 22.4%, respectively. Cooking causes an increasing internal water vapour (Institution 2011). However, cooking in the bedroom was the most popular choice, preferred by almost 45% of people. This is due to the layout of one-bedroom flat in Thailand (the layout is presented in Figure 5- 3). Nonetheless, the bedroom is not design for cooking activity, which will increase heat and water vapour accumulating in the room. The common material in the bedroom is fabric (in the bed area and wardrobe), which easily absorbs moisture then germinate mould in the room. A large number of participants, 35.3%, also did cooking in room but had partition to separate cooking from bed area. Laundry should be dried in a dedicated ventilated area. 77.6% of respondents use the balcony for clothes drying while 14.7% dry clothes in the room. Typical apartment rooms in Thailand ventilates air through window and door without a mechanical extraction fan. Even while drying clothes on, the moist air can transfer into the room depending on the air flow (Institution 2011). Clothes hanging for drying in the room bring about excess moisture in the room, resulting in further health problems and damage due to condensation.

Figure 5- 6 presents the percentage of occupants regarding their perception levels of IEQ. The figure includes two types of bar charts, which are diverging stack bar charts and stacked bar charts. A diverging stack bar chart is similar to a regular stacked bar chart, but it contains a centre dividing line or axis that represents a neutral point. The bars on either side of this central line reflect positive and negative values, allowing for comparing the distribution of positive and negative responses within each category. In contrast, a regular stacked bar chart is commonly used to show the composition of a whole and how each part contributes to the total. Diverging stack bar charts exhibit perception levels of air temperature (a1), natural lighting (a2), and air humidity (a3), in which zero is neutral on satisfactory. Stacked bar charts also show perception levels of air freshness (b1), ventilation (b2), and mould (b3).

Participant in air temperature perception tends to move toward “excessively hot” during summer (four times more than winter). This is likely to be attributable to seasonal air temperature variations as there is approximately 5°C between winter and summer. In Chiang Mai. The average outdoor air temperature in summer ranges from 26.4 °C to 32.0°C (ThaiMeteorologicalDepartment 2021).

The natural lighting perception was divided into two purposes: the lighting for general purpose and the working purpose. Approximately 50% of the respondents perceived natural lighting as the level of “not bright” for general purposes. This increased close to 60% for working purposes. The majority of participants responding to air humidity and ventilation lean toward “excessively humid” and “not significant”, respectively. In addition, over half of the participants were reporting stale air in their rooms.

With the relative humidity exceeding 80%, surfaces can support the germination of various mould spores. In addition, in warm, humid air within the building, the excess moisture on the surface can be accumulated as condensation, which can be a risk of construction damage. The percentage of mould growth in the room can represent the actual room environment. 55.2% of the respondents had mould happening on between 10% and 30% of their rooms’ surface areas. A further, 20% of the respondents had mould occurring over 40% or more of the rooms’ surface.

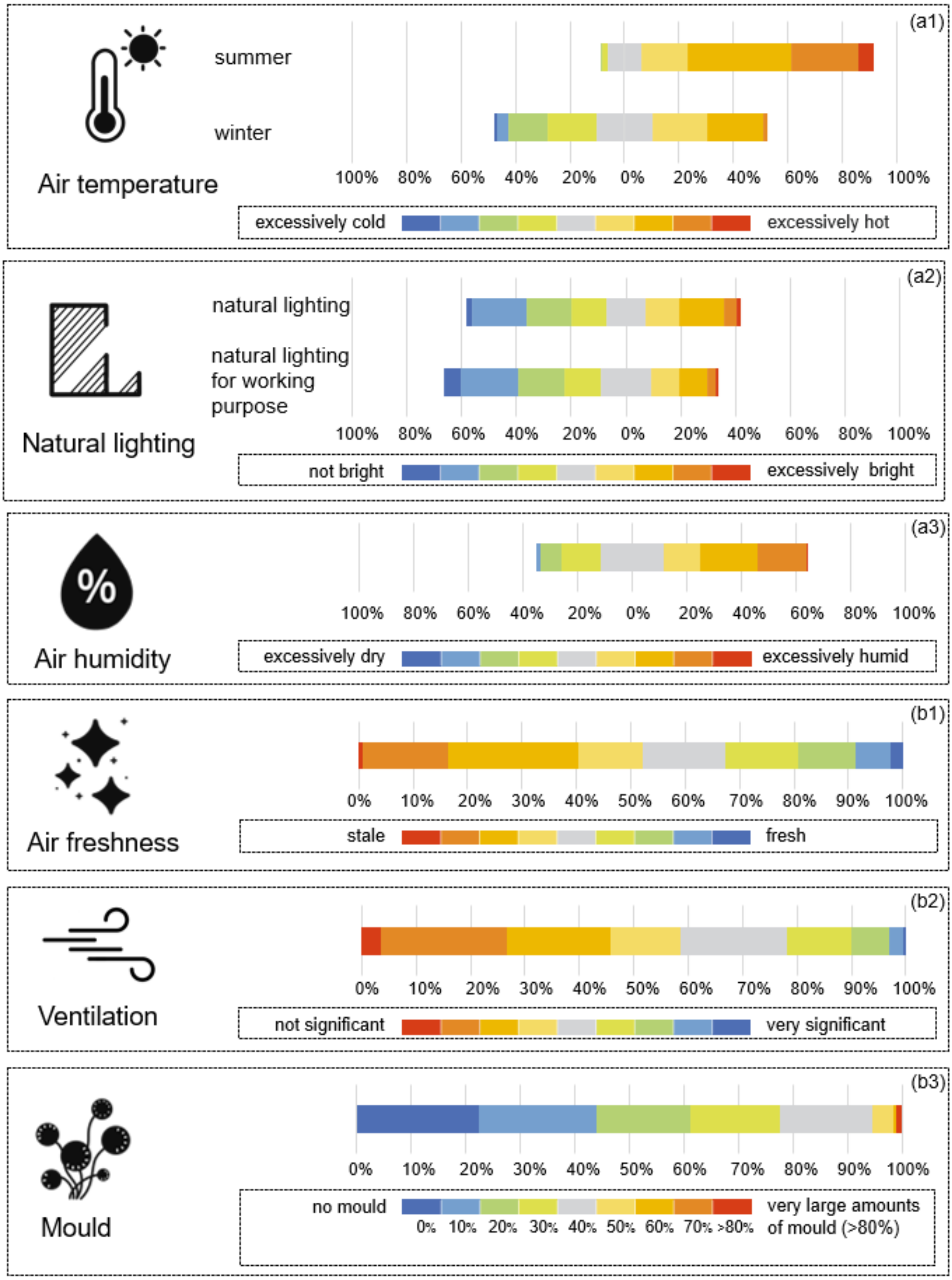


Figure 5- 6 Indoor environmental quality perception level
(Source: Author)

The percentage of the five comfort points on the Likert scale was exhibited in a diverging stacked bar chart (in Figure 5- 7). The proportion of participants who agreed with the statements is shown to the right of the zero line in the bar chart, while the participants who disagreed are shown to the left. Generally, approximately 30% of respondents were satisfied with their rooms in the neutral zone, while the average satisfaction zone of the respondents was roughly 20%. A considerable number of responders remained in the dissatisfaction. The percentage of dissatisfaction with room humidity (38%) exceeds the dissatisfaction with natural ventilation (28%) but lags behind the dissatisfaction with natural lighting, air temperature, location and room size (over 40%).

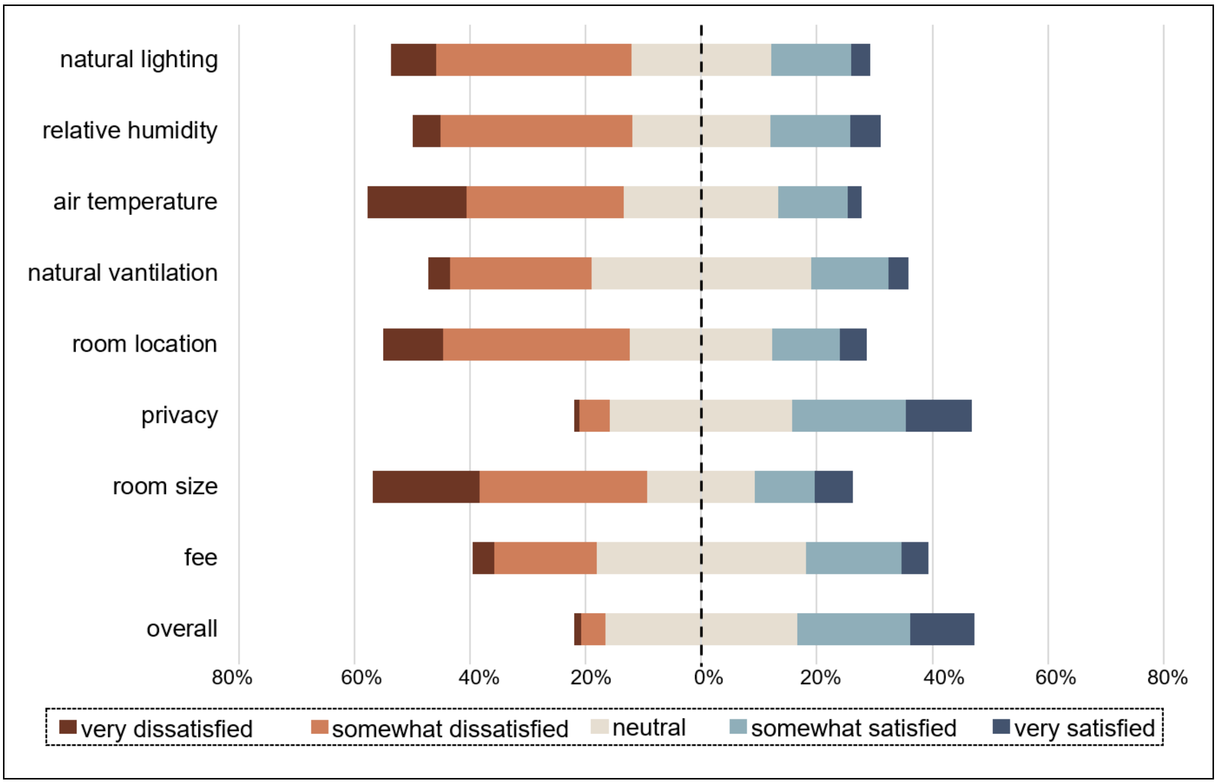


Figure 5- 7 occupants' comfort satisfaction
(Source: Author)

5.5 Relationship between indoor environment quality scale and occupants' comfort satisfaction

This section used two steps to examine the relationship between IEQ perception and occupant satisfaction. Firstly, Pearson's correlation coefficient was applied to define the strength of any linear relationship between two variables (Pearson 1931). Secondly, multiple regression was used to determine the main contributing factors in the relationship between variables.

The occupants' satisfaction involved two primary aspects, which are the physical environment and IEQ perception. Figure 5- 8 exhibits all the factors which have a correlation significant at the 0.01 level to the IEQ scale. The relationship between human behaviour and indoor quality rating was estimated by Spearman correlation, while the Pearson's correlation was applied to assess the relationship between ratio scale, e.g., building height and natural lighting perception. Referring to Cohen rules, a correlation coefficient (reported as the statistic r) of 0.1 means a small correlation, 0.3 means a moderate correlation and 0.5 means a large correlation (see an example of different correlation coefficients' graph in Figure 5- 8).The p-value (quoted under significant (2-tailed) at the 0.01 level ($p<0.01$)) is considered significant if the value is between 0.001 to 0.010, which also indicates 99% confidence levels. The p-value between 0.010 to 0.050 will be considered significant at 95% confidence level (Chetty 2015).

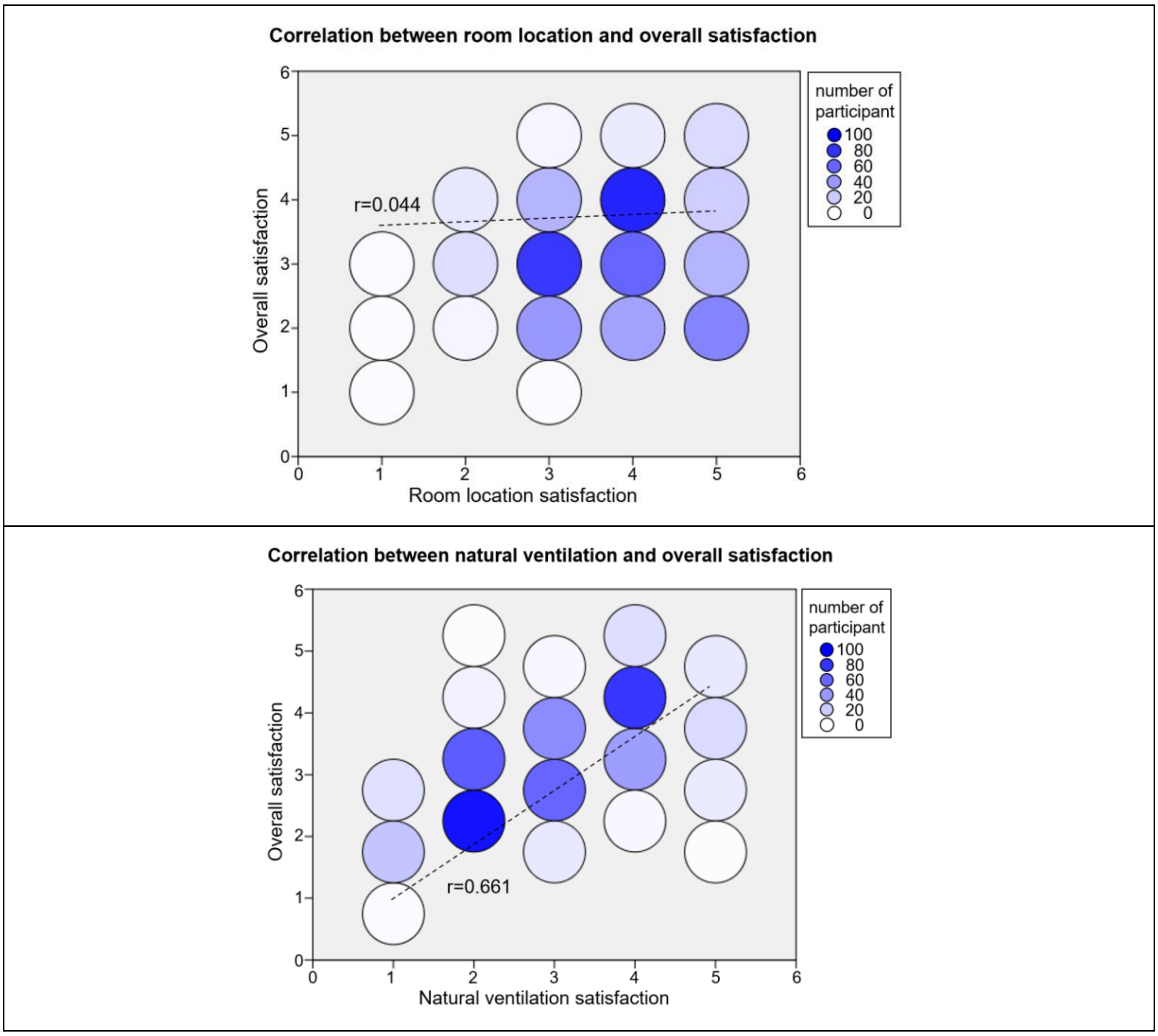


Figure 5- 8 example of different Pearson correlation coefficient
(Source: Author)

Human behaviour characteristics such as cooking, washing clothes, and hanging clothes for drying had a strong significant correlation ($p<0.01$) with IEQ perception. For example, the washing characteristic had a solidly negative correlation with the mould rating scale, which can conclude that mould could occur more if they wash clothes in rooms. The correlations between the physical environment and IEQ scale were also significant, at the 0.01 level. The coefficients between the distance between the participant's building and nearby building were 0.509 with natural lighting, 0.530 with fresh air scale, and 0.542 with ventilation scale. This can signify that such a positive relationship had large strength of association because the coefficients were above 0.5. However, the distance between the participant's building and a nearby building was negatively correlated with the air humidity air scale. This means that greater distance between the participant's building and nearby building can influence the air humidity perception in a room.

Table 5- 2 Spearman and Pearson correlation coefficient of human behaviour characteristic, physical environment and IEQ perception scale

		Spearman Correlation			Pearson's Correlation
Cooking characteristic	air freshness	-.510**	**Room cleaning frequency**	humidity satisfaction	-.212**
	air humidity	.563**		temperature satisfaction	-.245**
	ventilation	-.504**		room privacy satisfaction	-.157**
	mould level	.499**		overall satisfaction	-.318**
Washing characteristic	air freshness	-.582**	**Room size**	room size satisfaction	.566**
	air humidity	.670**			
	ventilation	-.548**	**Building tall**	natural lighting	-.363**
	mould level	.617**		natural lighting for working purpose	-.368**
Cloth hanging characteristic	air freshness	.364**	**Distance between the building and nearby building**	natural lighting	.509**
	air humidity	-.433**		natural lighting for working purpose	.478**
	ventilation	.374**		air freshness	.530**
	mould level	-.411**		air humidity	-.601**
				ventilation	.542**
				mould level	-.417**

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

The relationship between indoor quality scale and occupants' comfort satisfaction is presented in Table 5- 2. The overall satisfaction had significant relationship ($p<0.01$) with indoor environment perception scale including air temperature, ventilation, humidity, and mould level. As seen in Table 5- 3, humidity satisfaction can be increased if higher natural lighting, greater fresh air, less wet air, more ventilation, and less mould level are attained. Additionally, higher fresh air, less wet air, more ventilation and reduced mould level could enhance ventilation satisfaction level. Table

5- 4 shows the relationship between each thermal environmental satisfaction and overall satisfaction. Most of satisfaction categories had significant association with p-value lower than 0.01 with overall satisfaction, except location satisfaction.

Table 5- 3 Pearson correlation coefficient of occupants' comfort satisfaction and indoor environment perception scale

		Pearson's Correlation			Pearson's Correlation
natural lighting satisfaction	air temperature in winter	-.438**	**ventilation satisfaction**	air freshness	.737**
	air temperature in summer	-.218**		air humidity	-.701**
	natural lighting	.783**		ventilation	.781**
	natural lighting for working purpose	.757**		mould level	-.605**
humidity satisfaction	natural lighting	.688**	**room privacy satisfaction**	natural lighting	.536**
	natural lighting for working purpose	.650**		natural lighting for working purpose	.533**
	air freshness	.688**		air freshness	.544**
	air humidity	-.621**		air humidity	-.500**
	ventilation	.666**		ventilation	.575**
	mould level	-.645**			
			overall comfort satisfaction	air temperature in winter	-.529**
air temperature satisfaction	air temperature in winter	-.515**		air temperature in summer	-.352**
	air temperature in summer	-.550**		natural lighting	.579**
	air freshness	.493**		natural lighting for working purpose	.582**
	air humidity	-.339**		air freshness	.622**
	ventilation	.540**		air humidity	-.490**
	mould level	-.342**		ventilation	.644**
				mould level	-.482**

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

Table 5- 4 Pearson correlation coefficient of occupants' overall comfort satisfaction with each thermal environmental satisfaction

		Pearson's Correlation
overall comfort satisfaction	natural lighting satisfaction	.635**
	humidity satisfaction	.595**
	air temperature satisfaction	.596**
	ventilation satisfaction	.661**
	room location satisfaction	0.044
	room privacy satisfaction	.596**
	room size satisfaction	.150**
	room fee satisfaction	.304**

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

After the correlation analysis, the strong significant relationship (Pearson's coefficient either between -1.0 and -0.5, or between 0.5 and 1.0) will be analysed stepwise by multiple regression. Multiple regression was applied to further find the main factors of occupants' satisfaction. Regression is a statistical technique to model the relationship between a single dependent variable and multi-independent variables.

For estimating the coefficients in the regression equation, unstandardised value (B) shows the influence of independent variables on occupants' comfort satisfaction. The larger value of B can be considered as the larger influencer on such a dependent factor. P-value is the significance level of the regression, and t-value is used to measure a coefficient's standard error, in which t-value closing to zero indicates the low reliability of the predictive power on its coefficient (Sternstein 1996). Occupant's comfort satisfaction was determined as the dependent variable, and other significant factors were set as independent variables in six models (see Table 5- 5 to Table 5- 6).

Table 5- 5 coefficients of regression for natural lighting satisfaction

Dependent Variable	Independent Variable	Unstandardized Coefficients	t	p-value
		B		
natural lighting satisfaction	(Constant)	1.074	14.236	0.000
	natural lighting	0.282	8.918	0.000
	natural lighting for working purpose	0.175	5.333	0.000

A significant regression (B= 1.074, t= 14.236, p-value= 0.000) of natural lighting satisfaction shows in Table 5- 5Natural lighting (for general purposes) is the main influence on natural lighting satisfaction level (B= 0.282, t= 8.918, p-value= 0.000) compared with natural lighting for working purposes (B= 0.175, t= 5.333, p-value= 0.000).

Table 5- 6 coefficients of regression for humidity satisfaction

Dependent Variable	Independent Variable	Unstandardized Coefficients	t	p-value
		B		
humidity satisfaction	(Constant)	2.036	6.932	0.000
	natural lighting	0.146	3.948	0.000
	natural lighting for working purpose	-0.026	-0.669	0.504
	air freshness	0.143	4.849	0.000
	air humidity	-0.079	-2.605	0.009
	ventilation	0.084	2.557	0.011
	mould level	-0.131	-4.349	0.000

Most independent variables are significant at 0.05 level (p-value <0.05), except natural lighting for working purpose. The regression in Table 5- 6 shows that natural lighting (B= 0.146, t= 3.948, p-value= 0.000) and air freshness level (B= 0.143, t= 4.849, p-value= 0.000) are principal influences on humidity satisfaction. Natural lighting relates to humidity satisfaction because natural lighting can influence human subjective thermal perception from the psychological perspective (Chinazzo et al. 2019). Moreover, more natural lighting can associate with more solar radiation, which also effects human thermal perception. The relationship between natural lighting for working and humidity satisfaction is statistically significant at 0.5 level (p- value >0.5). Natural lighting for working purpose is not able to predict or influence on humidity satisfaction, while other factors have influenced on the humidity satisfaction with significant at 0.05 level (p-value <0.05).

Table 5- 7 coefficients of regression for ventilation satisfaction

Dependent Variable	Independent Variable	Unstandardized Coefficients	t	p-value
		B		
ventilation satisfaction	(Constant)	2.402	11.364	0.000
	air freshness	0.133	5.469	0.000
	air humidity	-0.205	-8.708	0.000
	ventilation	0.265	9.861	0.000

From the regression for ventilation satisfaction, there are three factors influencing ventilation satisfaction. Ventilation level is a major factor (B= 0.265, t= 9.861, p-value= 0.000), following by air humidity perception level (B= -0.205, t= -8.708, p-value= 0.000).

Table 5- 8 coefficients of regression for air temperature satisfaction

Dependent Variable	Independent Variable	Unstandardized Coefficients	t	p-value
		B		
air temperature satisfaction	(Constant)	6.714	32.804	0.000
	air temperature in winter	-0.235	-10.390	0.000
	air temperature in summer	-0.356	-11.801	0.000

The relationship between satisfaction and air temperature is stronger in summer than in winter. The negative coefficients of both the air temperature in winter and summer mean a negative correlation between the air temperature satisfaction level. In other word, the air temperature satisfaction could increase if the air temperature in winter and summer reduced.

Table 5- 9 coefficients of regression for room privacy satisfaction

Dependent Variable	Independent Variable	Unstandardized Coefficients	t	p-value
		B		
room privacy satisfaction	(Constant)	1.725	4.480	0.000
	natural lighting	0.068	1.299	0.194
	natural lighting for working purpose	0.054	0.998	0.319
	air freshness	0.087	2.101	0.036
	air humidity	-0.103	-2.484	0.013
	ventilation	0.190	4.118	0.000

The main influence of room privacy satisfaction is on ventilation rate (B= 0.190, t= 4.118, p-value= 0.000). Air humidity and air freshness perception level are the minor factors on the satisfaction, respectively. Ventilation perception correlates to privacy satisfaction because rooms with more privacy can open their rooms' opening and then benefit to more ventilation in rooms. However, natural lighting in general and for working purpose are not statistically significant at 0.05 level because theirs p-values are greater than significant level (0.05).

Table 5- 10 coefficients of regression for overall comfort satisfaction

Dependent Variable	Independent Variable	Unstandardized Coefficients	t	p-value
		B		
overall comfort satisfaction	(Constant)	0.896	9.907	0.000
	natural lighting satisfaction	0.172	4.803	0.000
	humidity satisfaction	0.080	2.358	0.019
	air temperature satisfaction	0.199	6.163	0.000
	ventilation satisfaction	0.159	4.426	0.000
	room privacy satisfaction	0.153	6.251	0.000

The multi-linear regression was calculated to predict the overall satisfaction based on indoor thermal environmental satisfaction. The coefficients of regression can see in Table 5- 10. Air temperature satisfaction is a major influence on overall satisfaction (B= 0.199, t= 6.163, p-value= 0.000). Natural lighting (B= 0.172, t= 4.803, p-value= 0.000) and ventilation satisfaction (B= 0.159, t= 4.426, p-value= 0.000) are the second and third influences on the overall satisfaction, respectively.

5.6 Summary Occupant Perception Survey

Physical environment, such as distance between occupants' building and nearby buildings and building height, affects IEQ perception. For example, occupants are likely to perceive inadequate natural lighting and low natural ventilation when another building is located between 0-3 m from their buildings. In contrast, the occupants perceive air rather humid when there is a smaller distance between the occupant's building and nearby building. Referring to (Foster and Oreszczyn 2001; Yan et al. 2015), Occupants in a building with a short distance between nearby buildings tend to keep privacy by keeping the blind down, which can block natural ventilation entering the room. Additionally, such tall buildings cause large “air shadows” which affect natural ventilation significantly. Designs should only allow short distance between nearby buildings if adequate privacy and IEQ can be guaranteed.

Occupant activities generating moisture content in the room, such as cooking, washing and hanging cloth for drying, cause occupants to perceive stale air, high air humidity, low ventilation and high level of mould occurring. Relevant sources (Yik et al. 2004; Zemitis et al. 2016) indicates that moisture is generated in residence from occupant not only via internal occupant’s body but also by various household activities such as cooking, clothes hanging, clothes washing etc. Occupancy activities, room function, usage duration and frequency cause different level of moisture generation in room. For example, 2,000-3,000 grams, 1,500 grams, 500 grams per day for cooking, drying clothes indoor and washing clothes respectively(Institution 2011). In tropical region, a priority in building design should be minimizing indoor moisture accumulation. However, from the survey results (Section 5.4), most building materials used in Chiang Mai are porous materials, such as wood door, brick wall and wood furniture, which are susceptible to moisture damage.

Relationship between IEQ scale and occupants’ comfort found that air temperature satisfaction is the primary influence on overall satisfaction. The result agrees with Tanabe et al mentioning that air temperature affects human mental and body perception. In addition, a high ventilation flow, adequate natural lighting, and low air humidity are also crucial to achieve room satisfaction (see Table 5- 3). Poor natural ventilation is reported as a significant challenge to residential occupancy, which increases the chance of indoor mould growth and increases sick building syndrome (Milton 2000). The limitation of natural lighting in buildings can affect occupants’ visual and atmosphere perception (Lee et al. 2013).

This questionnaire survey was analysed by statistical method. The conclusions about the factors influencing occupants' indoor environmental quality perception and their satisfaction are listed below:

- The most popular physical environment of participants' rooms will be used as a base case in CFD simulation in Chapter 7, such as type B and C of room planning (see Figure 5- 3 Room type and area), double-loaded corridor plan, single-sided window, room materials, and building height.
- Occupant IEQ perception has a significant influence on room satisfaction. The humidity satisfaction is also determined by those perceptions as well as indoor air quality perception of natural lighting and mould level. The occupants' ventilation satisfaction is mainly influenced by ventilation, air humidity and air freshness perception, respectively.
- The environmental satisfaction of natural lighting, humidity, air temperature ventilation and room privacy are the five key factors of the overall comfort satisfaction. In such vital factors, air temperature satisfaction is the primary factor of the overall satisfaction, followed by natural lighting and ventilation, respectively.

The results of this study will assist the process of CFD modelling and design options. The study examines the data influencing occupants' comfort satisfaction to be a guideline for developing the design to improve occupants' ventilation room and achieve room satisfaction.

6 CFD sensitivity analysis result: outdoor

6.1 Introduction

The rationale for the scenarios to be analysed was described in Chapter 3.5. Within this investigation the key factors investigated were wind speed and direction relating to season and position on building (Section 6.2), the relationship between building height and road width (Section 6.3), the effect of nearby buildings (Section 6.4)

6.2 Wind speed and position on building

Further details regarding the methodology can be found in Chapter 3.5.1.

6.2.1 Wind speed

CFD analysis investigated air movement characteristics around a building. Key seasons in Thailand are summer (occurring between mid-February to mid-May, initial wind coming from the south), winter (encompassing the period from mid-October to mid-February, initial wind appearing from the north) and rainy season (marked during mid-May to mid-October, initial wind coming from south-west). Initial wind speed of 1 $m.s^{-1}$, 2 $m.s^{-1}$, 4 $m.s^{-1}$ and 6 $m.s^{-1}$ was analysed because this range includes the most typical wind condition in Chiang Mai, Thailand (see detail of typical wind in Chapter 2).

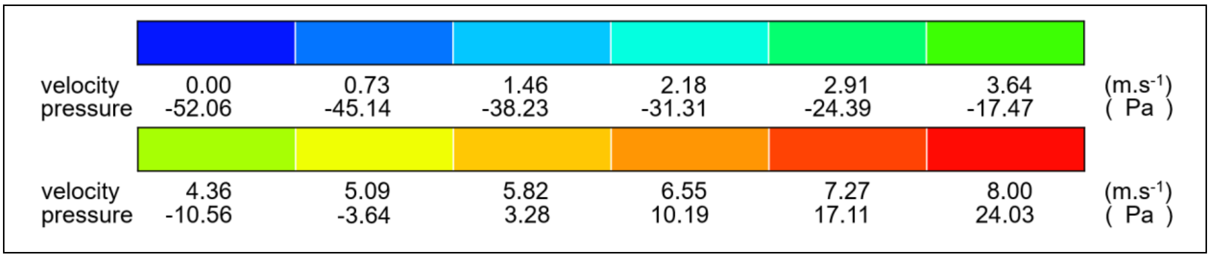


Figure 6- 1 shows a legible scale bar of CFD simulation result used in this chapter

6.2.1.1 Summer (south wind)

The wind impinged the buildings from south direction, then distributed around the building. In this season, there was positive pressure on the south, south-west and south-east of the building wall, while negative pressure was on the north, north-west and north-east. Therefore, the highest wind speed was on the south surface while the lowest was on the north surface.

Findings have been presented in full for 4 m.s^{-1} because it was experienced more often. Results for other wind speeds have been summarised in Table 6- 1. The air movement speed at different points of the building were compared for all simulated wind speeds (Figure 6- 4).

Table 6- 1 summary of air movement in summer

wind speed (m.s^{-1})	Average air speed (m.s^{-1}) on windward side (South wall)	Average air speed (m.s^{-1}) on leeward side (North wall)	Air speed ratio (7th floor : 1st floor) on windward side (South wall)	Air speed ratio (7th floor : 1st floor) on South East and South West wall	Air speed ratio (7th floor: 1st floor) on leeward side (North wall)
1	2.14	0.86	0.82	1.67	1.00
2	4.27	1.71	0.82	1.66	1.00
4	8.54	3.41	0.82	1.67	1.00
6	12.79	5.12	0.82	1.67	1.00
8	17.06	6.82	0.82	1.67	1.00

Initial wind speed is at 4 m.s^{-1} from south

Air movement could reach 9.39 m. s^{-1} on the south wall, which was the windward side. Then, the air continues along the building side. The velocity decreased to 3.41 m. s^{-1} at the leeward side (see Figure 6- and Figure 6- 3). On the windward side, the air movement ratio between the top to the bottom floor was 0.82 on the south wall and 1.67 on south-east and south-west wall. There was little variation of air movement between simulated points on the leeward side.

view from the south (see a legible CFD scale bar in Figure 6- 1)

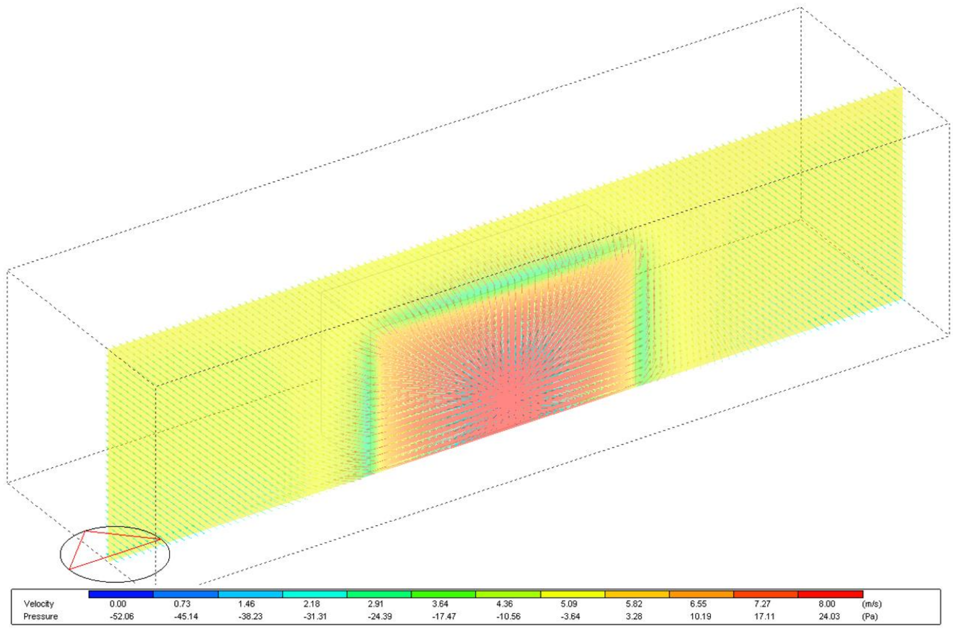


Figure 6- 2 Wind characteristic in summer at 4m.s^{-1}

view from the north (see a legible CFD scale bar in Figure 6- 1)

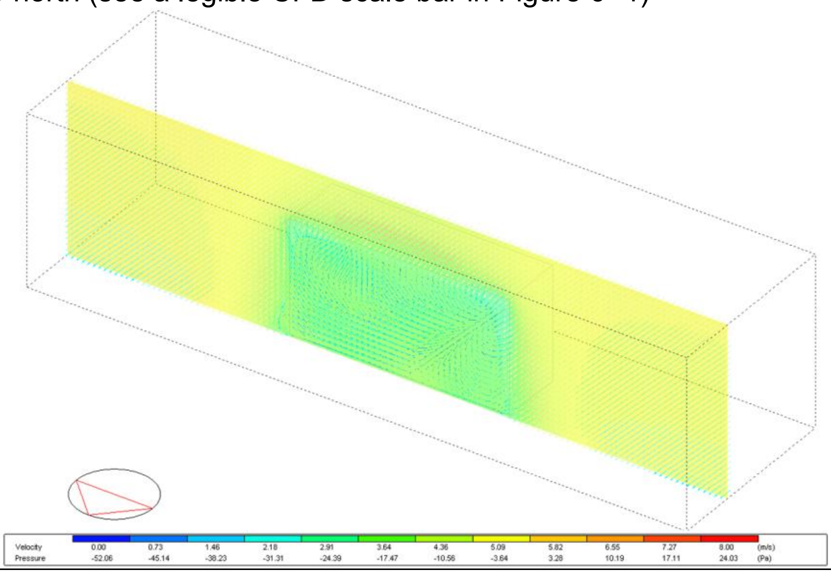
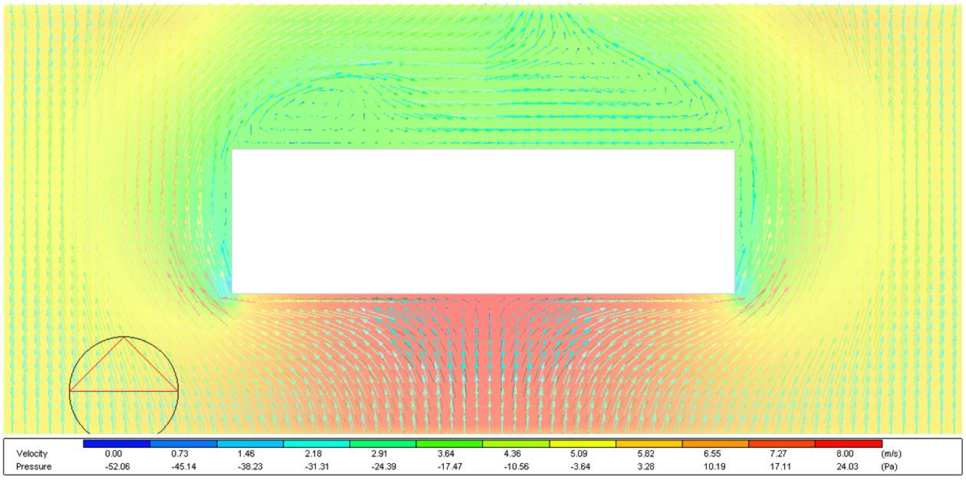


Figure 6- 2 Wind characteristic in summer at 4m.s^{-1} (continued)

at 1st floor level (from above) (see a legible CFD scale bar in Figure 6- 1)



at 7th floor level (from above) (see a legible CFD scale bar in Figure 6- 1)

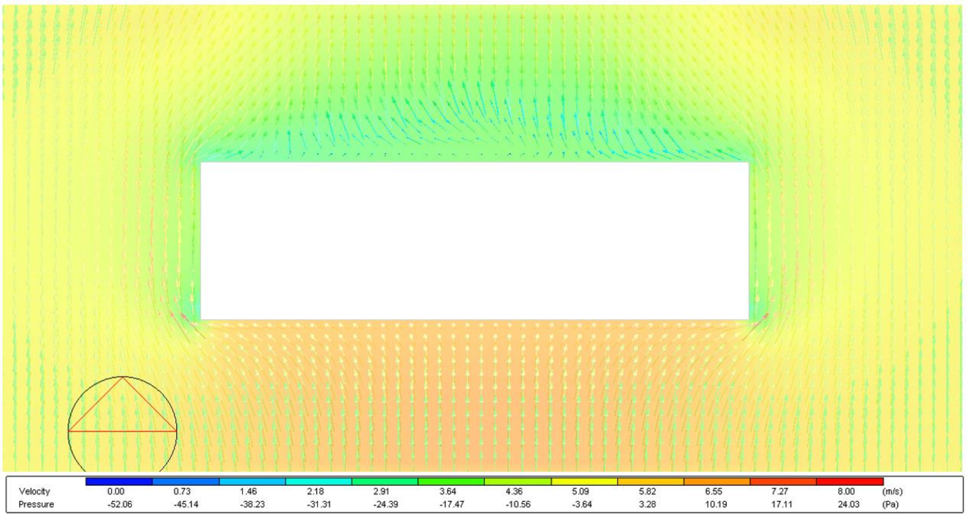


Figure 6- 3 Wind characteristic in summer at 4m.s^{-1}

6.2.1.1.1 Summary of air movement in summer

In summer, the wind speed is typically from south direction and wind speeds of 1, 2, 4 ,6 and 8 m.s^{-1}. The CFD results show that the wind impinged on the south wall created the higher air movement velocity on the south wall. The air movement on the south wall was approximately 235% of initial wind speed. Then the air diverted along the side walls to the suction region on the north wall, which was around 86% of original wind speed. From the air moving, eddy was created at the corner of the building resulting in the lower air movement value on the south- east and south- west corners. In addition, the air movement ratio on S, S-E and S-W walls do not vary with wind speed always 0.82 for S and 1.67 for SE and SW. The air movement of the 1st floor (3.6 m high) was higher than the top floor (19.2 m high). Varying the initial wind speed resulted in the same pattern of changes of air movement. The overall air movement velocity changes are illustrated in Figure 6- 4.

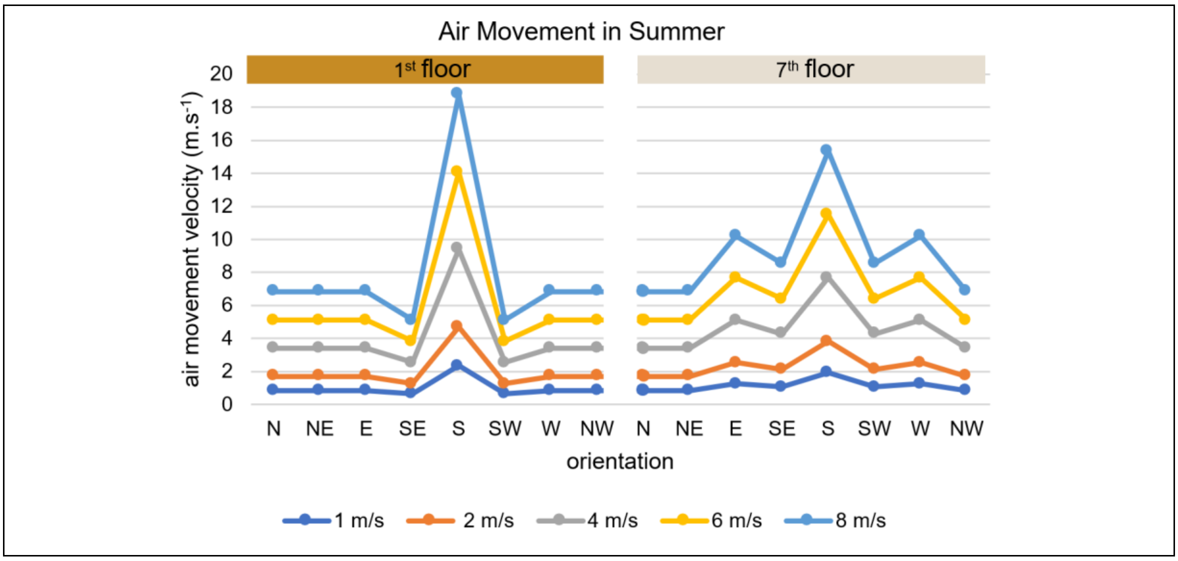


Figure 6- 4 air movement on different building façade locations and height in summer

6.2.1.2 Rainy season (south-west wind)

The wind impinged the buildings from south-west direction, then distributed around the building. In this season, there is positive pressure on the south-west, south and west of the building wall, while negative pressure is on the north-west, north and north-east. The highest wind speed was on the south-west surface while the lowest was on the south-east surface. This is because there was turbulent wake region around this wall.

The findings were fully visualized for 4 m.s^{-1} as it took place frequently, while the results for the other wind speeds were summarised in Table 6- 2. The air movement speed at different points of the building were compared for all simulated wind speed (Figure 6-7).

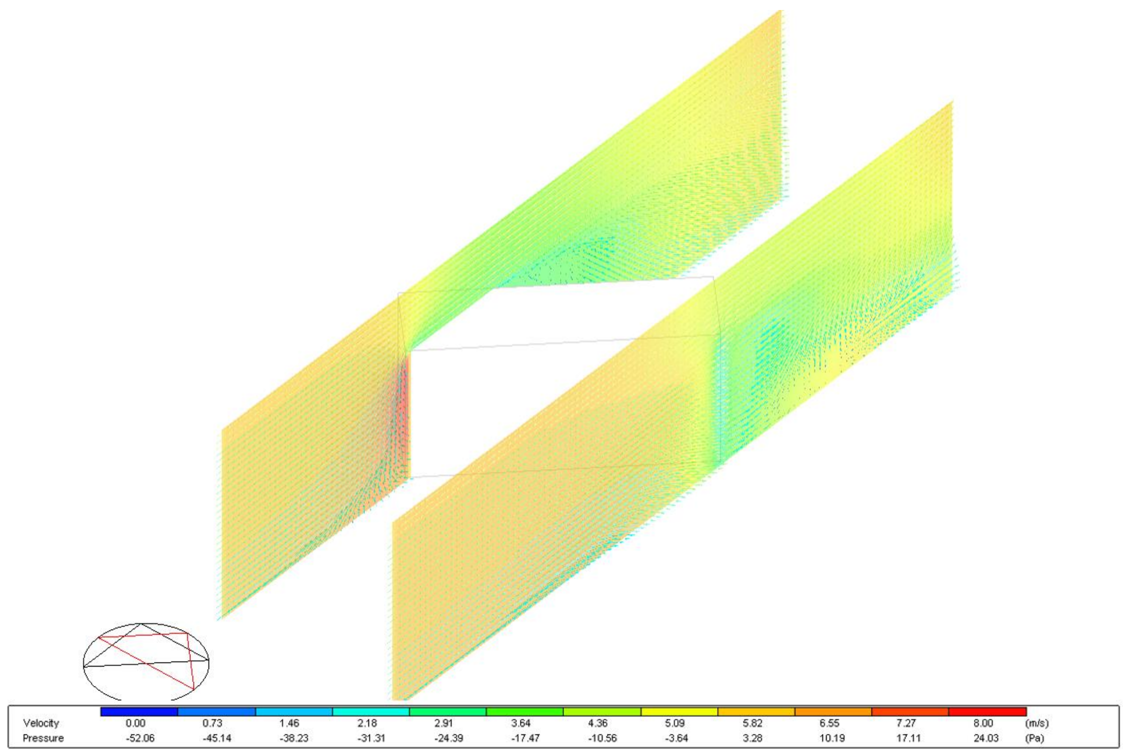
Table 6- 2 summary of air movement in rainy season

wind speed ($m.s^{-1}$)	Average air speed ($m.s^{-1}$) on windward side (South West wall)	Average air speed ($m.s^{-1}$) on leeward side (North East wall)	Air speed ratio (7th floor : 1st floor) on windward side (South West wall)	Air speed ratio (7th floor : 1st floor) on West and South wall	Air speed ratio (7th floor : 1st floor) on leeward side (North East wall)
1	1.25	0.75	1.00	0.95	1.00
2	2.48	1.49	1.00	0.95	1.00
4	4.91	2.96	1.00	0.95	1.00
6	7.33	4.40	1.00	0.95	1.00
8	9.72	5.83	1.00	0.95	1.00

Initial wind speed is at 4 $m.s^{-1}$ from south-west

Air movement could reach 4.91 $m.\ s^{-1}$ on the south-west wall which was the windward side. Then, the air continuingly distributed along building side. The velocity reduced to 2.96 $m.\ s^{-1}$at the leeward side (see Figure 6- 5, Figure 6- 6). The highest air movement velocity at the 1st floor level was on south and south-west wall, while highest air movement velocity at the top floor level was only on the south-west wall. On the leeward side, the air movement velocity had the same value for both the top and lower floor. The wake occurred at the north-west and south-east wall of the building.

view from the south (see a legible CFD scale bar in Figure 6- 1)



view from the north (see a legible CFD scale bar in Figure 6- 1)

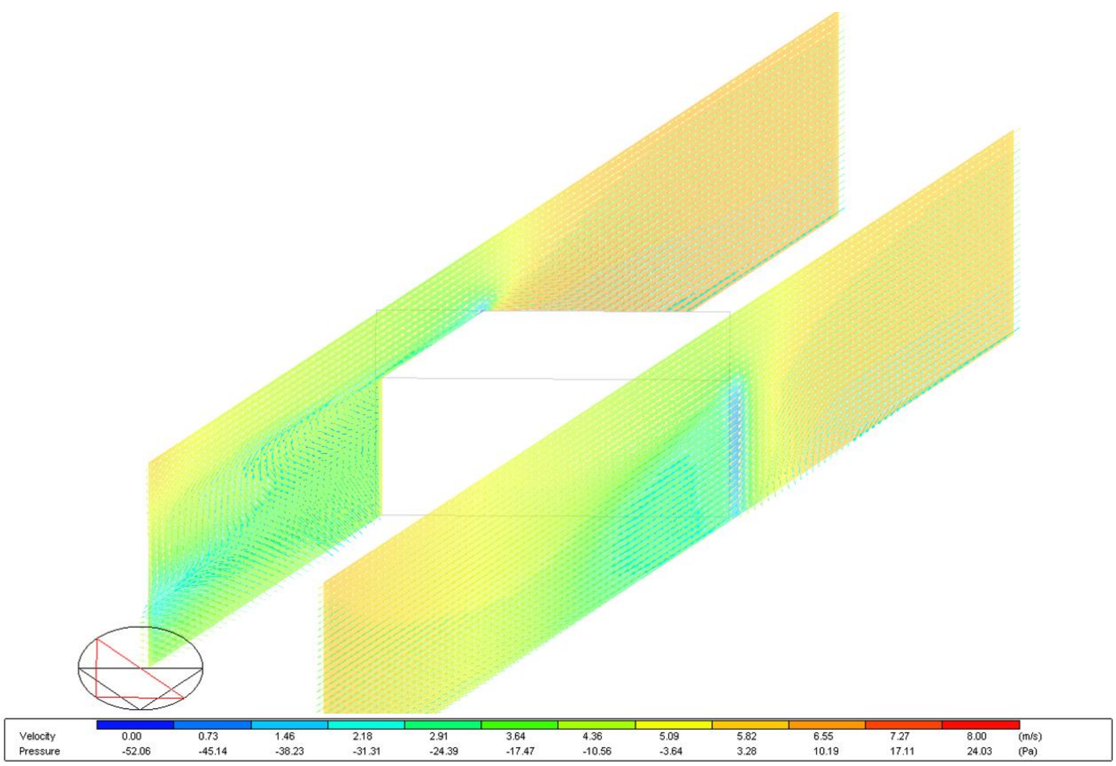
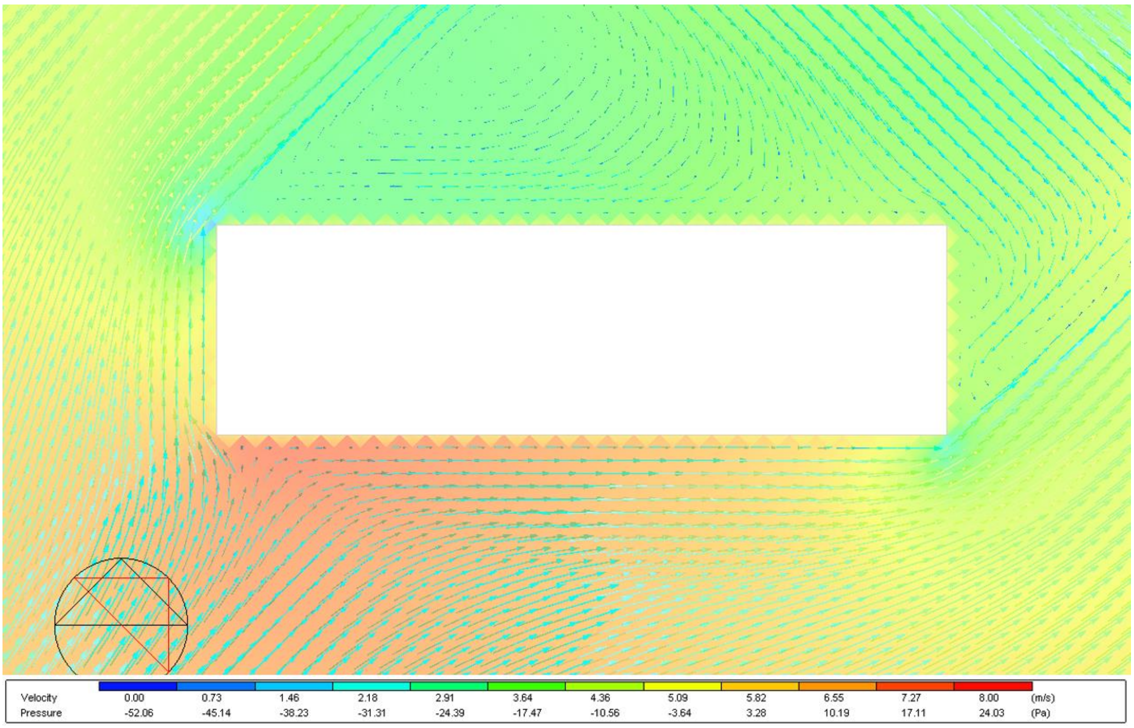


Figure 6- 5 Wind characteristic in rainy season at 4m.s^{-1}

at 1st floor level (from above) (see a legible CFD scale bar in Figure 6- 1)



at 7th floor level (from above) (see a legible CFD scale bar in Figure 6- 1)

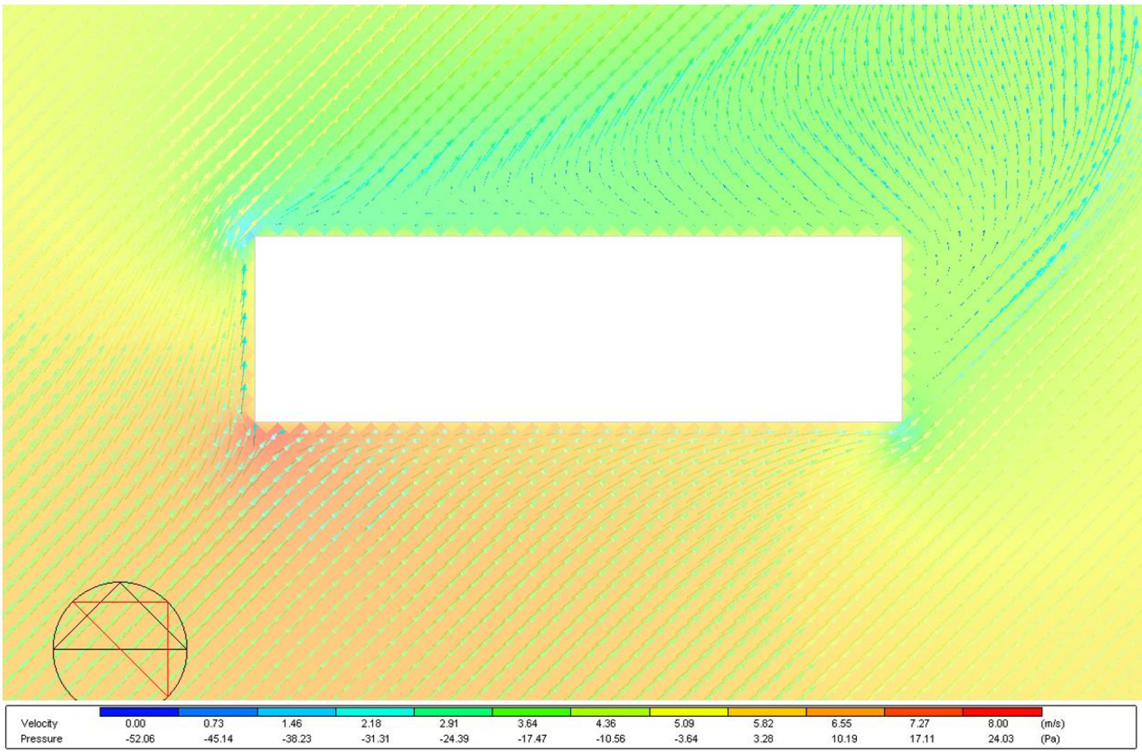


Figure 6- 6 Wind characteristic in rainy season at 4m.s^{-1}

6.2.1.2.1 Summary of air movement in rainy season

In rainy season, the wind speed was typically from south-west and wind speeds of 1, 2, 4 ,6 and 8 m.s^{-1}. The CFD results show that the wind impinged on the south-west (windward) wall created the higher air movement velocity on the south-west wall, then the air diverted along the side walls to the suction region on the north-east (leeward) wall. From the air moving, eddy was created at the corner of the building resulting in the lower air movement value on the north- east and south- east corners. On windward side, air movement velocity was less different between bottom (3.6 m high) and the top floor (19.2 m high), while, on the leeward side, the air movement velocity had the same value for both the top and lower floor. Varying the initial wind speed resulted in the same pattern of changes of air movement. The overall air movement velocity changes are illustrated in Figure 6- 7.

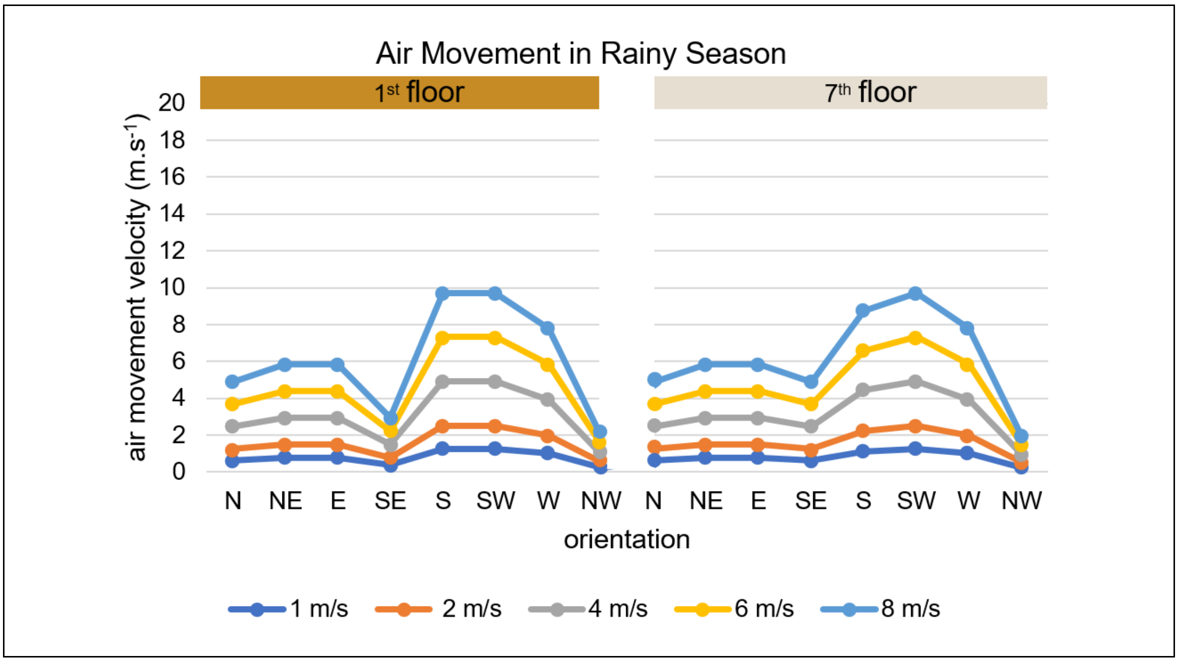


Figure 6- 7 Air movement on different building façade locations and heights in rainy season

6.2.1.3 Winter (north wind)

The wind impinged the buildings from north direction, then distributed around the building. In this season, there is positive pressure on the north, north-west and north-east of the building wall, while negative pressure is on the south, south-west and south-east. The highest wind speed was on the north surface while the lowest was on the south surface.

The simulation results were fully visualized with a wind speed of 4 $m.s^{-1}$ as it is experienced more frequently. The results of the other wind speeds were summarised in Table 6- 3. The air movement speed at different points of the building were compared for all simulated wind speed (Figure 6- 10).

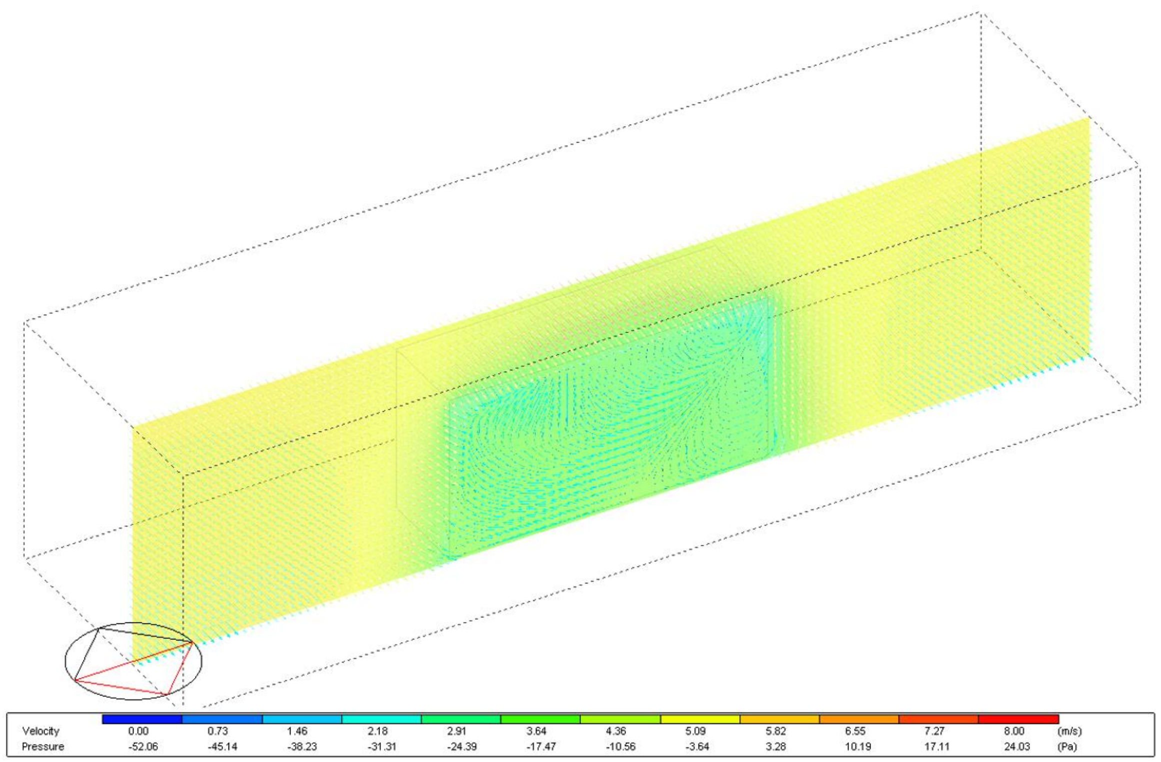
Table 6- 3 summary of air movement in winter

wind speed ($m.s^{-1}$)	Average air speed (m.s-1) on windward side (North wall)	Average air speed (m.s-1) on leeward side (South wall)	Air speed ratio (7th floor : 1st floor) on windward side (North wall)	Air speed ratio (7th floor : 1st floor) on North East and North West wall	Air speed ratio (7th floor : 1st floor) on leeward side (South wall)
1	2.14	0.86	0.82	1.67	1.00
2	4.27	1.71	0.82	1.66	1.00
4	8.54	3.41	0.82	1.67	1.00
6	12.79	5.12	0.82	1.67	1.00
8	17.06	6.82	0.82	1.67	1.00

Initial wind speed is at 4 $m.s^{-1}$ from north

Air movement reached 9.39 $m.\ s^{-1}$ on the windward wall, north wall. The air continued to flow alongside of building. The velocity decreased to 3.41 $m.\ s^{-1}$ on the leeward wall (see Figure 6- 8, Figure 6- 9). At the windward side, the air movement ratio between the top to bottom floor were 0.82 on the north wall and 1.67 on north-east and north-west wall, while air movement at any measurement points on the leeward side were the same value.

view from the south (see a legible CFD scale bar in Figure 6- 1)



view from the north (see a legible CFD scale bar in Figure 6- 1)

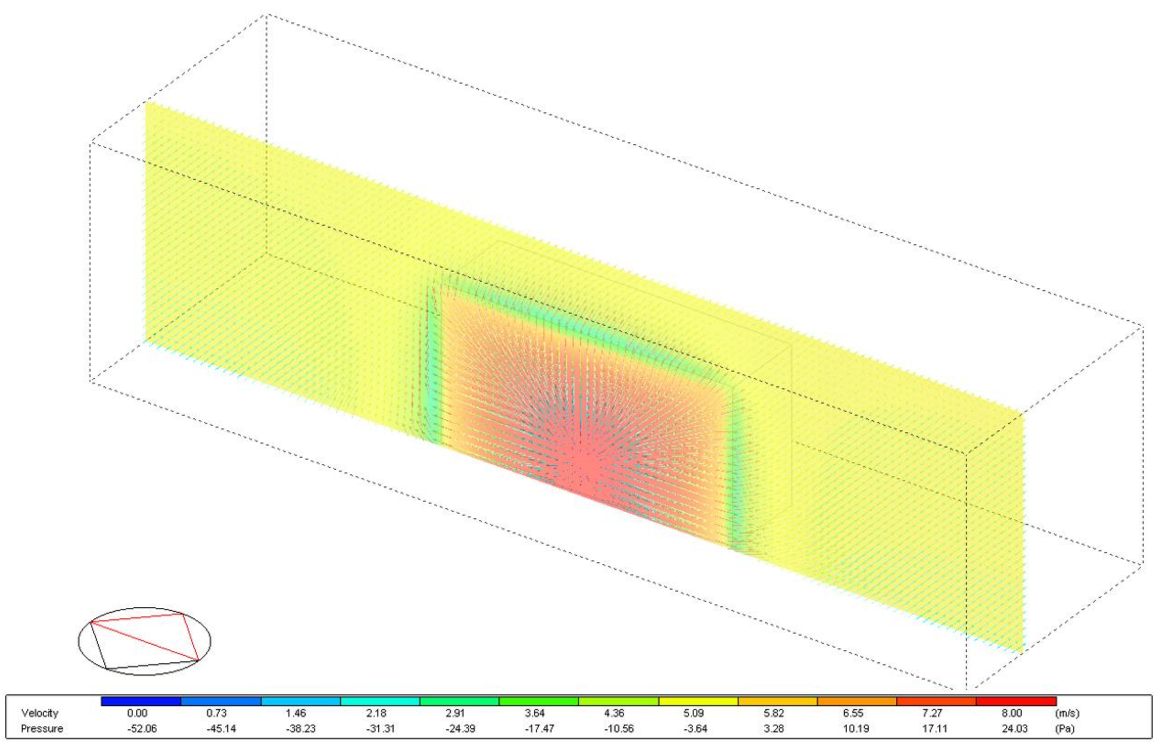
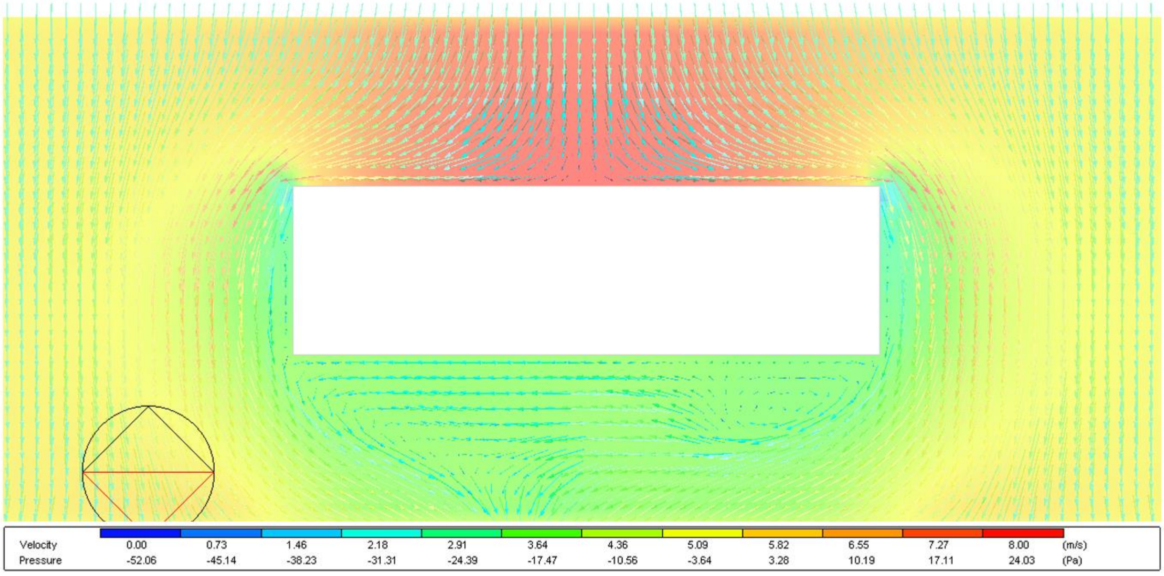


Figure 6- 8 Wind characteristic in winter at 4m.s^{-1}

at 1st floor level (from above) (see a legible CFD scale bar in Figure 6- 1)



at 7th floor level (from above) (see a legible CFD scale bar in Figure 6- 1)

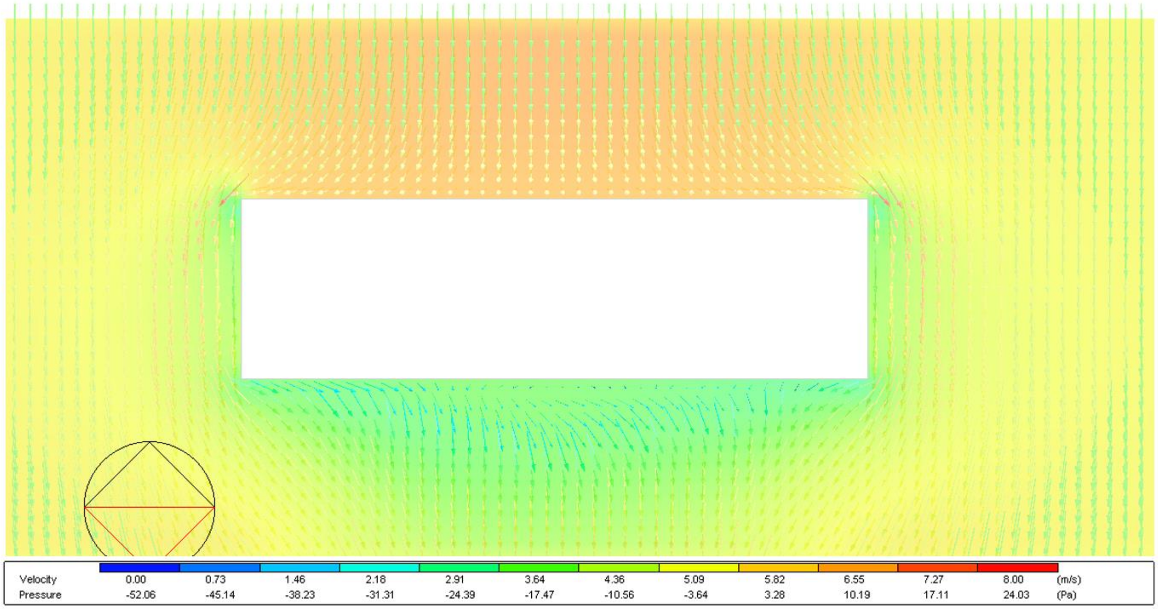


Figure 6- 9 Wind characteristic in winter at 4m.s^{-1}

6.2.1.3.1 Summary of air movement in winter

In winter, the wind speed is typically from north direction and wind speeds of 1, 2, 4 ,6 and 8 m.s^{-1}. The CFD results show that the wind impinged on the north wall created the higher air movement velocity on the north wall, then the air diverted along the side walls to the suction region on the south corners. From the air moving, eddy was created at the corner of the building resulting in the lower air movement value on the north- east and north- west walls. In addition, the air movement of the bottom floor (3.6 m high) was higher than the top floor (19.2 m high). Varying the initial wind speed resulted in the same pattern of changes of air movement. The overall air movement velocity changes are illustrated in Figure 6- 10.

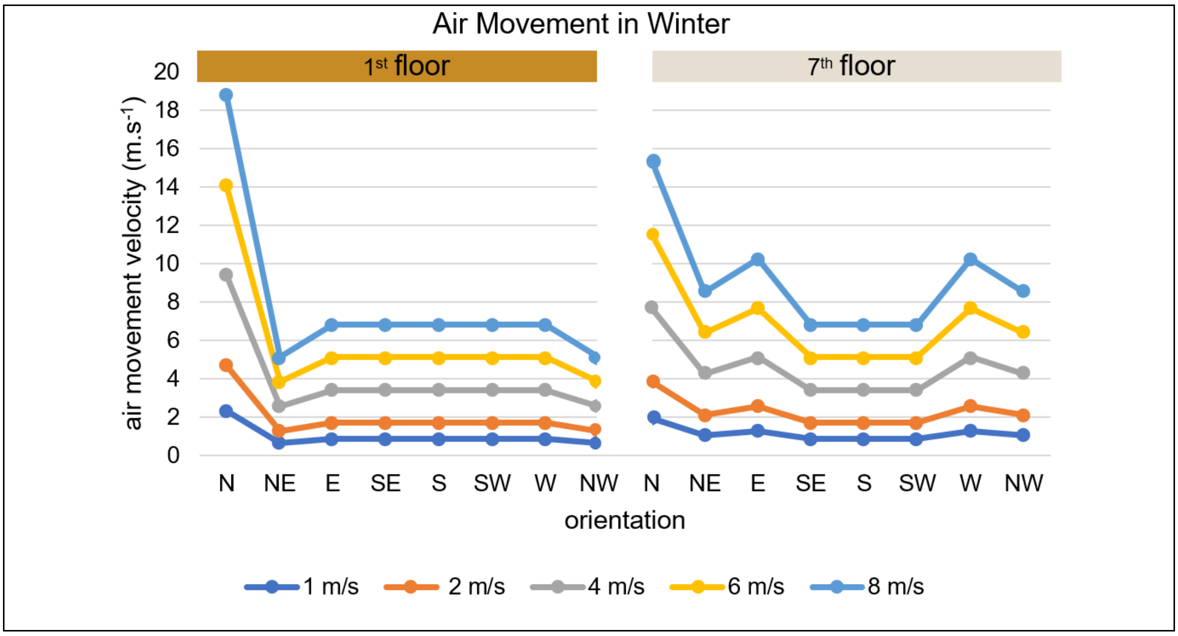


Figure 6- 10 Air movement on different building façade locations and heights in winter

6.2.1.4 Summary of annual air movement at different façade locations and heights

From the simplified model CFD simulation results, the air movement at opposite direction (with same wind speed) behaved the same, for example the air movement on the south wall performed the same as the air on the north wall. So, this can be used to justify reducing the number of further CFD simulation (i.e. simulate for summer and apply to winter). In summer and winter, inline flow, the highest ratio of air movement velocity between windward building envelope to leeward side was 2.75 (see Figure 6- 4, Figure 6- 10). However, in rainy season, oblique flow, the ratio of air movement velocity between windward building envelope to leeward side was 0.72 lower than such ratio between windward building envelope to leeward side in summer and winter (see Figure 6- 7).

6.2.2 Position on building (vertical and horizontal)

The findings from 6.1.1 reveal the air movement velocity and pattern occurring on different orientations of the building based on varying wind direction during different seasons. However, this section focuses primarily on air movement velocity and pattern on different room locations of the building including middle (M) and corner room (C) (see measurement points in Figure 3-13).

In summer, the wind regularly comes from the south direction. The data in Figure 6-11 was obtained from CFD simulations in section 6.2.1. Figure 6- 11 shows that shifting the initial wind speed resulted in the same pattern of changes of air movement. On windward wall, the air movement velocity differences between M2 on bottom and top floor were more obvious at higher wind speeds, which were 0.43 m. s^{-1} and 3.41 m. s^{-1} for 1 $m.s^{-1}$ wind speed and 8 $m.s^{-1}$ wind speed respectively. However, there was no different velocity between bottom and the top floor of both C3 and C4. On leeward wall (C1, M1, C2), there was little difference in air movement velocity.

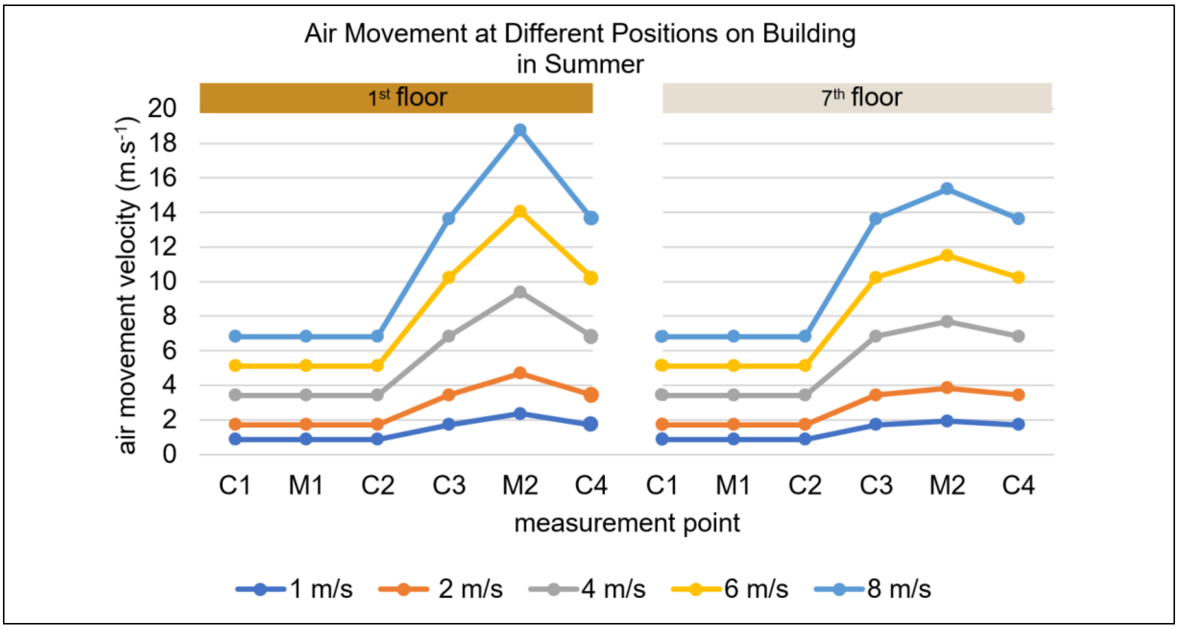


Figure 6- 11 Air movement at different positions on building in summer

In rainy season, the wind regularly comes from south-west direction. The data in Figure 6- 12 were obtained from CFD simulations in section 6.2.1.2. Figure 6- 12 shows that shifting the initial wind speed resulted in the same pattern of changes of air movement. In this season, most of windward and leeward measurement points had no velocity difference between the top and bottom floor. However, on 1st floor, position M2 had air movement velocity of 1.25 $m.s^{-1}$, while position C4 had air movement velocity of 0.87 $m.s^{-1}$ (for wind speed of 1$m.s^{-1}$) compared to the 7th floor was a little higher.

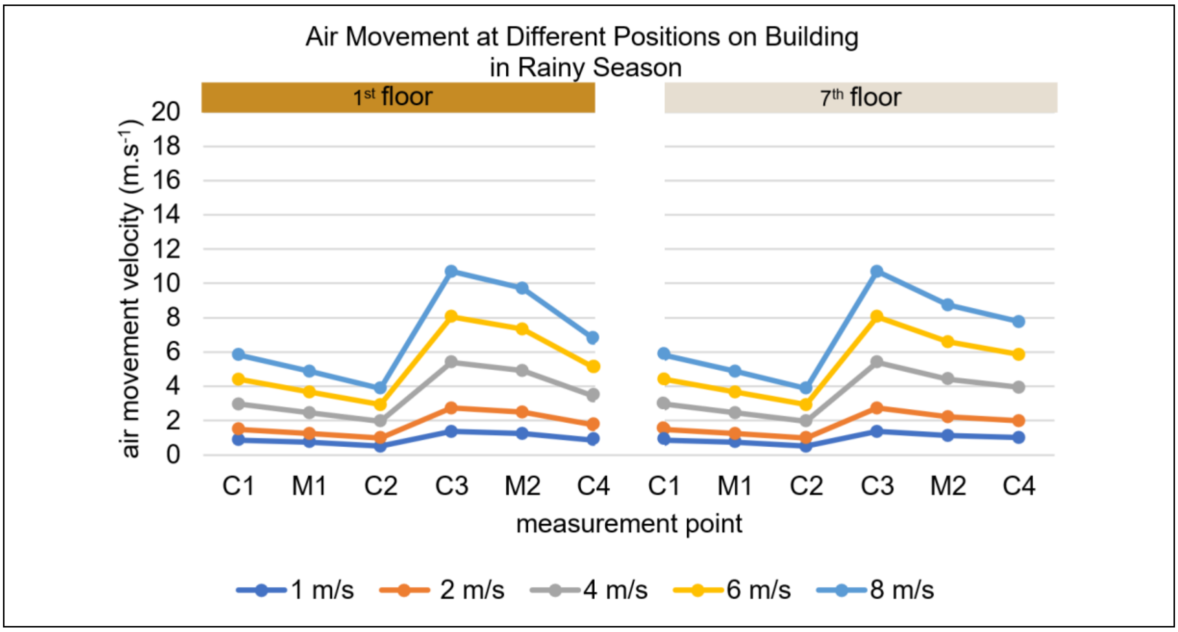


Figure 6- 12 Air movement at different positions on building in rainy season

In winter, the wind regularly comes from north direction. The data in Figure 6- 13 were obtained from CFD simulations in section 6.2.1.3. Figure 6- 13 shows that the shift in the initial wind speed resulted in the same pattern of changes of air movement. On windward wall, the air movement velocity differences between M1 on bottom and top floor were more obvious at higher wind speeds, which were 0.43 m. s^{-1} and 3.41 m. s^{-1} for wind speed of 1 m.s^{-1} and 8 m.s^{-1}, respectively. However, there was no different velocity between bottom and the top floor of both C1 and C2. On the leeward wall, the air movement velocity at any measurement points had close value.

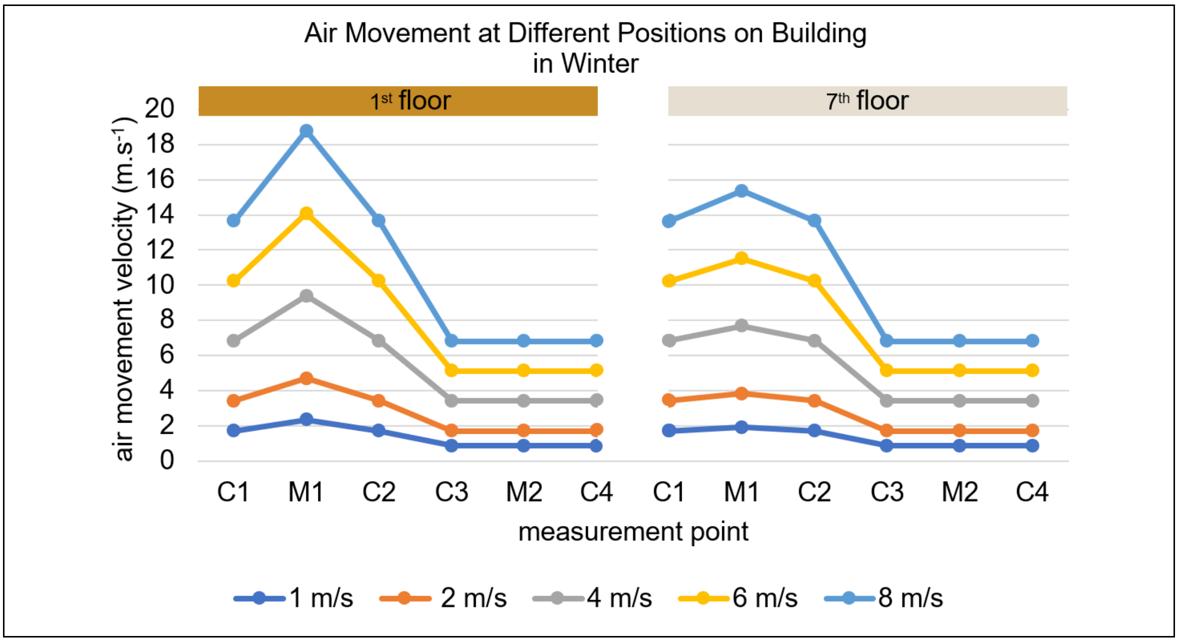


Figure 6- 13 Air movement at different positions on building in winter

Inline flow pattern occurred on the building envelope in summer and winter while oblique flow occurred on the building envelope in rainy season. The flow pattern led to the higher velocity on windward wall in summer (M2) and winter (M1) than the windward wall in rainy season (C3) (illustrated in Figure 6- 11 to Figure 6- 13). The velocity of the middle room position of the windward wall of the building in summer and winter was higher than the corner on the same side. Additionally, velocity at the middle building position of the bottom floor was higher than the top floor. However, velocity of leeward (C3, M2, C4) was the same value at any room positions. In rainy season, there was less difference in the velocity between bottom and the top floor.

6.2.3 Summary wind speed and position on building

In winter and summer, windward wall of building had greater air movement due to the direct exposure of initial wind. The air movement on the windward wall reached up to 235% of the original wind speed, indicating a significant wind force impact the wall surface. The leeward wall had lower air movement as a result of sheltered area. The air movement velocity on the leeward wall surface was approximately 86% of the original wind speed. On the other hand, in rainy season, air movement on the windward wall surface had 125% of the originated wind speed due to obliqued flow. Eddy was created at the corner of building resulting in the lower air movement value on building corners. Varying the initial wind speed created the consistent pattern of air movement changing. The air movement at opposite orientation (with same wind speed) behaved the same. The simulation for summer (south wind) will be applied but with opposite orientation to winter (north wind).

In conclusion, air movement velocity at different room locations in building, such as corner or middle room and height of the room, varied depending on wind direction and wind speed. It is crucial to take the potential wind speed and direction into account when designing building, especially in passive design.

6.3 Building height and Road width

Further details regarding the methodology can be found in Chapter 3.5.2.

This section will analyse the effect of road width to building height ratio for the key seasons (summer - south wind, winter – north wind and rainy season – south-west wind). The CFD analysis of same ratio of road width to building height are in section 6.3.1, while the varying ratios considered for 4 floors building and 8 floors building are in section 6.3.2. Measurement locations (C_x1, C_x2, C_y1, C_y2, M_x, and M_y) of this section were shown in Figure 3-14.

6.3.1 CFD of the same ratio of road width to building height

This section provides the results of CFD exploration, utilising the same ratio of road width to building height (a ratio of 0.55). The exploration aims to compare how the ratio affects airflow patterns at different measurement points of the building surfaces.

This comparison will be carried out in two parts, which are south and winter (Section 6.3.1.1) and rainy season (Section 6.3.1.2). Figure 6- 14 illustrates three cases of same ratio of road width to building height (0.55).

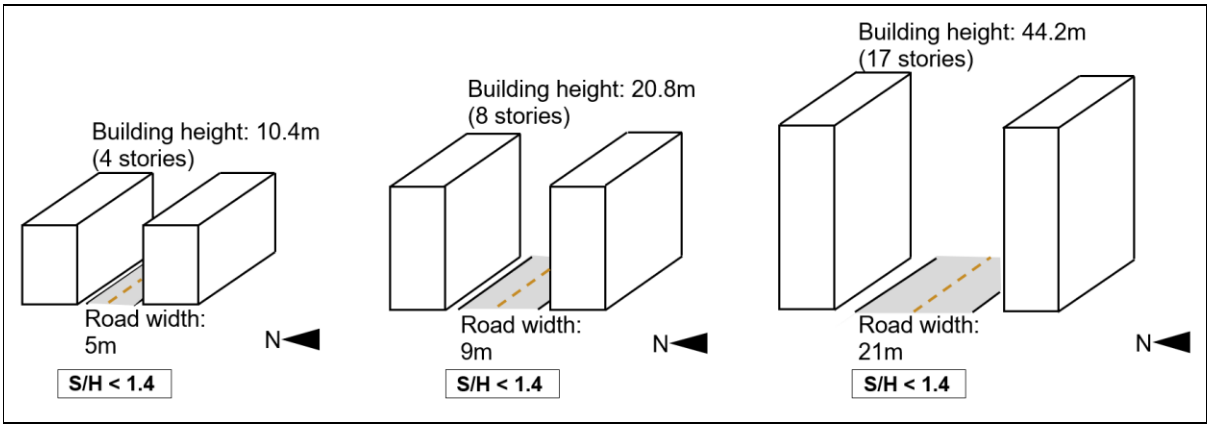


Figure 6- 14 three cases of same ratio of road width to building height
(Source: Author)

6.3.1.1 Summer and winter

Regarding the CFD simulation results in Section 6.2.1, the air movement at opposite orientation (with same wind speed) behaved the same. The simulation for summer (south wind) will be applied but with opposite orientation to winter (north wind).

This investigation provided CFD analysis of wind speed 1 $m.s^{-1}$ and 6 $m.s^{-1}$ based on the minimum and maximum of typical wind speed. The details of CFD results were visualised for 6 $m.s^{-1}$ because air movement pattern exhibited significantly clearer more than 1 $m.s^{-1}$. The visualisations represented only summer; otherwise, opposite orientation would apply for winter.

For all the road width and wind speed options analysed:

- The wind impinged perpendicularly on the south of the building.
- The south building reduced the air velocity and created a vortex inside the street canyon.

- Air movement at any measurement points at 1st floor level (3.6m high) and the top floor (8.8 m high, and 19.20 m high for 4 and 8 floors building, respectively) of these buildings in the street canyon behaved the same. However, for 21 m road width, air movement behaved differently due to the wider road causing the wind to impinge on both corners of the north building. Air movement of same ratio of road width to building height was summarised in Table 6- 4.

Table 6- 4 summary of air movement in summer and winter for same road width/ building height ratio (0.55)

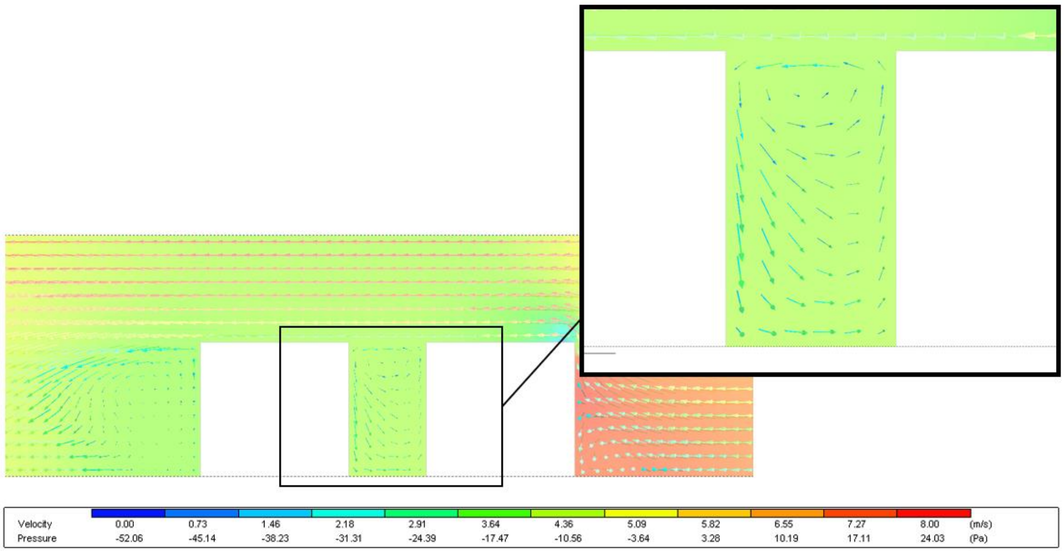
		average wind speed				air speed ratio (top floor : bottom floor)		comparison to average wind speed (%)
		initial wind speed 1 $m.s^{-1}$		initial wind speed 6 $m.s^{-1}$		initial wind speed 1 $m.s^{-1}$	initial wind speed 6 $m.s^{-1}$	
		1st floor	top floor	1st floor	top floor	average	average	
road width	5m	0.68	0.68	4.07	4.07	1.00	1.00	-32.08%
	9m	0.86	0.86	5.04	5.04	1.00	1.00	-15.00%
	21m	1.23	1.46	5.99	7.32	1.19	1.22	22.81%

The air movement velocity between such buildings was reduced approximately 32% for road width 5 m and 0.68 $m. s^{-1}$ and 15% for road width 9 m. Air movement at both 1st floor and top floor level were similar for road width of 5 m and 9 m (see Figure 6-15). However, for road width 21 m, average velocity between such buildings was approximately 23% higher air movement velocity than initial wind speed. The air movement at both corners (at C_x1 and C_x2) of the north building on the top floor was higher than other measurement points on the same floor level (see Figure 6- 16). This is because this road width induced the wind to impinge at the corner of the north building (see Figure 6- 17).

Building on either side of the road performed as barriers, which resulted in canyon effect. Skimming flow region occurred in the space between the buildings of all road width in this section. This is because air from initial wind flowed over the buildings. The air movement close to the buildings' surface characterised the flow to move along building surface. The surrounding flow in the region then transitioned into turbulent flow (see Figure 6- 15). Even though all cases in this section had same ratio of road width to building height, the wider road allowed more air to be dispersed in the space between the buildings. The presence of skimming flow in the space between such buildings needs to be taken consideration when designing and simulation building. This is because it might result in differing wind direction pattern from initial wind speed.

Road width 5 m (view from the west)

(see a legible CFD scale bar in Figure 6- 1)



Road width 9 m (view from the west)

(see a legible CFD scale bar in Figure 6- 1)

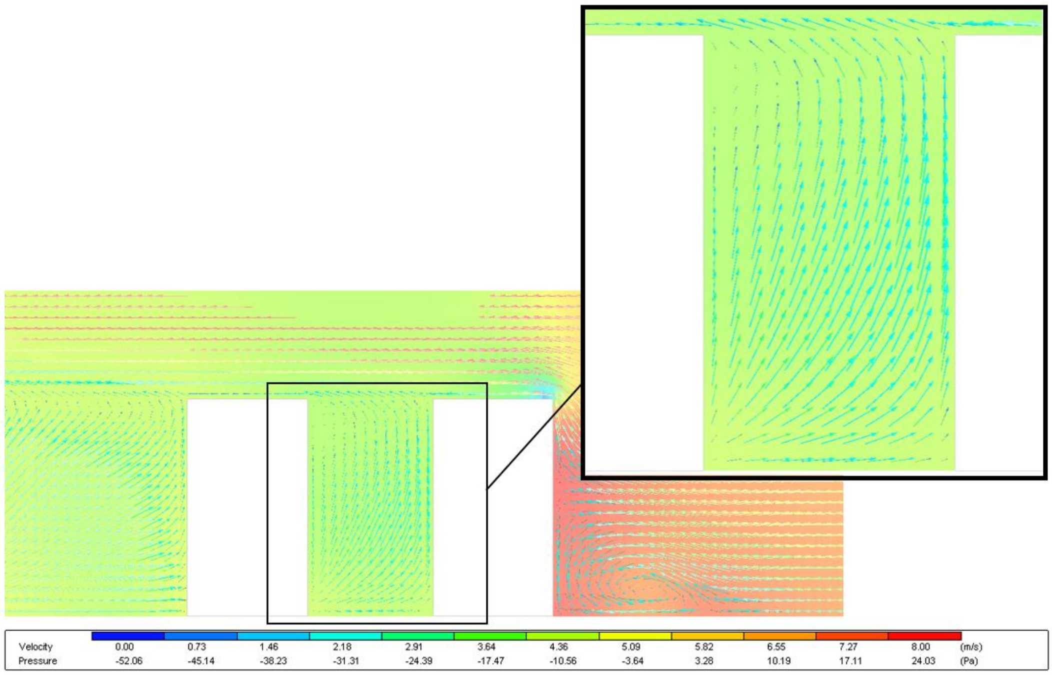
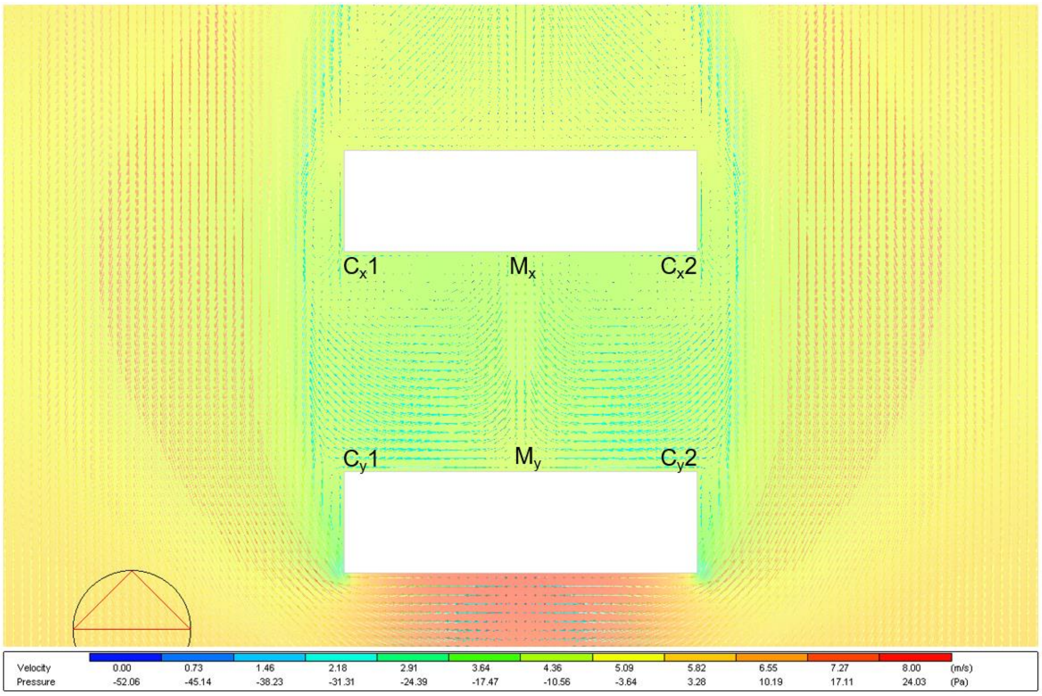


Figure 6- 15 Air movement at the space between two buildings in summer with 5m and 9m road width with initial wind speed at 6m.s^{-1}

at 1st floor level (see a legible CFD scale bar in Figure 6- 1)



at 16th floor level (see a legible CFD scale bar in Figure 6- 1)

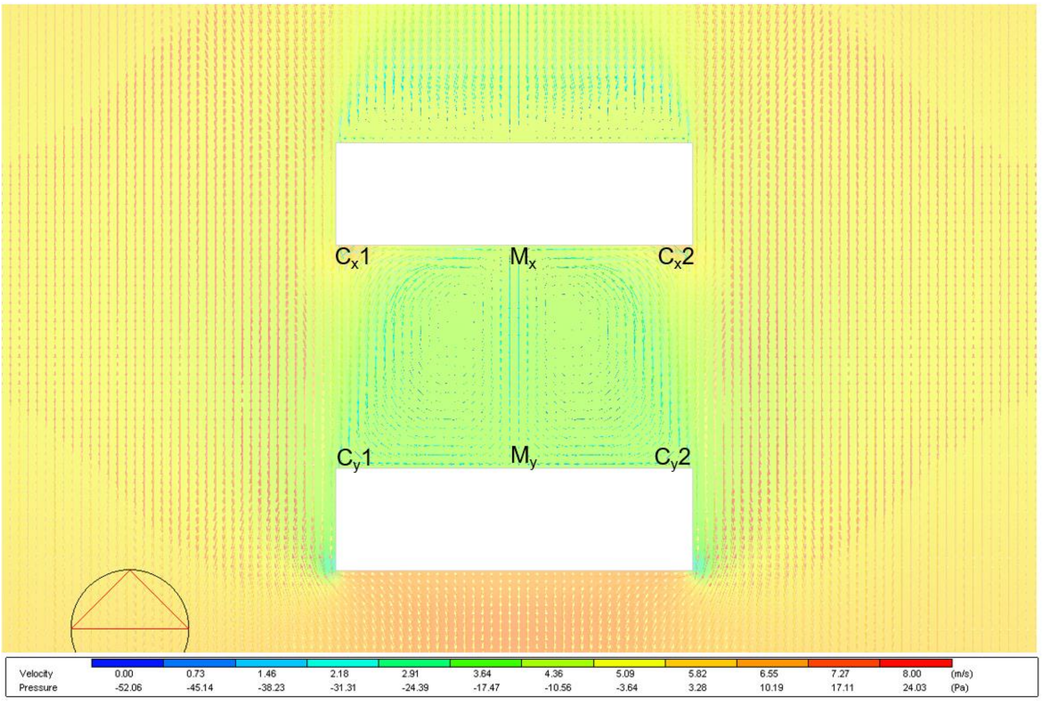


Figure 6- 16 Air movement at the space between two buildings in summer with 21m road width and initial wind speed at 6m.s^{-1}

Road width 21 m (view from the west) (see a legible CFD scale bar in Figure 6- 1)

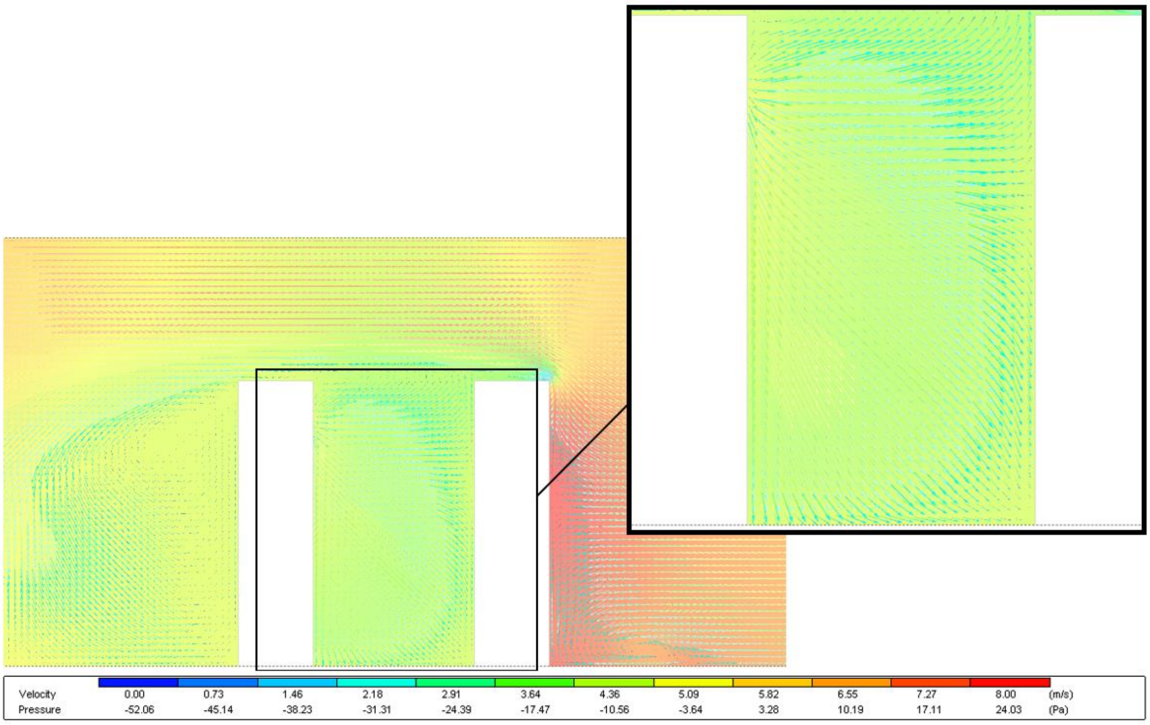
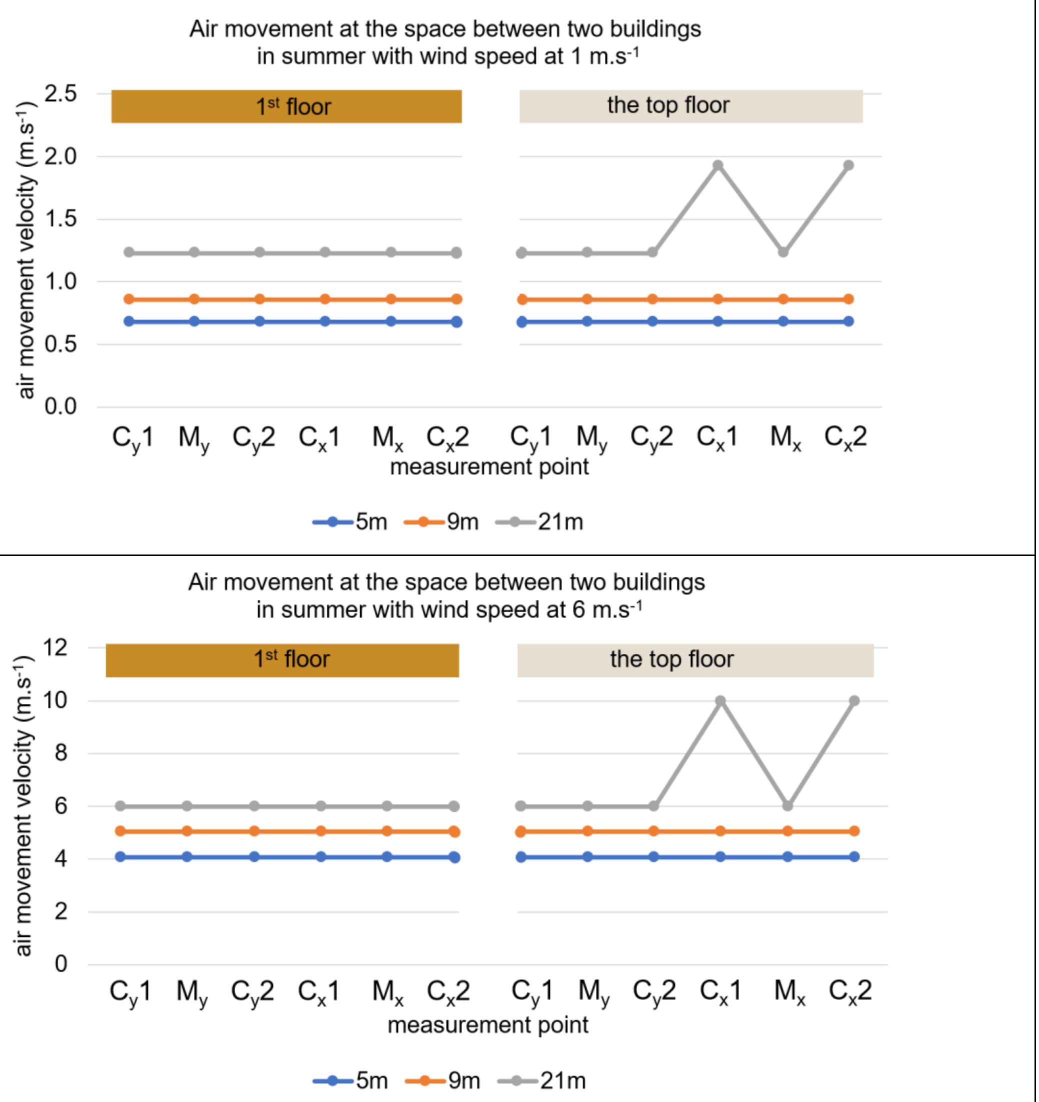


Figure 6- 17 Air movement at the space between two buildings in summer with 21m road width and initial wind speed at 6m.s^{-1}

6.3.1.1.1 Summary of the air movement at the space between two buildings at the same road width/ building height ratio (0.55) in summer

In summer, the wind mainly flows from south direction. Based on the CFD results, even though the ratio of road width to building height were the same, the wider road width led to higher air velocity. There was no different air movement between the bottom and the top floor for 5m and 9 m road width because the wind obstruction of the south building. For 21m road width, air movement behaved the same at any measurement points at the 1st floor, however the wind could interfere directly at the corners of the north building on the top floor. Thus, the interference resulted in the higher velocity than other measurement points. (see Figure 6- 18)

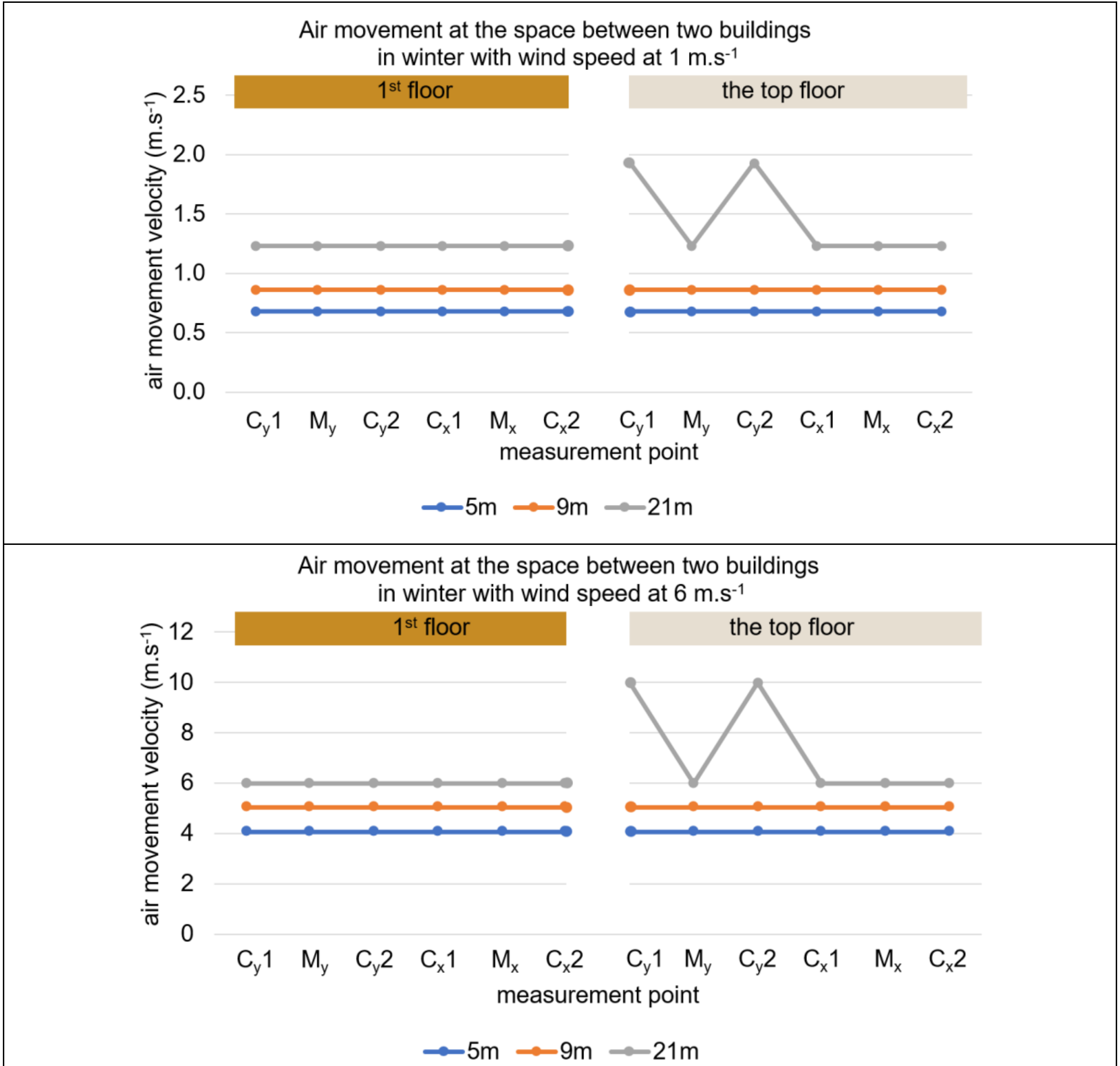


*The locations (C_x1, C_x2, C_y1, C_y2, M_x, and M_y) are defined in Chapter 3.5.2 (Figure 3-14)

Figure 6- 18 Air movement velocity at the space between two buildings in summer

6.3.1.1.2 Summary of the air movement at the space between two buildings at the for same road width/ building height ratio (0.55) in winter

In winter, the wind mainly flows from north direction. The air velocity in this season can be estimated from the CFD of summer results. The wider road width led to the higher air velocity, while the ratio of road width to building height was the same. There was no different air movement between the bottom and the top floor for 5m and 9 m road width because the wind obstruction of the south building. For 21m road width, air movement behaved the same at any measurement points at the 1st floor, however the wind could interfere directly at the corners of the north building on the top floor. Thus, the interference resulted in the higher velocity than other measurement points. (see Figure 6- 19)



* The locations (Cx1, Cx2, Cy1, Cy2, Mx, and My) are defined in Chapter 3.5.2 (Figure 3-14)

Figure 6- 19 Air movement at the space between two buildings in winter (Source: Author)

6.3.1.2 Rainy season

This investigation will provide CFD analysis of wind speed 1 m.s^{-1} and 6 m.s^{-1} based on the minimum and maximum of typical wind speed. The detailed information is for 6 m.s^{-1} because CFD results visualise air movement pattern more clearly than 1 m.s^{-1}.

For all the road width and wind speed options analysed:

- The wind impinged perpendicularly on south-west of the north buildings. The wind encounters the buildings in oblique angle. The wind can impinge directly at the corner (C_x1) of the north building, resulting higher velocity at this position.

- The south building reduced the air velocity and created a vortex inside the street canyon.
- Air movement at any measurement points at 1st floor level (3.6m high) and the top floor of these buildings in the street canyon behaved similarly. Air movement with same road width to building height ratio was summarised in Table 6- 5

Table 6- 5 summary of air movement in rainy season for same road width/ building height ratio (0.55)

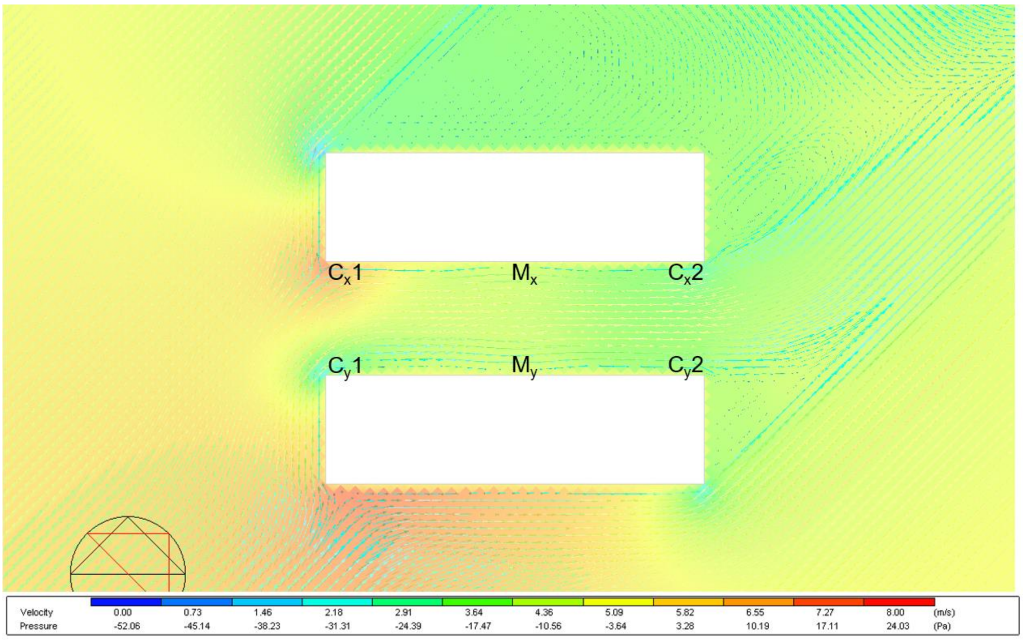
		average wind speed				air speed ratio (top floor : bottom floor)		comparison to average wind speed (%)
		initial wind speed 1 $m.s^{-1}$		initial wind speed 6 $m.s^{-1}$		initial wind speed 1 $m.s^{-1}$	initial wind speed 6 $m.s^{-1}$	
		1st floor	top floor	1st floor	top floor	average	average	
road width	5m	0.73	0.73	4.34	4.34	1.00	1.00	-27.42%
	9m	0.90	0.92	3.99	4.11	1.02	1.03	-20.76%
	21m	1.08	1.05	5.65	5.36	0.98	0.95	-0.94%

For both road width of 5m and 9m, the skimming flow regime occurred at both the west corner of the south building (C_y1) and the east corner of the north building (C_x2), which resulted in low air movement velocity. At M_y, C_y2 measurement points, there was no air velocity difference between the 1st floor and the top floor. However, at middle position of the north building (M_x), the air movement velocity at the top floor was higher than the bottom floor (see Figure 6- 20, Figure 6- 21).

On the other hand, for road width of 21 m, wind impinged directly at the corner (C_x1) and the middle (M_x) of the north building which brough about higher velocity at these positions. Meanwhile, the skimming flow regime occurred at both the west corner of the south building (C_y1) and the east corner of the north building (C_x2) resulting in low air movement velocity. At M_y, C_y2 measurement points, there was slightly different air velocity between the 1st floor and the top floor for initial wind speed. (see Figure 6- 22, Figure 6- 23)

While the ratio of road width to building height were the same, air movement at the measurement points for road width of 21 m was similar to the initial wind speed. However, for other road widths, air movement at the measurement points between the buildings was lower more than 20 % from the initial wind speed. This is because the buildings acted as the obstructions to wind flow, which forced the air in the space between the buildings to change direction. The deflected wind along the buildings formulated vortex in airflow patterns.

at 1st floor level (see a legible CFD scale bar in Figure 6- 1)



at 7th floor level (see a legible CFD scale bar in Figure 6- 1)

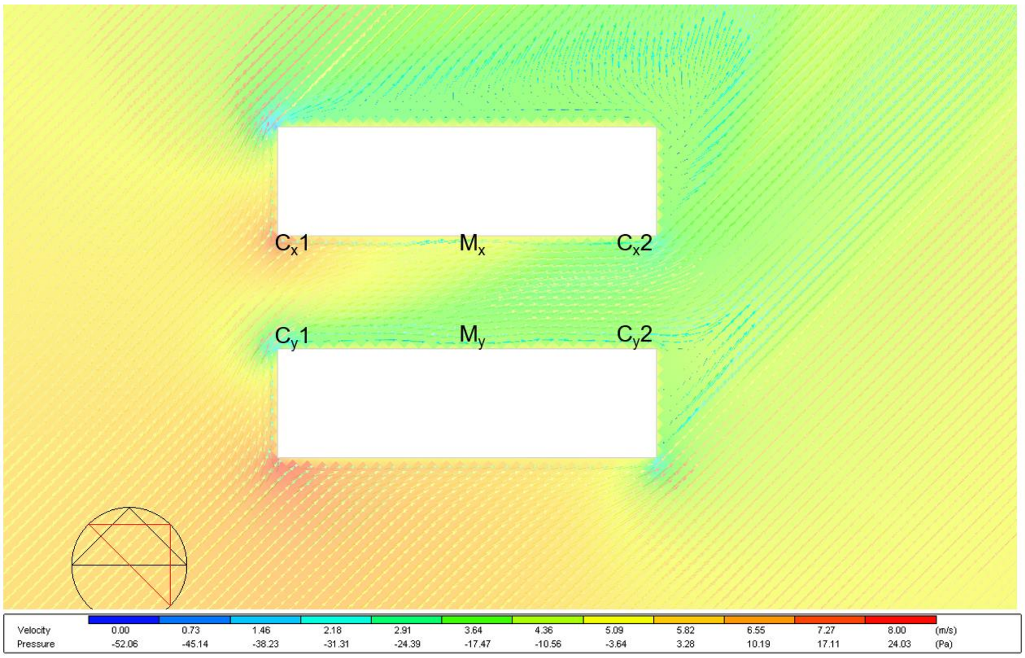
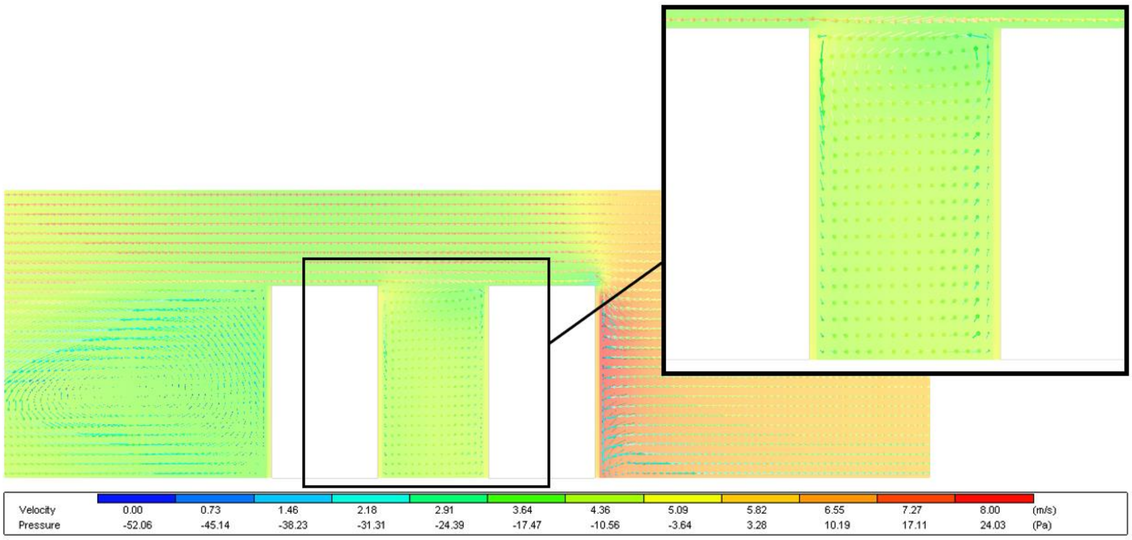


Figure 6- 20 Air movement at the space between two buildings in rainy season with 9m road width and initial wind speed at 6m.s^{-1}

view from the west (from above) (see a legible CFD scale bar in Figure 6- 1)



axonometric view (from above) (see a legible CFD scale bar in Figure 6- 1)

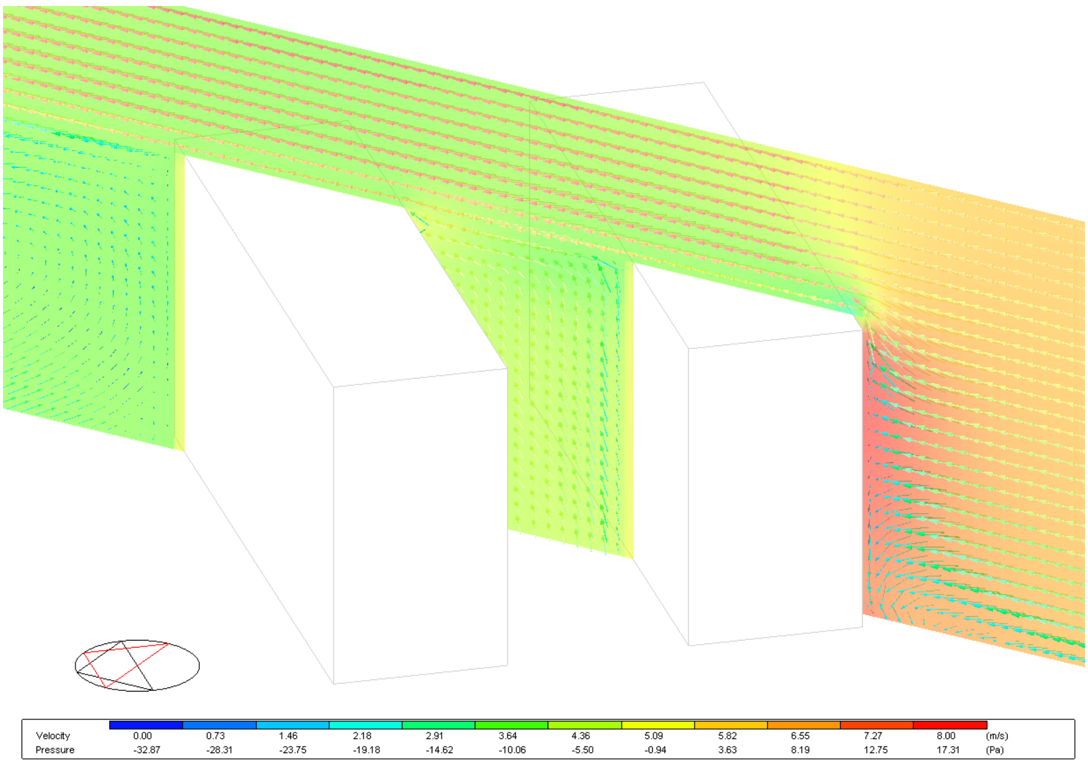
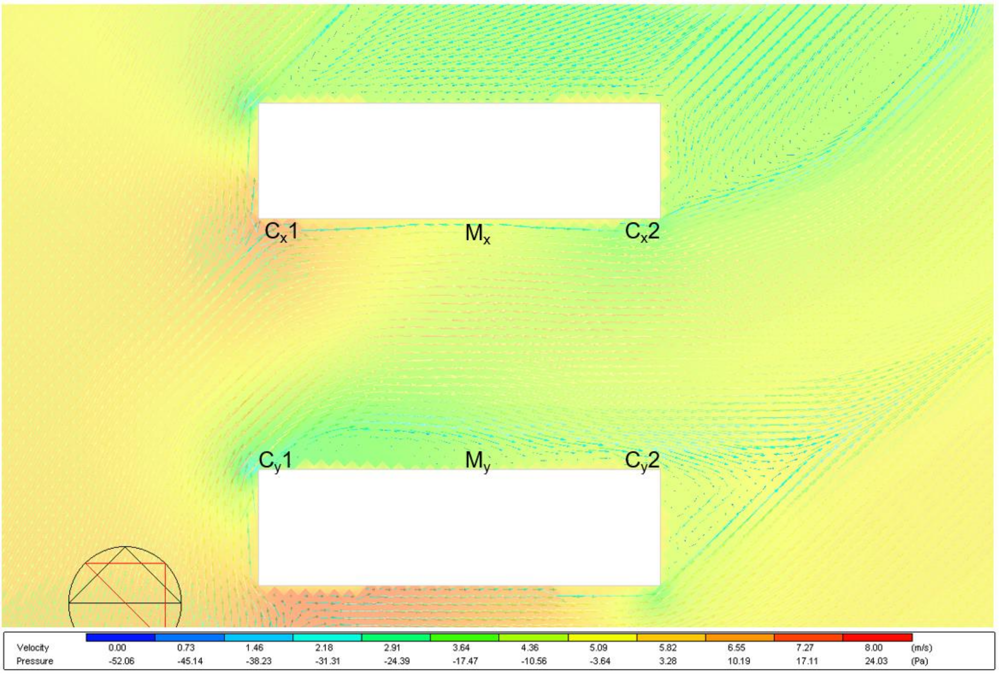


Figure 6- 21 Air movement at the space between two buildings in rainy season with 9m road width and initial wind speed at 6m.s^{-1}

at 1st floor level (see a legible CFD scale bar in Figure 6- 1)



at 16th floor level (see a legible CFD scale bar in Figure 6- 1)

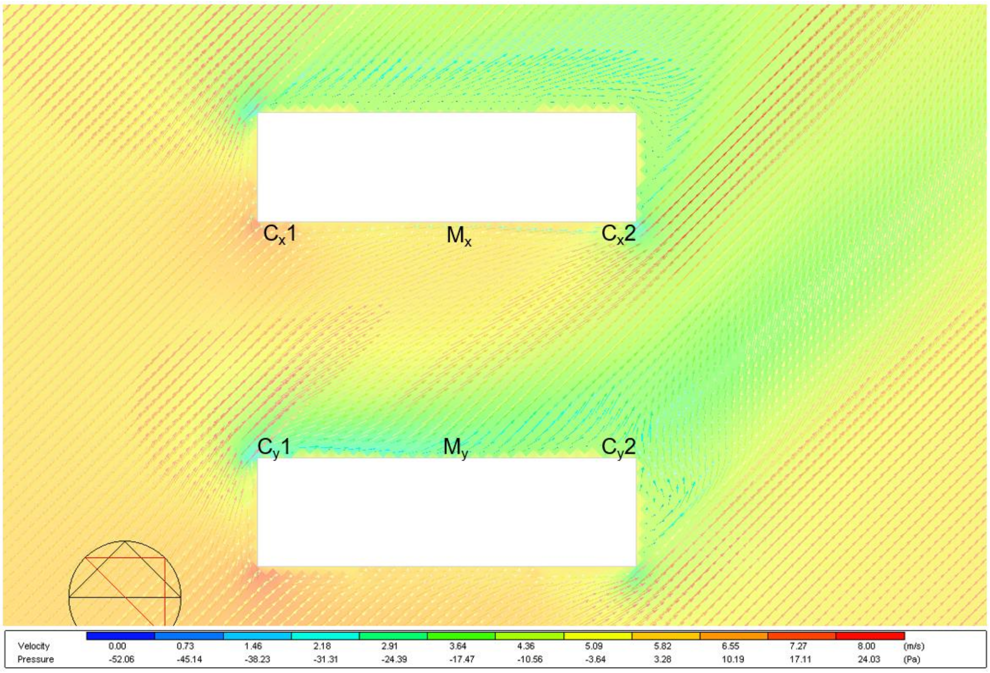
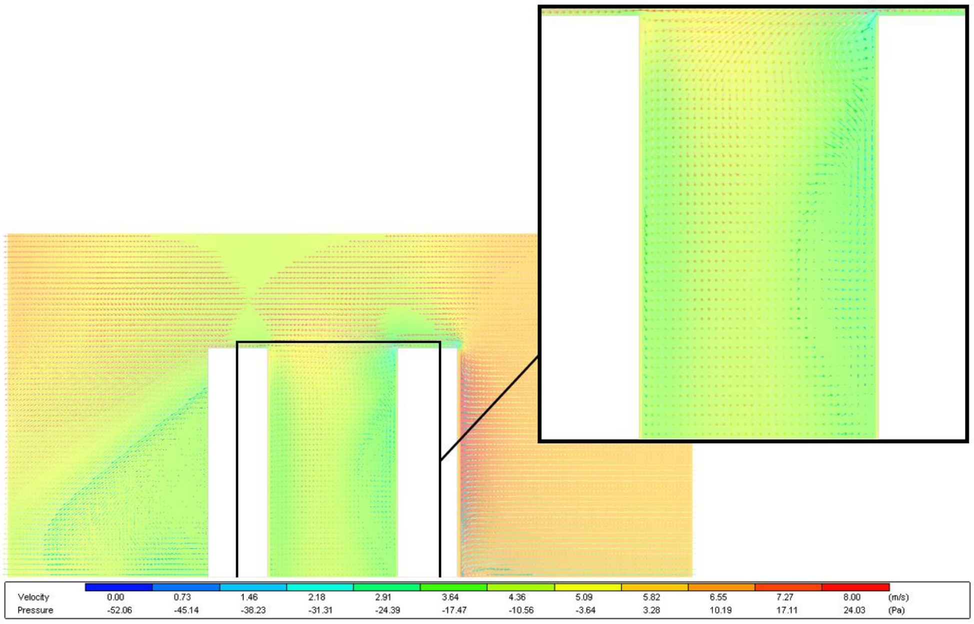


Figure 6- 22 Air movement at the space between two buildings in rainy season with 21m road width and initial wind speed at 6m.s^{-1}

view from the west (from above) (see a legible CFD scale bar in Figure 6- 1)



axonometric view (from above) (see a legible CFD scale bar in Figure 6- 1)

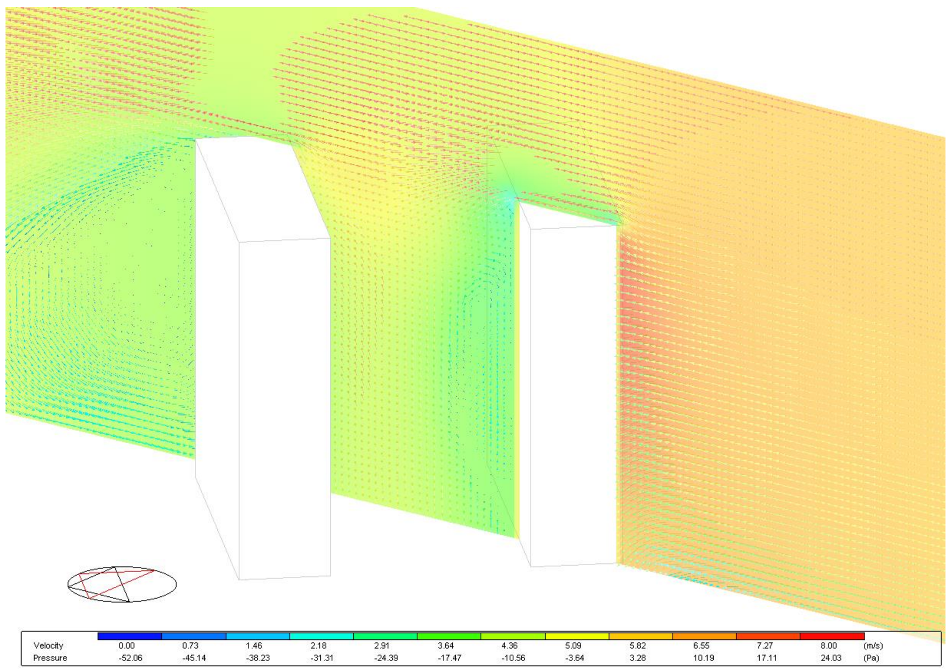
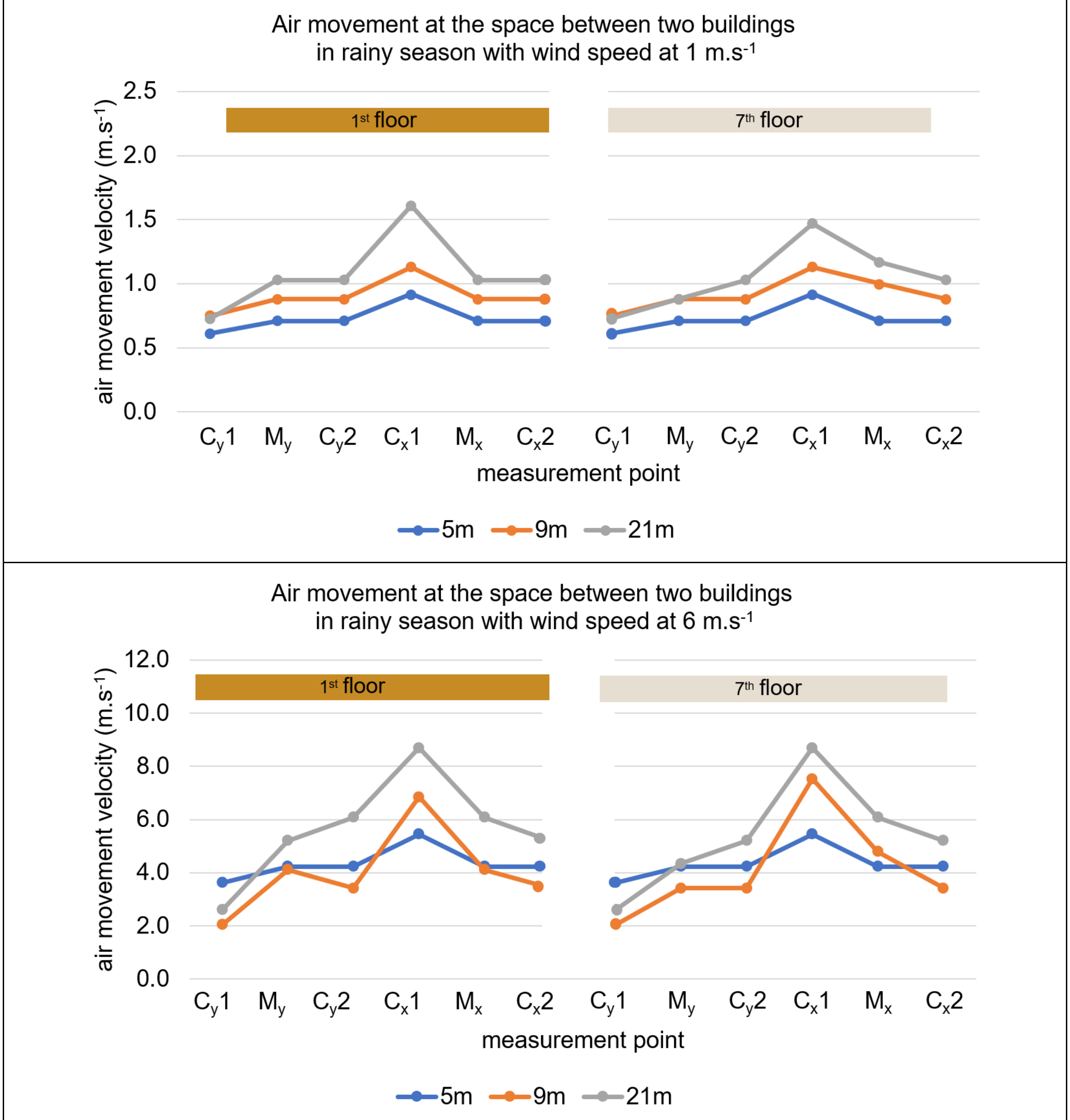


Figure 6- 23 Air movement at the space between two buildings in rainy season with 21m road width and initial wind speed at 6m.s^{-1}
(Source: Author)

6.3.1.2.1 Summary of the air movement at the space between two buildings at the same road width/ building height ratio (0.55) in rainy season

In rainy season, due to the oblique angle of the wind on the buildings, there was a fluctuation in the air movement velocity. This is because the wind can impinge directly on some positions of the buildings which caused significant difference in wind pressure along the street. (see Figure 6- 24).



The locations (C_x1, C_x2, C_y1, C_y2, M_x, and M_y) are defined in Chapter 3.5.2 (Figure 3-14)

Figure 6- 24 Air movement at the space between two buildings in rainy season

6.3.1.3 Summary of CFD of same road width/ building height ratio (0.55)

In summer and winter, the skimming flow regime is observed in all cases with the same aspect ratio of road width to building height (0.55). This is as expected for the same ratio of road width to building height (see Figure 3-15). The aspect ratio has a considerable influence on how the wind is channelled within the street canyon.

However, the distinct wind flow pattern emerges at the leeward building corners due to the aspect ratio of the building length to height. A larger aspect ratio indicates a longer building length relative to building height, which provides obstructions to the wind flow. For example, the air movement at the corner of second wind-impinged building with 21 m road width had higher velocity compared to the same measurement points of the building with the road width of 5 m.

In rainy season, due to the oblique angle of the wind on the buildings, there was a fluctuation in the air movement velocity because the wind can impinge directly on some positions of the buildings which created significantly different wind pressure and along the street. For both 1 $m.s^{-1}$ and 6 $m.s^{-1}$ initial wind speed, the air movement at 5 m road width at each building location between lower floor and the top floor had similar pattern. This is as expected for the same ratio of road width to building height (see Figure 3-15). In contrast, for both 9 m and 21 m road width, the air movement at each particular point of 1 $m.s^{-1}$ initial wind speed compared to 6 $m.s^{-1}$ initial wind speed behave different pattern. This is likely because the distances of the road are slightly different, so it does not behave the same as when wind direction is normal or parallel to the canyon.

6.3.2 CFD of varying aspect ratio of building height to road width

Further details regarding the methodology can be found in Chapter 3.5.2.2

This section provides CFD results of varying aspect ratio of building height to road width by comparison of the air movement of same building height with different road width. This section is divided into two sub-sections, which are 4 floors (8.8 meters high) with different road widths (Section 6.3.2.1) and 8 floors (19.2 meters high) with different road widths (Section 6.3.2.2). Figure 6- 25 illustrates five cases of varying aspect ratio to road width.

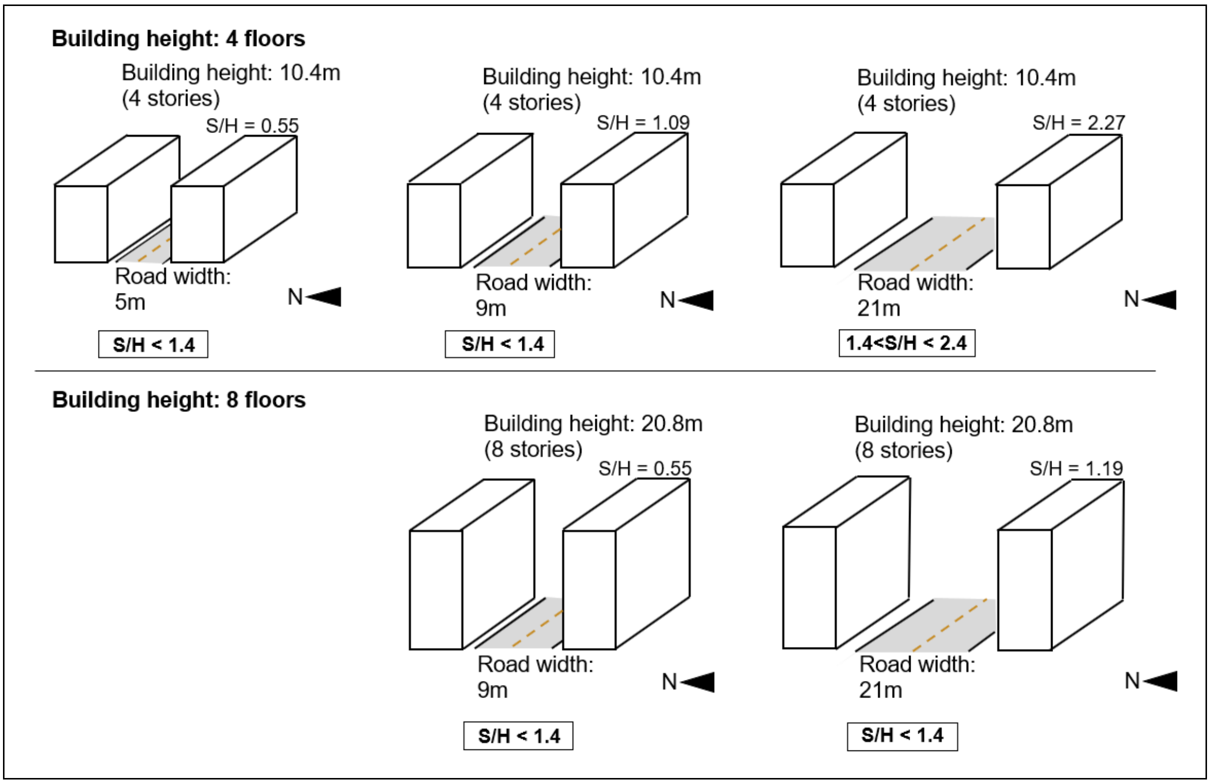


Figure 6- 25 five cases of varying aspect ratio of building height to road width (Source: Author)

6.3.2.1 Building height: 4 floors

6.3.2.1.1 Summer and winter

Regarding the CFD simulation results in Section 6.2.1, the air movement at opposite orientation (with same wind speed) behaved the same. The simulation for summer (south wind) will be applied but with opposite orientation to winter (north wind).

In summer, the wind impinged perpendicularly on the south of the building, which resulted in wake interference effect occurring in the space between such two buildings. Air movement at any measurement points at 1st floor level (3.6m high) and the top floor (8.8 m high) of these buildings in the street canyon behaved similar.

In summer and winter, air movement at the same measurement locations on the first and the top floor were slightly different. In all cases, air movement was approximately 34% lower than initial wind speed. The same trends were being experienced at all six measurement points for air movement relating to 5m (ratio of road width to building height: 0.55) and 9m roads (ratio of road width to building height: 1.09). This is as expected for the same ratio of road width to building height for ratio below 1.4 (See more detail in Section 3.5.1.2.1). However, 21m road width (ratio of road width to building height: 2.27) occurred some different responses at points C_x1 and C_x2 for summer (see Figure 6- 27) and point C_y1 and C_y2 for winter (see Figure 6- 28). This is because the wider space between the buildings encouraged the air to disperse and impinge on the corners of the buildings. As a result of wider space reducing funnelling effect, average air velocity in the space between buildings of 21 m to be lower than the space of 5m. In addition, eddies tend to appear prominently when the distance between such buildings becomes wider (Figure 6- 26).

Table 6- 6 summary of air movement in summer and winter for same building height (4 floors) with different road width

4 storey buildings		average wind speed				air speed ratio (top floor : bottom floor)		comparison to average wind speed (%)
		initial wind speed 1 m.s^{-1}		initial wind speed 6 m.s^{-1}		initial wind speed 1 m.s^{-1}	initial wind speed 6 m.s^{-1}	
		1st floor	top floor	1st floor	top floor	average	average	
road width	5m	0.68	0.68	4.07	4.07	1.00	1.00	-32.08%
	9m	0.65	0.65	3.88	3.88	1.00	1.00	-35.17%
	21m	0.63	0.66	3.71	3.92	1.05	1.06	-35.89%

CFD result of 4-storey buildings with road width of 5 m
(see a legible CFD scale bar in Figure 6- 1)

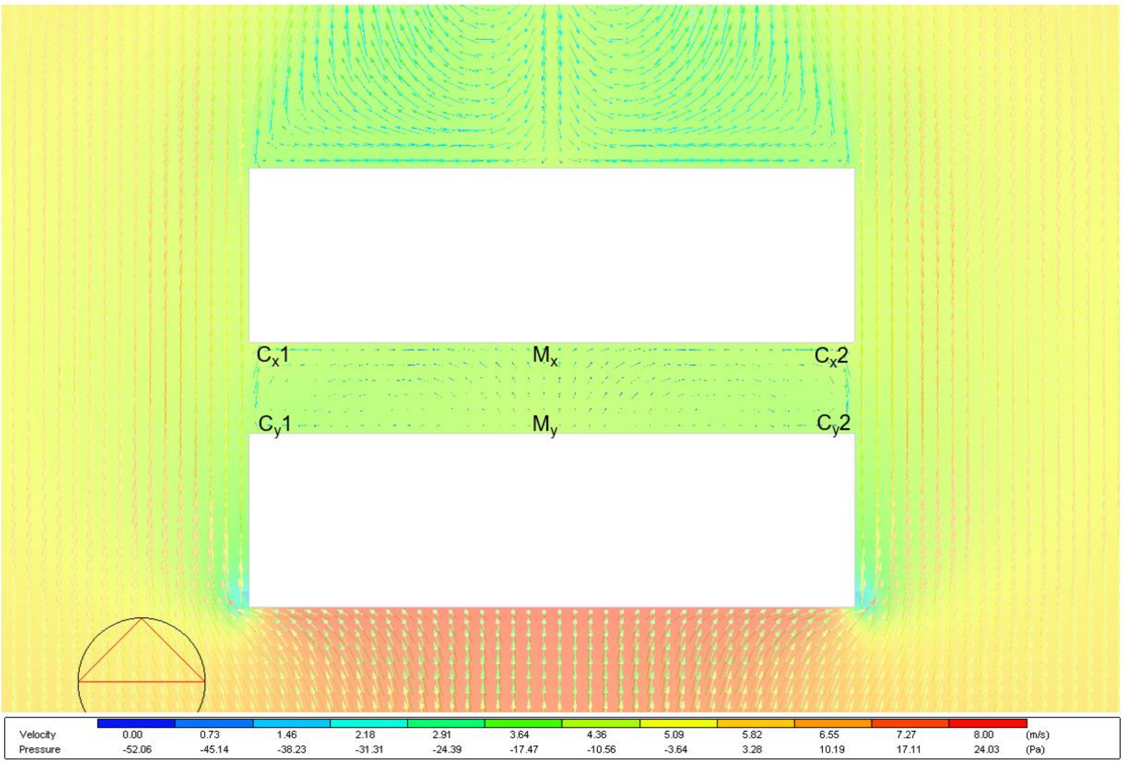


Figure 6- 26 the comparison of CFD results between 4 storey buildings with road width of 5 m and 21 m

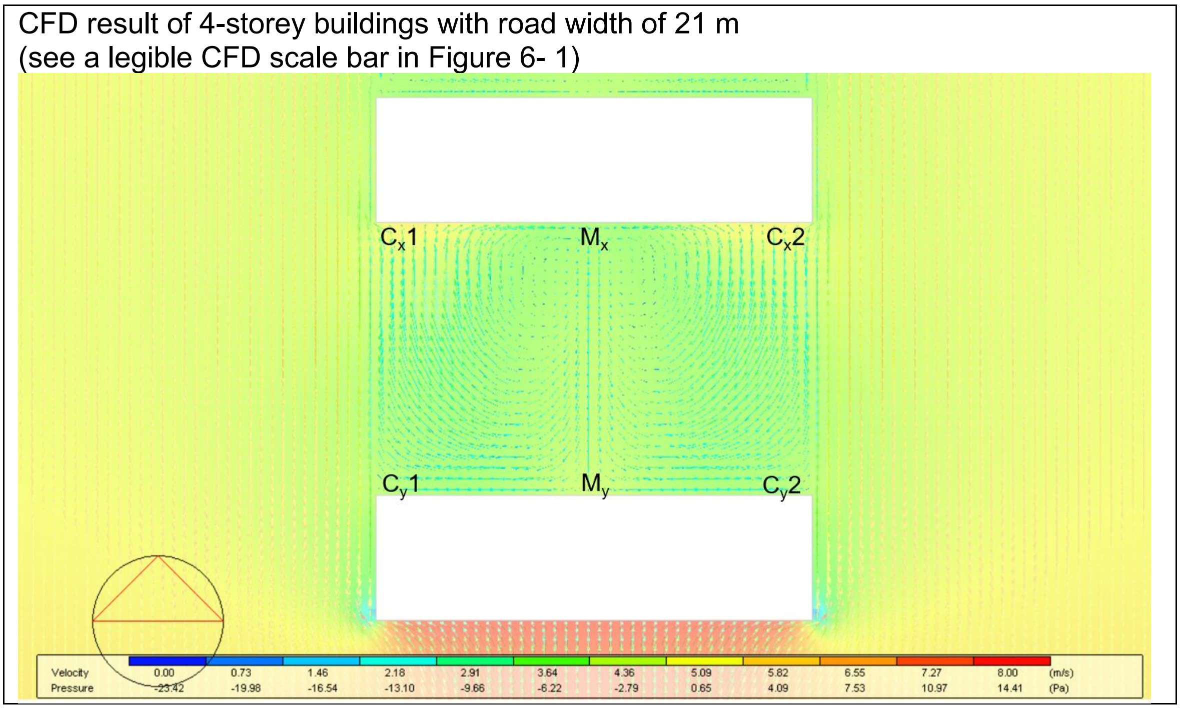


Figure 6- 26 the comparison of CFD results between 4 storey buildings with road width of 5 m and 21 m (continued)

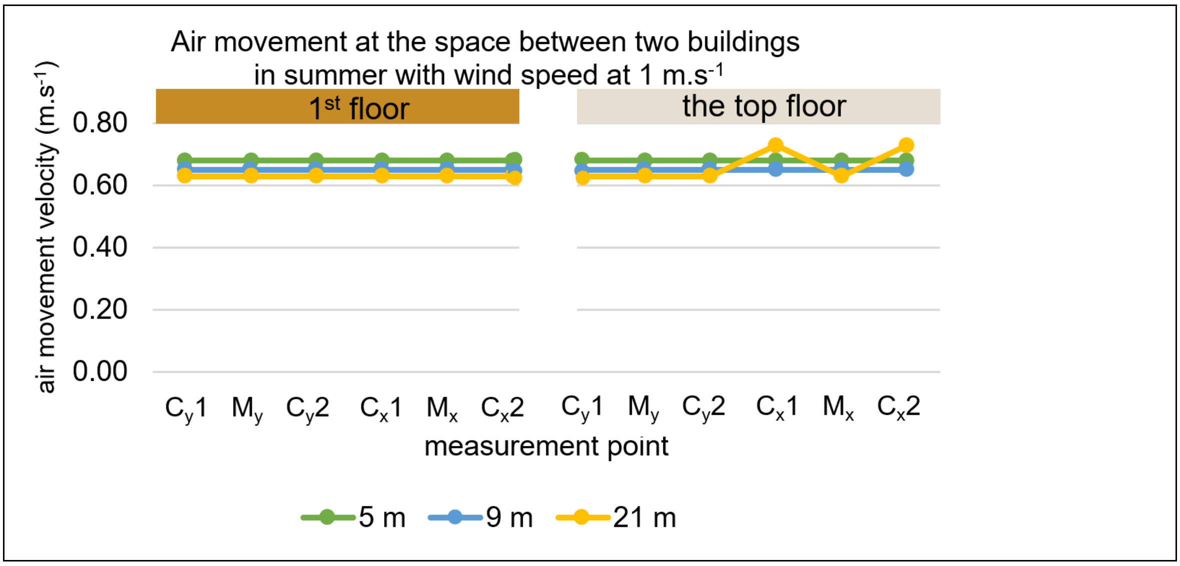


Figure 6- 27 Air movement velocity between 4-storey buildings with different road width in summer

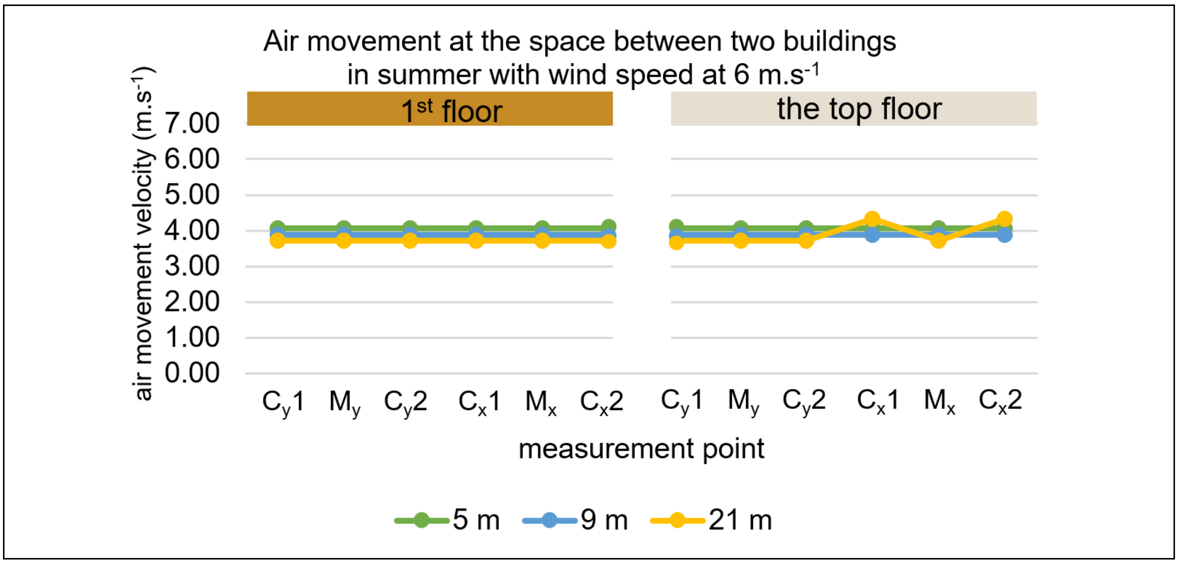


Figure 6- 27 Air movement velocity between 4-storey buildings with different road width in summer (continued)

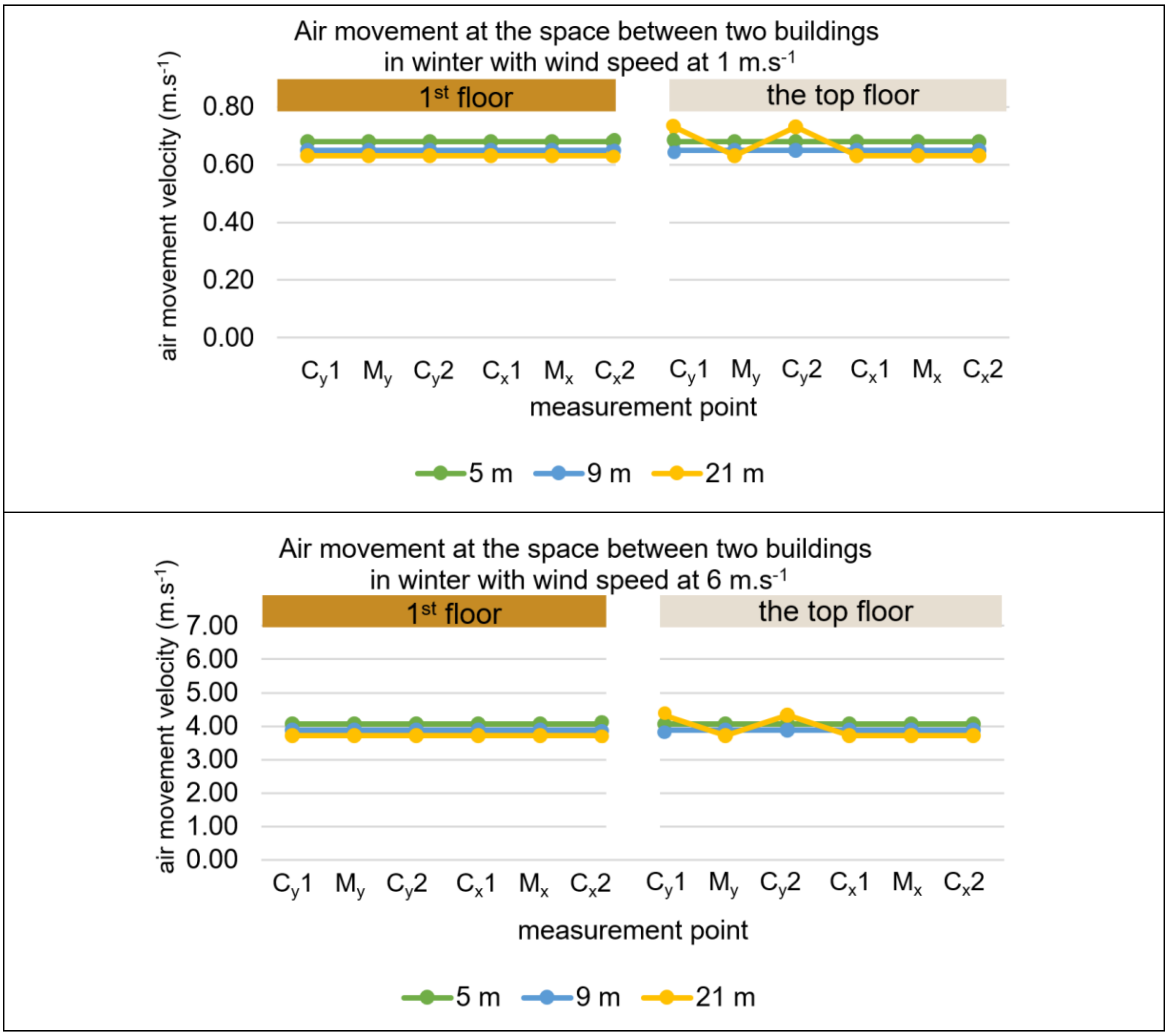


Figure 6- 28 Air movement velocity between 4-storey buildings with different road width in winter

6.3.2.1.2 Rainy season

The wind encounters the buildings in oblique angle, which impinged perpendicularly on south-west of the north buildings. There was no different velocity between lower floor (3.60 m high) and the top floor (8.8m high).

Table 6- 7 summary of air movement in rainy season for same building height (4 floors) and different road width

4 storey buildings		average wind speed				air speed ratio (top floor : bottom floor)		comparison to average wind speed (%)
		initial wind speed 1 $m.s^{-1}$		initial wind speed 6 $m.s^{-1}$		initial wind speed 1 $m.s^{-1}$	initial wind speed 6 $m.s^{-1}$	
		1st floor	top floor	1st floor	top floor	average	average	
road width	5m	0.73	0.73	4.34	4.34	1.00	1.00	-27.42%
	9m	0.68	0.69	4.00	4.00	1.02	1.00	-32.42%
	21m	0.66	0.64	3.86	3.76	0.97	0.97	-35.85%

The highest air movement velocity occurred on the west corner of the north building (C_x1) because the wind impinged directly at the corner. In addition, for road width of 21 m, wind could also strike directly on the middle of the north building façade (M_x). The presence of wind impingement on the building surface brings about higher velocity. Meanwhile, Vortices and eddies occurred at both the west corner of the south building (C_y1) and the east corner of the north building (C_x2) resulting in low air movement velocity. There was slightly different velocity between lower floor (3.60 m high) and the top floor (8.8m high). The average air movement between the buildings' space tends to be less when the space becomes broader. Due to the increased open area, air movement was less influenced because of less obstruction. In Table 6- 7, road width of 5 m had higher air velocity than road width of 21 m by approximately 9%. This is because narrower road formulates a channelling effect to accelerate the air velocity within the confined space.

In rainy season, the air movement at the space between two buildings in this season was fluctuating due to the oblique impinged wind. The wind can impinge directly on some positions of the buildings which occurred the significant different wind pressure and negative pressure along the street. The air movement between 1st floor (3.6 m high) and the top floor (8.8m high) behave similar flow pattern.

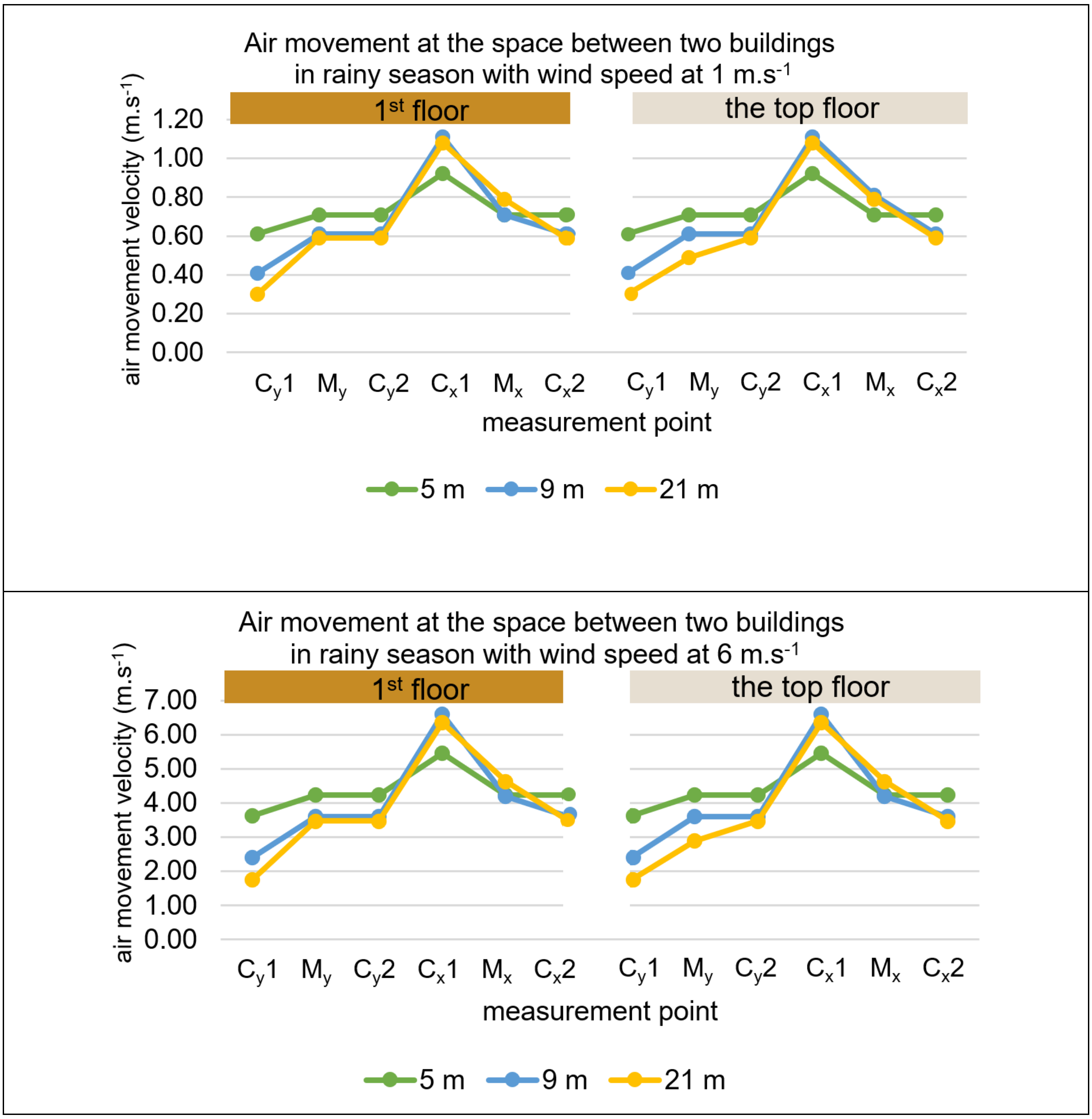


Figure 6- 29 Air movement velocity between 4-storey buildings with different road width in rainy season
(Source: Author)

6.3.2.2 Building height: 8 floors

6.3.2.2.1 Summer and winter

Regarding the CFD simulation results in Section 6.2.1, the air movement at opposite orientation (with same wind speed) behaved the same. The simulation for summer (south wind) will be applied but with opposite orientation to winter (north wind).

In summer, the wind impinged perpendicularly on the south of the building, which resulted in wake interference effect occurred in the space between such two buildings. Air movement at any measurement points at 1st floor level behaved the same as the top floor of these buildings. Air movement at any measurement points at 1st floor level (3.6m high) and the top floor (19.20 m high) of these buildings in the street canyon behaved the same.

Table 6- 8 summary of air movement in summer and winter for same building height (8 floors) and different road width

8 storey buildings		average wind speed				air speed ratio (top floor : bottom floor)		comparison to average wind speed (%)
		initial wind speed 1 $m.s^{-1}$		initial wind speed 6 $m.s^{-1}$		initial wind speed 1 $m.s^{-1}$	initial wind speed 6 $m.s^{-1}$	
		1st floor	top floor	1st floor	top floor	average	average	
road width	9m	0.86	0.86	5.04	5.04	1.00	1.00	-15.00%
	21m	0.81	0.81	4.78	4.78	1.00	1.00	-19.67%

In summer and winter, the air movement at any measurement points between 1st floor (3.6m high) and the top floor (19.20m high) behaved the same. In addition, all six measurement points of each road width also had the same trends. This is as expected for the same ratio of road width to building height (see more detail in Section 3.5.1.2.1). Air velocity between road width of 9 m and 21 m were approximately 15% and 20% respectively less than the initial wind speed. (see Figure 6- and Figure 6- 31)

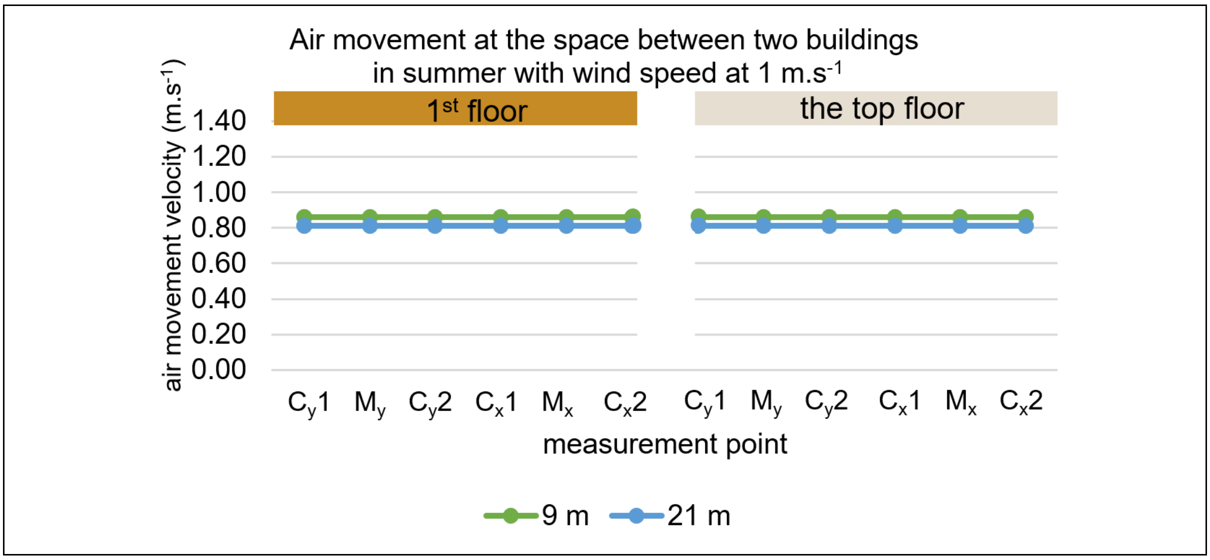


Figure 6- 30 Air movement velocity between 8-storey buildings with different road width in summer

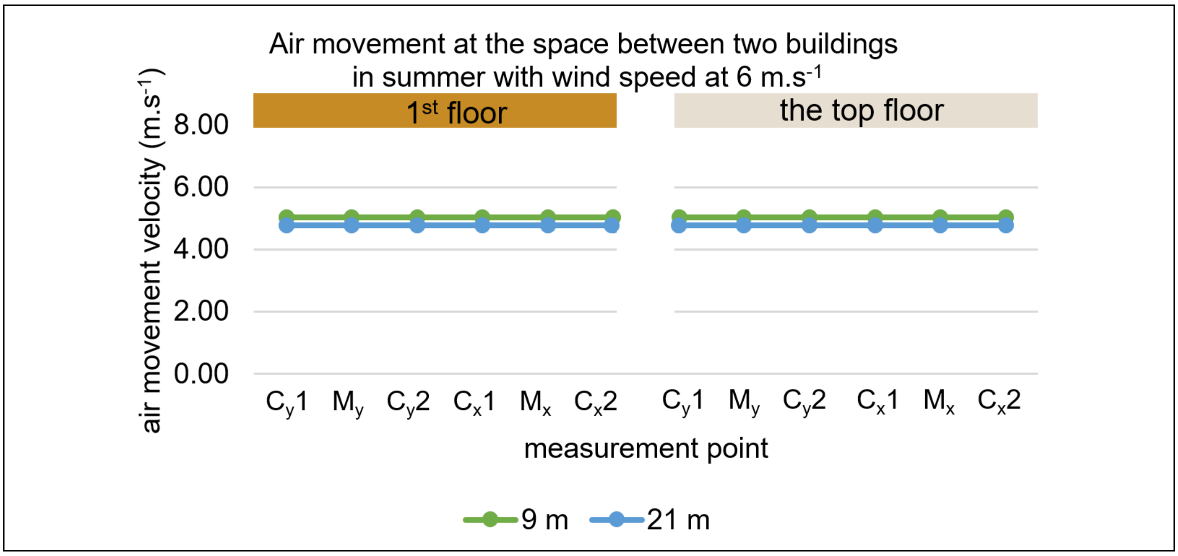


Figure 6- 30 Air movement velocity between 8-storey buildings with different road width in summer (continued)

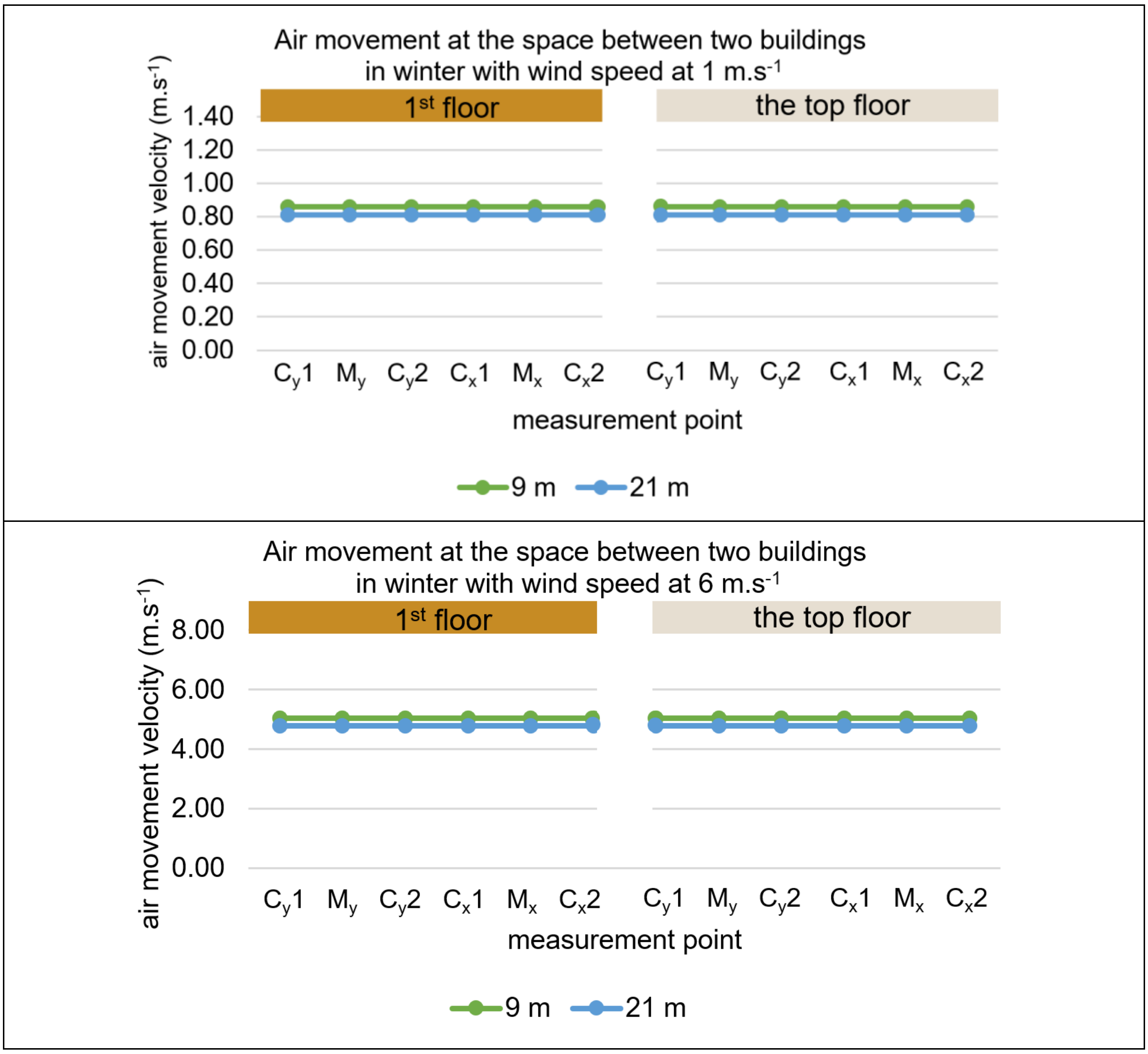


Figure 6- 31 Air movement velocity between 8-storey buildings with different road width in winter

6.3.2.2.2 Rainy season

For all the building height and wind speed options analysed, the wind encounters the buildings in oblique angle. The wind impinges directly at the south-west corner (C_x1) of the north building which bring about higher velocity at this position. Meanwhile, the skimming flow regime occurred at both the west corner of the south building (C_y1) and the east corner of the north building (C_x2), which resulted in low air movement velocity. Air movement at any measurement points at 1st floor level (3.6m high) and the top floor (19.20 m high) of the buildings within a street canyon with a width of 9 metres exhibited consistent behaviour. Similarly, in the street canyon with a width of 21 m, the airflow at any measurement points on the 1^{st} and the top floor of the buildings also behaved uniform characteristics.

Table 6- 9 summary of air movement in rainy season for same building height (8 floors) and different road width

8 storey buildings		average wind speed				air speed ratio (top floor : bottom floor)		comparison to average wind speed (%)
		initial wind speed 1 $m.s^{-1}$		initial wind speed 6 $m.s^{-1}$		initial wind speed 1 $m.s^{-1}$	initial wind speed 6 $m.s^{-1}$	
		1st floor	top floor	1st floor	top floor	average	average	
road width	9m	0.86	0.86	3.99	3.99	1.00	1.00	-23.85%
	21m	0.70	0.72	4.14	4.26	1.03	1.03	-29.49%

In rainy season, due to the oblique angle of the wind on the buildings, there was a fluctuation in the air movement velocity. This is because the wind can impinge directly on some positions of the buildings which occurred the significant different wind pressure and negative pressure along the street. The air movement between 1^{st} floor (3.6 m high) and the top floor (19.2 m high) behaved similar flow pattern for both 1 $m.s^{-1}$ and 6 $m.s^{-1}$ initial wind speed cases.

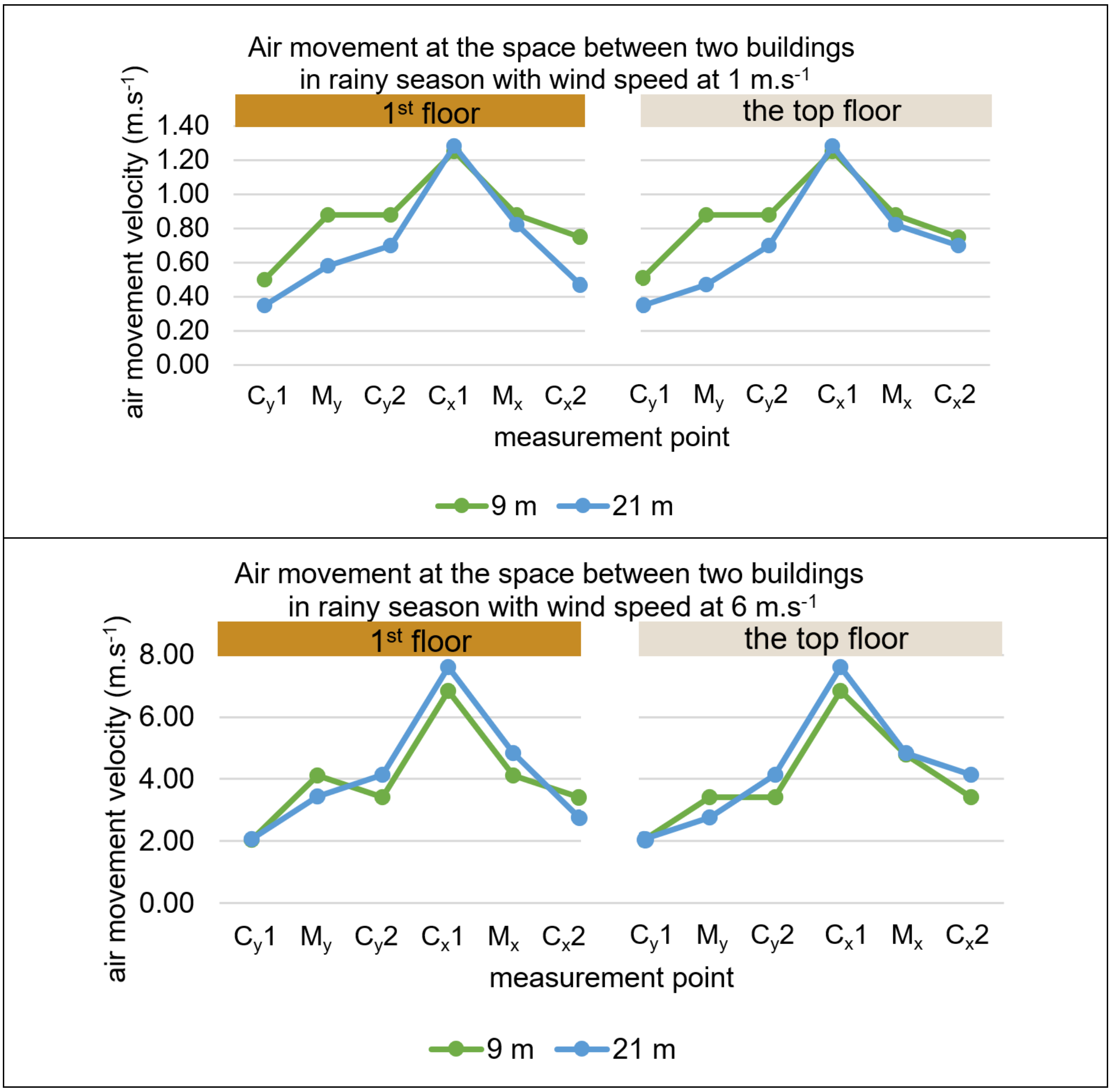


Figure 6- 32 Air movement velocity between 8-storey buildings with different road width in rainy season

6.3.2.3 Summary of CFD of varying aspect ratio of building height to road width

In summer, when considering the ratio of building height to road width of less than 1.4, air movement at both the 1st floor and the top floor within the street canyon exhibited consistent behaviour. For example, the air movement at any measurement points for both the 1st floor and top floor within the street canyon of 5 metre width remained consistent. However, when considering the ratio of building height to road width within range of 1.4 and 2.4, as a case of 4 floors buildings with a road width of 21 metre, the difference of air movement between the 1st and top floor are approximately 2.5%.

In rainy season, due to the oblique angle of the wind on the buildings, there was a fluctuation in the air movement velocity. However, the pattern of flow between lower floor and the top floor were similar.

As predicted in Chapter 3.5.2.1, air movement within the street canyon exhibits diverse behaviour based on the aspect ratio of building height to road width. A skimming flow regime is observed when the aspect ratio is below 1.4 such as the 4 floors buildings with road width of 5 metre and 9 metre This influences similar air movement values at any measurement points. However, when the aspect ratio between 1.4 to 2.4, a wake interference flow regime prevails. This causes the wind to impinge directly on certain façades of the building. Notably, narrower road created higher velocity through funneling effect.

6.3.3 Summary of building height and road width

This section explored the effect of air movement within street canyons through both the same aspect ratio of building height to road width and various ratios of building height to road width. The CFD sensitivity was explored during key seasons summer, winter and rainy season. To summarise, the air movement within the street canyon is influenced by the following factors:

Building height and road width: Street canyon geometry significantly impacts on the air movement within the canyon. The air movement exhibits the same flow patterns when the aspect ratio of building height to road width remains the same. For example, a skimming flow regime is observed in the street canyons with the ratio less than 1.4, whereas wake interference occurs when the ratio ranges between 1.4 and 2.4.

In addition, building length to building height, another aspect ratio, can influence airflow pattern within the street canyon. Increasing building length can obstruct the flow of initial wind to the canyon. In case where the ratio of building height to road width remains constant, ratio of 0.55, the air movement within the street canyon of 5 metre wide is approximately 45% lower than the street canyon of 21 metre wide. This is because the aspect ratio of building length to road width of 5 metre road width is higher than the ratio of 21 metre road width. Additionally, lower aspect ratio of building length to road width allows the wind to impinge directly on the leeward building facades.

The narrower street canyon influences the higher air movement in the street canyon.

Wind direction: wind direction has a significant impact on how it interacts on the building surface. The wind approaches perpendicularly to the building façade during summer, while the wind strikes the building surface at an oblique angle during rainy season. This results in distinct air movement patterns within the street canyon.

Wind speed: higher initial wind speed influences proportionally higher wind in the street canyon.

6.4 Nearby buildings

Referring to the results of the previous section, building height and road width have significant impact on air movement in the street canyon. In this section, deeper exploration will be undertaken into how nearby buildings affect the focus building.

This section provides an analysis of the CFD result for the exploration of air movement around the focus building influenced by increasing nearby building layers. Three different layers of nearby buildings are one layer of nearby building (Section 6.4.1), two layers of nearby building (Section 6.4.2) and three layers of nearby building (Section 6.4.3).

6.4.1 one layer of nearby buildings

Details regarding the methodology can be found in Chapter 3.5.3.1.

Simulated data points were illustrated in Figure 3-18. The 16 different possibilities of focus building surrounded by different range of 3 and 8 floor buildings is illustrated in Figure 6- 33. The comparison of the 16 different possibilities involving one layer of nearby buildings will be categorised into three groups based on the heights of the nearby buildings. Within each group, the exploration will be explained throughout different seasons, including summer and winter and rainy seasons. The three groups are the focus building surrounded by all 3-storey building (Section 6.4.1.1), surrounded by a mixture between 3-storey and 8-storey buildings (Section 6.4.1.2), and surrounded by all 8-storey buildings (Section 6.4.1.3).

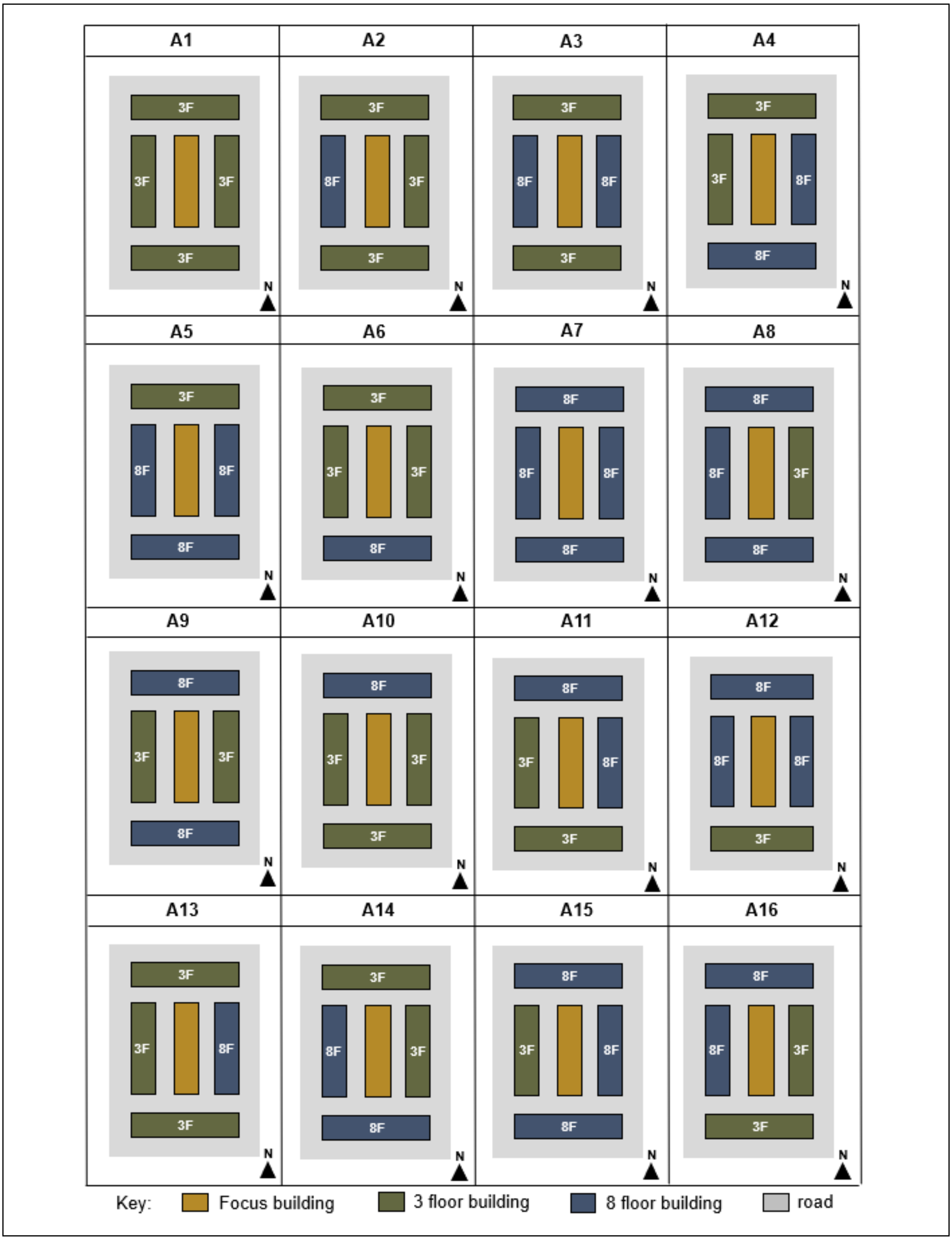


Figure 6- 33 schematic of one nearby-buildings layer cases
(Source: Author)

Table 6- 10 summary of air movement in summer and winter for one layer of nearby buildings

nearby buildings		Average air speed (m.s^{-1})				air speed ratio top floor : bottom floor)		comparison to initial wind speed (%)	
		corners on windward side		corners on leeward side		corners on windward side	corner on leeward side	windward corners	leeward corner
		1st floor	7th floor	1st floor	7th floor				
all 3-storey buildings	A1	2.51	1.25	2.51	2.51	0.50	1.00	-53.0	-37.3
mixture 3-storey and 8-storey buildings	A2	2.66	1.33	2.66	2.66	0.50	1.00	-50.1	-33.5
	A3	2.66	1.33	2.66	2.66	0.50	1.00	-50.1	-33.5
	A4	3.10	2.59	3.10	3.10	0.84	1.00	-28.9	-22.5
	A5	3.09	2.58	3.09	3.09	0.83	1.00	-29.1	-22.8
	A6	3.11	2.59	3.11	3.11	0.83	1.00	-28.8	-22.3
	A8	3.09	3.09	3.09	3.09	1.00	1.00	-22.8	-22.8
	A9	3.10	3.10	3.10	3.10	1.00	1.00	-22.5	-22.5
	A10	3.98	2.49	3.98	3.98	0.63	1.00	-19.1	-0.5
	A11	3.97	2.48	3.97	3.97	0.62	1.00	-19.4	-0.7
	A12	3.26	2.33	3.26	3.26	0.71	1.00	-30.1	-18.5
	A13	2.66	1.33	2.66	2.66	0.50	1.00	-50.1	-33.5
	A14	3.10	2.59	3.10	3.10	0.84	1.00	-28.9	-22.5
	A15	3.09	3.09	3.09	3.09	1.00	1.00	-22.8	-22.8
	A16	3.97	2.48	3.97	3.97	0.62	1.00	-19.4	-0.7
all 8-storey buildings	A7	3.09	3.09	3.09	3.09	1.00	1.00	-22.8	-22.8

The graphical comparisons will be presented in Figure 6- 34and Figure 6- 35.

Table 6- 11 summary of air movement in rainy season for one layer of nearby buildings

nearby buildings of		Average air speed ($m.s^{-1}$)				air speed ratio top floor : bottom floor)		comparison to initial wind speed (%)	
		corners on windward side		corners on leeward side		corners on windward side	corner on leeward side	windward corners	leeward corner
		1st floor	7th floor	1st floor	7th floor				
all 3-storey buildings	A1	3.63	4.27	2.13	2.13	1.18	1.00	-1.3%	-46.8%
mixture 3-storey and 8-storey buildings	A2	2.79	2.79	2.14	2.14	1.00	1.00	-30.4%	-46.5%
	A3	2.84	2.84	2.40	2.40	1.00	1.00	-29.0%	-40.0%
	A4	3.15	4.50	2.25	2.25	1.43	1.00	-4.4%	-43.8%
	A5	2.49	2.49	2.26	2.26	1.00	1.00	-37.8%	-43.5%
	A6	3.18	4.55	2.27	2.27	1.43	1.00	-3.4%	-43.3%
	A8	2.82	2.82	1.88	1.88	1.00	1.00	-29.5%	-53.0%
	A9	4.71	4.96	2.48	2.48	1.05	1.00	20.8%	-38.0%
	A10	4.51	4.75	2.37	2.37	1.05	1.00	15.7%	-40.8%
	A11	4.70	4.95	3.46	3.46	1.05	1.00	20.5%	-13.5%
	A12	3.43	3.43	2.75	2.75	1.00	1.00	-14.3%	-31.3%
	A13	2.14	2.14	2.36	2.36	1.00	1.00	-46.5%	-41.1%
	A14	2.25	2.25	3.15	3.60	1.00	1.14	-43.8%	-15.6%
	A15	1.88	1.88	2.82	2.82	1.00	1.00	-53.0%	-29.5%
	A16	3.46	3.46	4.70	4.20	1.00	0.89	-13.5%	11.2%
all 8-storey buildings	A7	2.82	2.82	2.35	2.35	1.00	1.00	-29.5%	-41.3%

The graphical comparisons will be presented in Figure 6- 36 to Figure 6- 39.

6.4.1.1 surrounded by all 3-storey buildings

Case A1 is the only scenario in which the focus building is entirely surrounded by 3-storey buildings.

<u>Summer and winter</u>

Regarding the CFD simulation results in Section 6.2.1, the air movement at opposite orientation (with same wind speed) behaved the same. The simulation for summer (south wind) is very similar but with opposite orientation to winter (north wind).

The initial wind originates at 4 $m.s^{-1}$ from the south (summer) and north (winter). At 1st floor, air movement at any measurement points of focus building remains constant at 2.51 $m.s^{-1}$. The constancy is due to the obstructing effect caused by a nearby building. However, at the 7th floor, the focus building is not obstructed by nearby building. The wind impinges directly on the short façade of the focus building, which causes a vortex at both corners of the façade on the windward side. Therefore, air movement at both corners of the windward sides is reduced by approximately 50.2% compared to other measurement points on the same level.

Rainy season

The initial wind from the south-west at 4 $m.s^{-1}$ impinge obliques at an angle on the building. At 1^{st} level, the initial wind cannot directly strike on the focus building because it is obstructed by adjoining building to the west. However, at the 7th floor, the wind directly reaches on the west façade of the focus building because there is no obstruction at this level. The air movement at the windward side of the focus building is greater than the leeward side by 70% at the 1^{st} and 100% at 7^{th} floor respectively.

6.4.1.2 surrounded by a mixture between 3-storey and 8-storey buildings

There are 14 cases (A2, A3, A4, A5, A6, A8, A9, A10, A11, A12, A13, A14, A15, and A16) in which the focus building is surrounded by a mix of 3 and 8 storey buildings.

Summer and winter

The initial wind originates at 4 $m.s^{-1}$ from the south (summer) and north (winter). At 1st floor level, the wind speed was obstructed by a nearby building, which brought about the air movement at all measurement points each case behaving the same pattern. At 7th floor level, the wind impinged directly on the short façade of the focus building which resulted in negative pressure occurring at the corner of the building on the windward side. Although the air flow pattern in each case was similar; there were minor building layout differences which caused individual variation to the air movement velocity results.

The primary factor influencing air movement within the canyon is the height of the windward building. This can be categorised into two groups based on the height of the windward building, which includes 3 storey buildings and 8-storey building.

In the case of 3-storey building on windward side of the focus building, this can be divided into two sub-groups regarding the height of leeward buildings.

- Windward building: 3-storey and leeward building:3-storey building:

This includes A2, A3 and A13 had a 3-storey building at the leeward side. The key difference between A2, A3 and A13 was one and two adjacent 8-floor buildings on the east and west of the focus building. An 8-floor building was located only on the western side in case A2 and only on the eastern side in case A13, whereas located both side of the focus building in case A3. However, the air movement of case A2, A3 and A13 on each floor level had a similar velocity of 2.66 $m.s^{-1}$. This is except at C2 and C4 on the 7th floor, where the velocity reduced to 1.33$m.s^{-1}$ (reduced 50%). This is because the initial wind encountered directly on the windward façade of focus building and then the air clung along the corner which occur vortex at both corners. This is why the velocity at these points are lower.

- Windward building: 3-storey and leeward building:8-storey building:
  This includes A10, A11, A12 and A16. The distinction between A10, A11, A12 and A16 and was zero, one and two adjacent 8-storey buildings on the east and west of the focus building. 8-storey building was non-existent in case A10, while the building was located only the east side in case A11 and west sides of the focus building in case A16. The air movement on each floor level of case A10, A11 and A16 had a similar velocity. However, the air movement velocity in case A12 was approximately 18.50% lower than the air movement velocity in case A10, A11 and A16 because the focus building in case A12 has more friction caused from surrounding building walls.

In the case of 8-storey building on windward side of the focus building, this includes A4, A5, A6, A8, A9, A14 and A15.

At 1st floor level, the wind speed was obstructed by the 8-storey windward building, which brought about the air movement of all measurement points each case behaving the same pattern and had a similar velocity. (see Figure 6- 35)

At 7th floor level, the wind also impinged directly on the windward building but the air movement velocity in each case had different velocity depending on the height of other surrounding building (see Figure 6- 35). The velocity varies between 2.06 $m.\ s^{-1}$ and 3.11 $m.\ s^{-1}$.

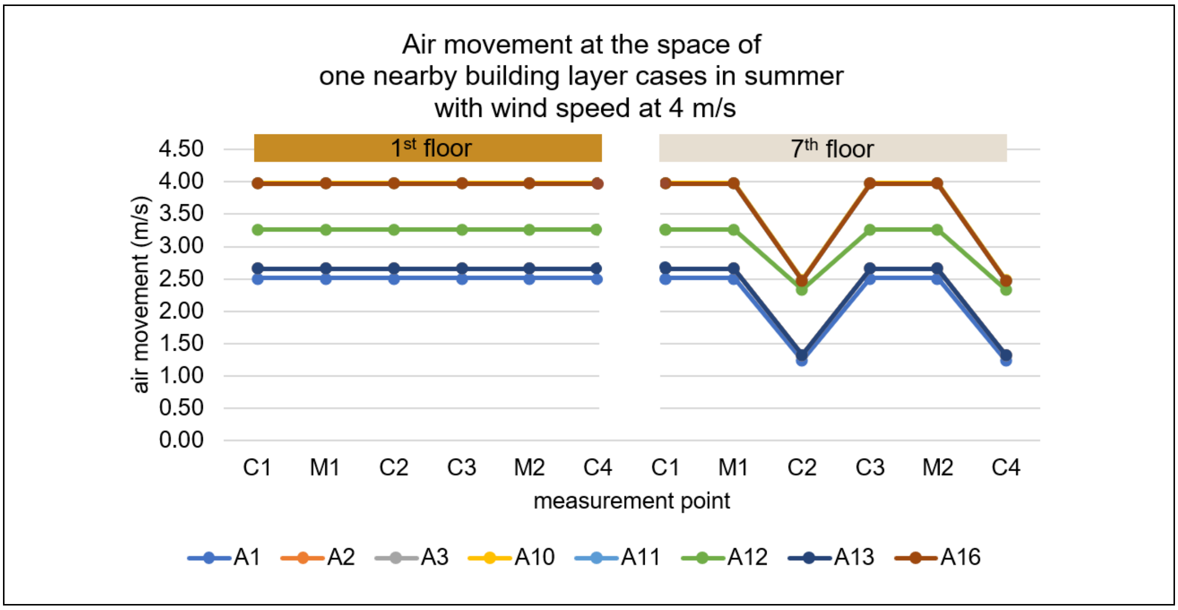


Figure 6- 34 Air movement of one layer of nearby building with a 3-storey building at windward side of the focus building in summer with wind speed at 4 m.s^{-1}

(Only data for 4 cases clearly visible due to similarities between certain layouts e.g. A13 is visible which covers similar data for A2 and A3, A16 is visible which covers similar data for A10 and A11)

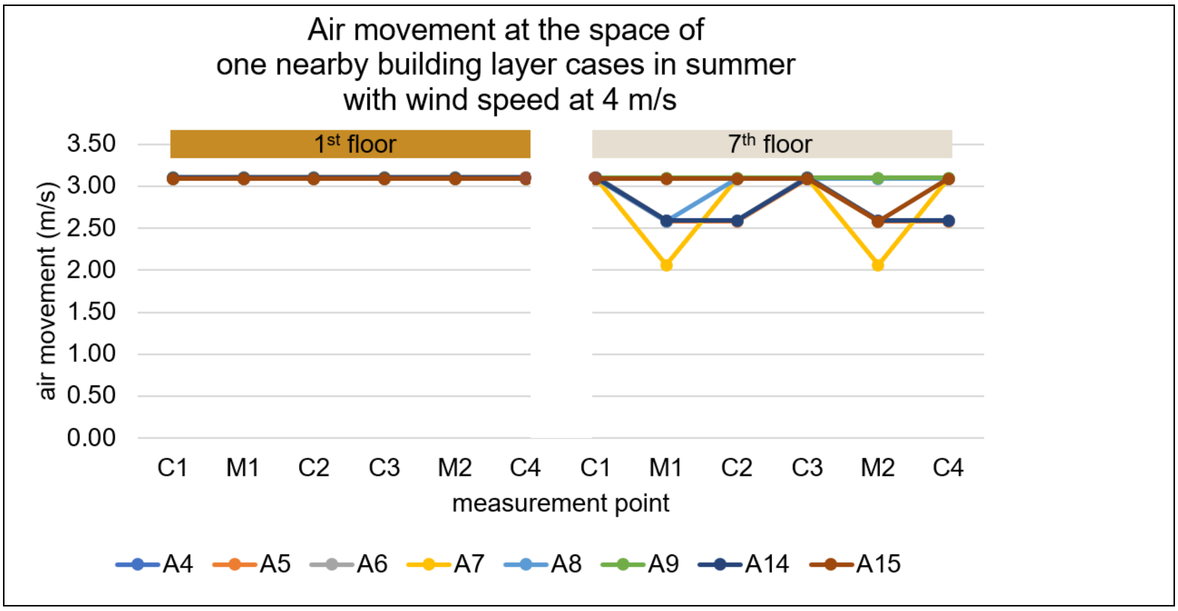


Figure 6- 35 Air movement of one layer of nearby building with an 8-storey building at windward side of the focus building in summer with wind speed at 4 m.s^{-1}

(1st floor- indicate that data was so similar for all buildings, that A15 overlays the data. 7th floor - Only data for 4 cases clearly visible due to similarities between certain layouts e.g. A14 is visible which covers similar data for A4, A5 and A6).

Rainy season

In this season, the wind mainly flows from the south-west direction. The wind was consequently obstructed by the west and south nearby buildings. As a result, the primary factor influencing airflow is the height of both the west and the south buildings. With 4 $m.s^{-1}$ initial wind speed, the average air movement velocity of all cases was 2.90 $m. s^{-1}$. The maximum and minimum air movement velocities were 5.45 $m. s^{-1}$ and 1.88 $m. s^{-1}$ respectively. From the CFD result of air movement of one nearby building layer, airflow pattern can be categorised mainly into four groups depended on both west and the south buildings height, which are:

- 3-storey southern building and 3-storey western building in relation to the focus building: This includes A10, A11.
- 3-storey southern building and 8-storey western building in relation to the focus building: This includes A2, A3, A12.
- 8-storey southern building and 3-storey western building in relation to the focus building: This includes A4, A6, A9.
- 8-storey southern building and 8-storey western building in relation to the focus building: This includes A5, A8.

3-storey southern building and 3-storey western building the focus building

On the 1st floor, the wind was obstructed by the west building, whereas the wind could impinge directly on the focus building at 7th floor. The air movement velocity on the western side of the focus building (C1, M1 and C2) was higher in comparison to the eastern side of such building. The air movement on the eastern side had a similar velocity. (see Figure 6- 36)

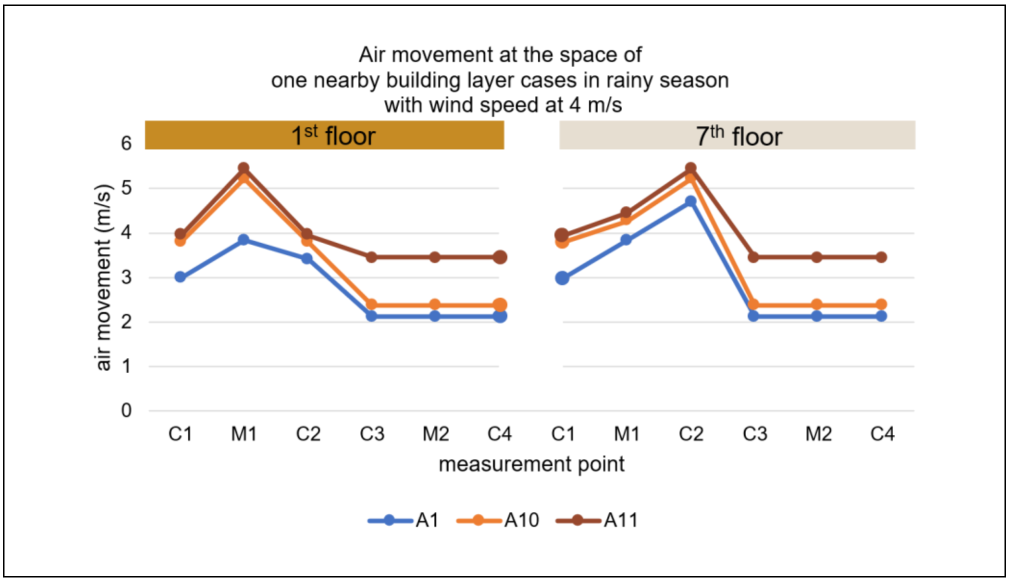


Figure 6- 36 Air movement at the space of one nearby building layer cases in rainy season with wind speed at 4 m.s^{-1}

<u>3-storey southern building and 8-storey western building the focus building</u>

The wind was obstructed by 8-storey western building before blowing to the focus building. On the western side of the focus building, the air movement at the same location on both the 1st and 7th floor behaved similar pattern. However, the air movement velocity on the eastern side varied depending on the east and the north buildings' height. The average air movement, in these cases, was 2.65 m. s^{-1} which had the maximum and minimum velocity at 3.66 m. s^{-1} and 2.14 m. s^{-1} respectively (see Figure 6- 37).

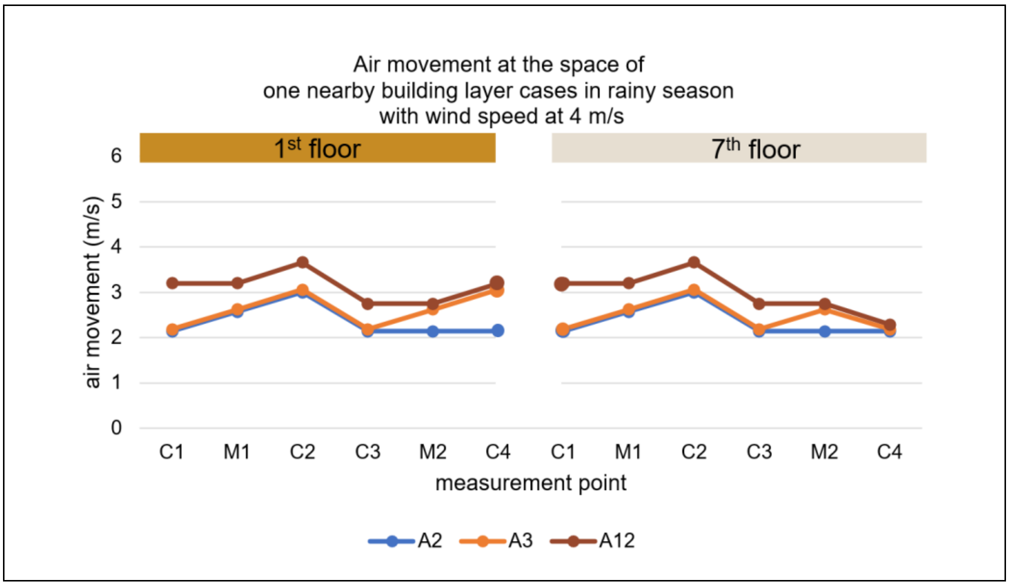


Figure 6- 37 Air movement at the space of one nearby building layer cases in rainy season with wind speed at 4 m.s^{-1}

8-storey southern building and 3-storey western building the focus building

On the 1st floor level, the wind was obstructed by a 3-storey western building which resulted in the wind encountered directly on such 3-storey building and then reached at M2 before clinging with the building façade to other areas. This impact of this encounter conducted M1 had the peak velocity compared to other locations on the same floor. On the 7th floor, the wind could impinge directly on the focus building which enhanced C2 which had the highest air velocity. The air movement at the eastern side, of all measurement points, of the focus building had similar velocity (see Figure 6- 38).

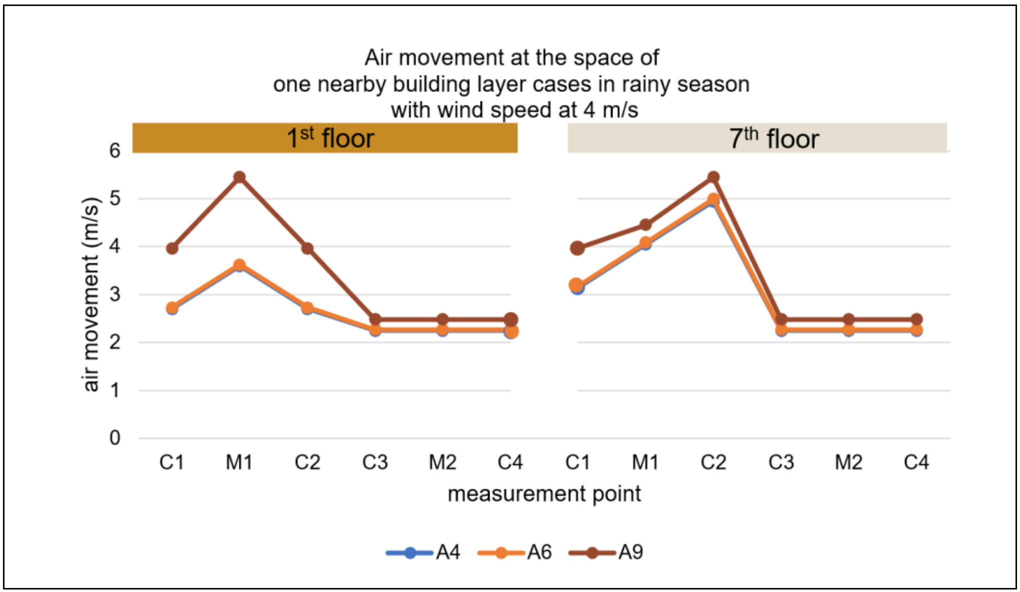


Figure 6- 38 Air movement at the space of one nearby building layer cases in rainy season with wind speed at 4 m.s^{-1}
(Only data for 2 cases clearly visible due to similarities between certain layouts e.g. A9 is visible and A6 overlays similar data for A4.)

8-storey southern building and 8-storey western building the focus building

The wind was minimised by such two 8-storey buildings on the west and south before encountering the focus building. The average air movement, in these cases, was 2.42 m. s^{-1} which was 39.5% lower velocity than initial speed, and the maximum and minimum velocity was 2.82 m. s^{-1} and 1.88 m. s^{-1} respectively (see Figure 6- 39).

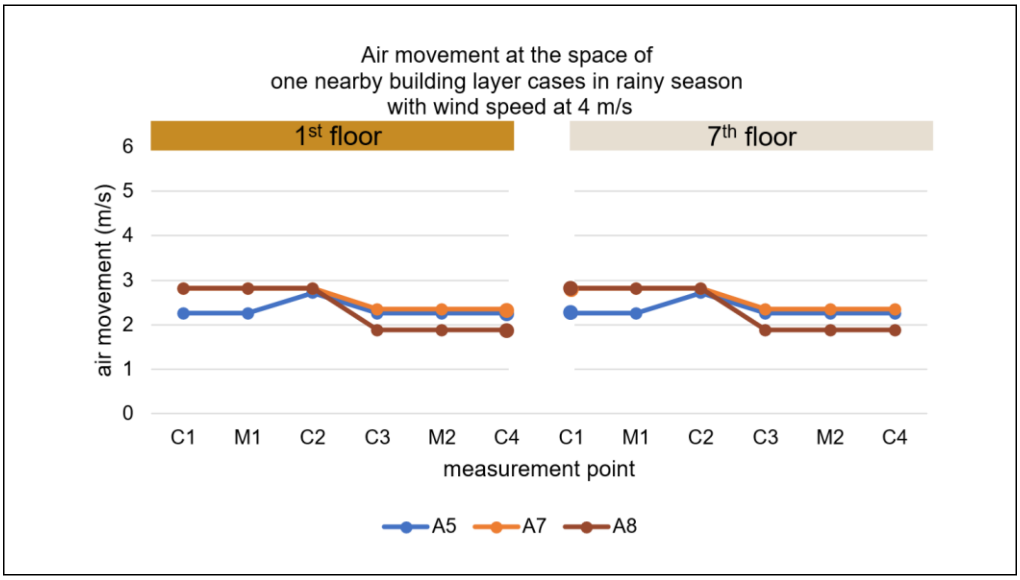


Figure 6- 39 Air movement at the space of one nearby building layer cases in rainy season with wind speed at 4 m.s^{-1}

6.4.1.3 surrounded by all 8-storey buildings

Case A7 is the only scenario in which the focus building is entirely surrounded by 8-storey buildings.

Summer and winter

In case A7, the air movement velocity at all measurement points was consistently at 3.09 m.s^{-1}.

Rainy season

The wind typically comes from an oblique angle. The air movement on the windward side of the focus building (C1, M1, C2) remained constantly at 2.82 m.s^{-1} for both the 1st floor and 7th floor. On the leeward side, the air movement was also constant but reduced to 2.35 m.s^{-1}.

To compare Case A1 (surrounded by all 3-storey buildings) and A7 (surrounded by all 7-storey buildings), air movement on the windward side of Case A1 exhibited more fluctuations, ranging from 2.99 to 3.84 m.s^{-1}. In contrast, in case A7, the air movement has maintained uniform velocity of 2.82 m.s^{-1}. This discrepancy was related to obstruction of the west and the south buildings' height.

6.4.1.4 Summary of the air movement at the space of one nearby building layer cases

The main influence on the wind flow pattern is the direction of the initial wind. The average air movement velocity of all summer and winter cases were similar to the average velocity in the rainy season, 2.98 m. s^{-1} in summer and winter and 2.90 m. s^{-1} in the rainy season. The maximum and minimum velocity in summer and winter were 3.98 m. s^{-1} and 1.25 m. s^{-1}, while the velocity in rainy season was 5.45 m. s^{-1} and 1.88 m. s^{-1} respectively. In summer and winter, the wind could not impinge directly on the measurement locations' focus building resulting in the negative pressure occurring at the corner of the building. However, in the rainy season, the wind could blow directly on the focus building depending on the height of the buildings towards the south and west, the air movement on focus building façade had higher velocity than the initial wind speed.

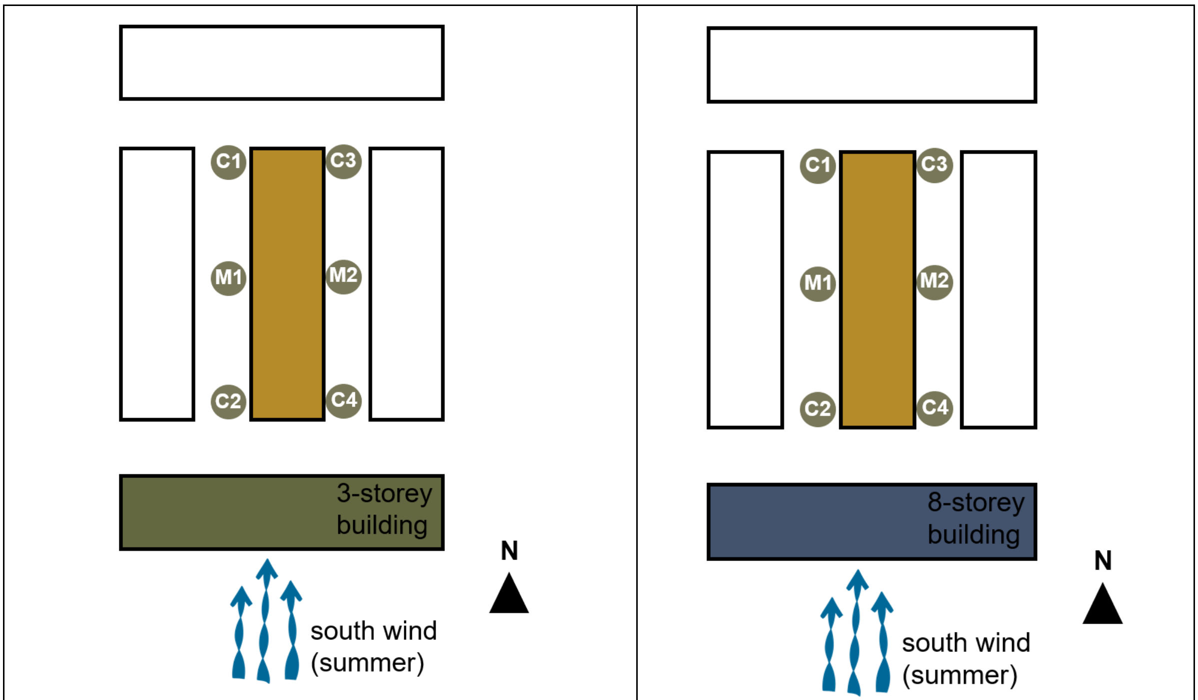
6.4.1.4.1 Summary of one nearby building layer cases for summer and winter

Regarding the CFD simulation results in Section 6.2.1, the air movement at opposite orientation (with same wind speed) behaved the same. The simulation for summer (south wind) is very similar but with opposite orientation to winter (north wind).

In this season, the wind mainly flows from the south direction. With 4 m.s^{-1} initial wind speed, the average air movement velocity of all cases was 2.98 m. s^{-1}. The maximum and minimum air movement velocities were 3.98 m. s^{-1} and 1.25 m. s^{-1} respectively.

Air movement of one nearby building layer pattern can be categorised mainly into 2 groups, which are

- Wind speed encountering directly on a 3-storey building at southern side (summer) of the focus building (see Figure 6- 40 (a)). This includes A1, A2, A3, A10, A11, A12, A13, A16
- Wind speed encountering directly on 8-storey building at southern side (summer) of the focus building. (see Figure 6- 40 (b)). This includes A4, A5, A6, A7, A8, A9, A14, A15.



(a) a 3-storey building at southern side of the focus building

(b) an 8-storey building at southern side of the focus building

Figure 6- 40 schematic shows two different height of southern building of the focus building

(This figure illustrates summer wind (south wind), while winter wind is very similar but with opposite orientation (north wind))

Air movement varied depending on locations of the building and the height of nearby buildings (see Table 6- 10). Air movement ratio between top floor to bottom floor were the same for the corner rooms at leeward side (C1 and C3). However, at the corner rooms at windward side, the air speed ratio between the top floor and the bottom floor altered mostly based on the height of the windward and leeward buildings. For example, in A1, A2, A3, and A13, the focus building surrounded by 3-storey buildings on both windward and leeward side had the air movement of top floor to bottom floor ratio of 0.50. At 1st floor level, the wind impinged directly on the south of nearby building, then the air progressed along the building façade and blew to other buildings later. However, at the 7th floor level, the wind encountered straight on the south façade of the focus building, then the air blew along the sides of the building. Negative pressure occurred at both corners of the south façade (C2 and C4), resulting in lower velocity at these points than other measurement points. On the other hand, the ratio of top floor to bottom floor of focus building surrounded by 8-storey buildings on both windward and leeward side (A7, A8, A9, and A15) were 1. This means there was no different between the top and the bottom floor, even though nearby buildings on the east and the west varied height.

To compare case A1 (surrounded by all 3-storey buildings) and A10, the difference between A1 and A10 relates to the leeward building. In case A1 the leeward building was 3-storey, whereas the building in case A10 was an 8-storey building. At 1st floor, the wind in both cases impinged directly on the windward building before blowing along the building façade to other building later. The air movement at all measurement points of case A10 were 3.98m.s^{-1} which was almost the same velocity as the initial wind speed, while the air movement at all measurement points of case A1 was 2.51 m. s^{-1}, which was approximately 37.25% lower velocity than initial wind speed. At 7th floor, after the wind encountering straight on the windward façade of the focus building, the air movement clung along with the building façade with 1.25 m. s^{-1} at both corners of windward wall of the focus building and 2.51 m. s^{-1} at other measurement locations of the building in case A1. In case A10, the air movement blew along with the building and then encountered on the leeward surrounding building which influenced this case had a higher velocity than case A1 because of the rebound flow.

To compare case A4, A5, A6 and A14, the focus building in these cases had 8-storey building on the windward side and 3-storey building on the leeward side. The air movement velocity of all cases behaved the same pattern regardless of whether the western or eastern buildings had different building height. The lower velocity occurred at both corners on windward side and middle positions (M1 and M2) of the focus building.

To compare case A7 (surrounded by all 8-storey buildings) A8, A9 and A15, the difference between A7, A8, A9 and A15 relates to the eastern and western building height. 8-storey buildings existed both the east and the west in case A7, while the building was located only on either one between the east and the west for case A8 and case A15. In case A9, there was no 8-storey building on the east and west of the focus building. The air movement velocity in case A7 decreased at the middle locations (M1 and M2) of the focus building, while the air movement velocity in case A8 and A15 dropped only one side of the building, which had an 8-storey building in parallel. In case A9, all measurement points had a similar velocity.

6.4.1.4.2 Summary of one nearby building layer cases for rainy season

In this season, the wind encounter directly on nearby building surface on the west of focus building. The air continued flowing along with the building façade to the space between each building. The highest air movement mainly occurred on the western side of the focus building at M1 and C2. In addition, on the west surface of the building, the air movement on the top floor tended to be higher than the lower floor when the nearby building on the west was 3 storeys. This is because the nearby building acted as a barrier for the lower floor, but the air could reach directly on higher floor level on the west wall of focus building. Contrastingly, the air movement had similar velocity between the lower floor and the top floor for the focus building with nearby building of 8 storeys. On the leeward side, the air movement of the focus building at any measurement points on both floor level had a similar value. (see Table 6- 11)

- 3-storey southern building and 3-storey western building the focus building (see Figure 6- (a)). This includes A1, A10, A11.
- 3-storey southern building and 8-storey western building the focus building (see Figure 6- (b)). This includes A2, A3, A12.
- 8-storey southern building and 3-storey western building the focus building (see Figure 6- (c)). This includes A4, A6, A9.
- 8-storey southern building and 8-storey western building the focus building (see Figure 6- (d)). This includes A5, A7, A8.

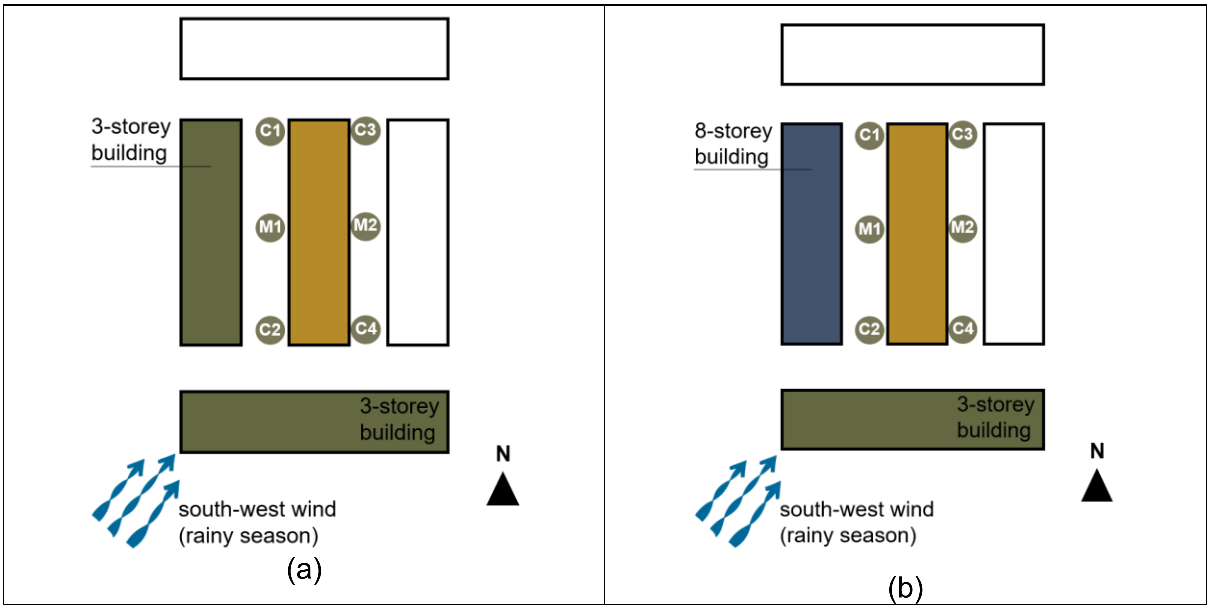


Figure 6- 41 schematic shows different southern and western building height of the focus building

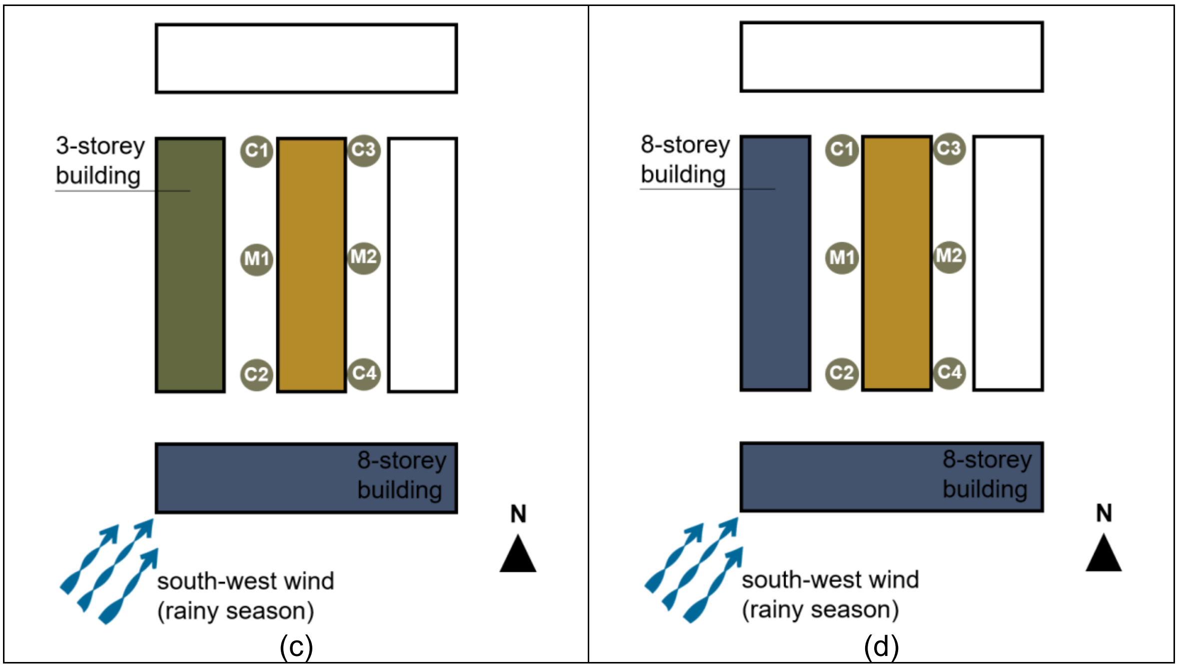


Figure 6- 41 schematic shows different southern and western building height of the focus building (continued)
(Source: Author)

6.4.2 two layers of nearby buildings

Details regarding the methodology can be found in Chapter 3.5.3.2.

Measurement points were illustrated in Figure 3-18 and Figure 3-21. The 4 different possibilities of focus building surrounded by different range of 3 and 8 floor buildings are illustrated in Figure 6- 42.

The comparisons involving 4 different possibilities with two layers of nearby buildings in this section will be categorised into three groups regarding the different heights of nearby buildings. Within each group, the exploration will be explained throughout different seasons, including summer and winter and rainy seasons. The three groups are the focus building surrounded by all 3-storey building (Section 6.4.2.1), surrounded by a mixture between 3-storey and 8-storey buildings (Section 6.4.2.2), and surrounded by all 8-storey buildings (Section 6.4.2.3).

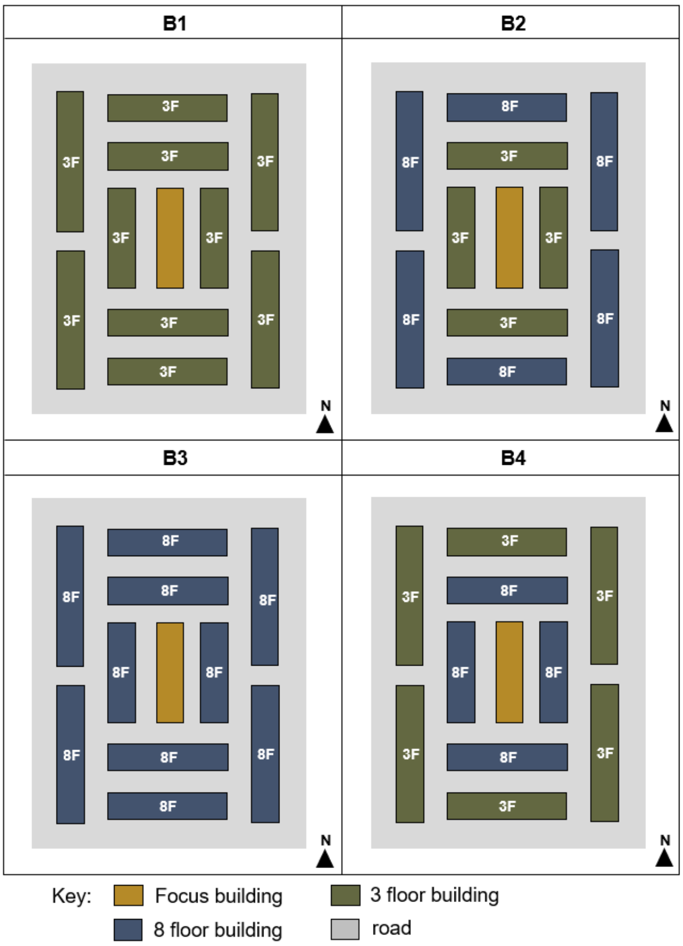


Figure 6- 42 schematic of two nearby-buildings layer cases
(Source: Author)

Table 6- 12 summary of air movement in summer and winter for two layers of nearby buildings

nearby buildings of		Average air speed ($m.s^{-1}$)				air speed ratio top floor : bottom floor)		comparison to initial wind speed (%)	
		corners on windward side		corners on leeward side		corners on windward side	corner on leeward side	windward corners	leeward corner
		1st floor	7th floor	1st floor	7th floor				
all 3-storey buildings	B1	2.42	1.21	2.42	2.42	0.50	1.00	-54.6%	-39.5%
mixture 3-storey and 8-storey buildings	B2	2.99	2.99	3.49	3.49	1.00	1.00	-25.3%	-12.8%
	B4	2.79	2.79	2.79	2.79	1.00	1.00	-30.3%	-30.3%
all 7-storey buildings	B3	3.00	3.00	3.00	3.00	1.00	1.00	-25.0%	-25.0%

Table 6- 13 summary of air movement in rainy season for two layers of nearby buildings

nearby buildings of		Average air speed ($m.s^{-1}$)				air speed ratio top floor : bottom floor)		comparison to initial wind speed (%)	
		corners on windward side		corners on leeward side		corners on windwar d side	corner on leeward side	windwar d corners	leeward corner
		1st floor	7th floor	1st floor	7th floor				
all 3-storey buildings	B1	3.71	4.13	2.06	2.06	1.11	1.00	-2.1%	-48.5%
mixture 3-storey and 8-storey buildings	B2	3.41	3.64	2.92	2.92	1.07	1.00	-11.9%	-27.0%
	B4	2.64	2.64	2.20	2.20	1.00	1.00	-34.0%	-45.0%
all 7-storey buildings	B3	2.70	2.70	2.45	2.45	1.00	1.00	-32.6%	-38.8%

6.4.2.1 surrounded by all 3-storey buildings

This can apply for Case B1.

<u>Summer and winter</u>

Regarding the CFD simulation results in Section 6.2.1, the air movement at opposite orientation (with same wind speed) behaved the same. The simulation for summer (south wind) is very similar but with opposite orientation to winter (north wind).

The main factor influencing the air pattern and velocity was the height of the nearby buildings on the windward side. The focus building was surrounded by all 3-storey buildings in vicinity as in B1. The air movement at the same measurement points on the 1st floor had a similar velocity. In contrast, on the 7th floor, negative pressure occurred at both corners of the windward façade, resulting in lower velocity at these points. The average air velocity in this case was the lowest compared to other cases. This is primarily due to the more open space between the focus buildings. The wind tends to be uniform flow along the building with less concentration of the wind.

Rainy season

The focus building was surrounded by 3-storey buildings on both the first and second layer. The wind encountered diagonal on the second layer's west building before flowing along with the building façade to other buildings later. On the west side of the focus building, on the 1st floor, the air movement at M1 and C2 was 3.71 m. s^{-1}, which was 7.25% lower than the initial wind speed, while the air movement at C1 was 2.06 m. $s^{-1,}$ which was 48.50% lower than the initial wind speed. On the east side of the focus building, on the 1st floor, the air movement had a similar velocity at all measurement points, 2.06 m. s^{-1}. However, on the 7th floor, the highest air velocity occurred at C2 because of the wind impinging directly on this focus building's façade, which was 13.5% higher than the initial wind speed. Additionally, the negative pressure occurred at C1 and C4, resulting in the lowest air velocity at these points.

6.4.2.2 surrounded by a mixture between 3-storey and 8-storey buildings

This can apply for 2 cases, which are B2 and B4.

Summer and winter

Regarding the CFD simulation results in Section 6.2.1, the air movement at opposite orientation (with same wind speed) behaved the same. The simulation for summer (south wind) will be applied but with opposite orientation to winter (north wind).

The focus building was surrounded by a mixture of 3-storey and 8-storey building on the windward side. A nearby building layer of 8 storeys was located at the first layer for B2 and located at the second layer for B4. The different location of 8-storey buildings resulted in the different airflow pattern. Case B4 had more friction surface closer than case B2. Consequently, the air movement of B4 is lower than B2.

In addition, the more obstructed building formulated more eddies and funnelled the air to accelerate along canyon along the focus buildings. This is why in case of B2 and B4 had higher air velocity than B1 (see Table 6- 12).

Rainy season

The distinction in air movement between B2 and B4 was dependent on the variation in the building height location. In case of B4, where 8-storey buildings located at the first layer, the air movement tended to be uniform compared to Case B2. Specifically, on the windward side of the focus building, the air movement of case B4 remained consistently at 2.64 $m.s^{-1}$, while the air movement of case B2 was fluctuated ranging from 2.92 $m.s^{-1}$ to 3.41 $m.s^{-1}$.

6.4.2.3 surrounded by all 8-storey buildings

This can apply for Case B3.

Summer and winter

The focus building was centrally located among two layers of 8-storey buildings. The wind encountered straight on the south building of the second layer, then the wind flowed along with the building façade and flew though the space to other buildings afterwards. The air movement at all measurement points had a similar velocity. The air velocity was approximately 3 $m.\ s^{-1}$, which was 25% lower than the initial wind speed.

Rainy season

All the first and the second nearby-building layer were 8-storey buildings. The air movement at both corners (C2 and C4) on the south surface of focus building was higher than other measurement points. As the wind from the southwest approached the corners, it changed direction and then created a vortex effect. This converging wind flow led to higher air movement at the corners. On both 1^{st} and 7^{th} floor, the air movement at C2 and C4 was 2.94 $m.\ s^{-1}$, which was 26.50% lower velocity than the initial wind speed, whereas other measurement points were 2.45 $m.\ s^{-1}$, which was approximately 39% lower velocity than the initial wind speed.

6.4.2.4 Summary of the air movement at the space of two nearby building layer cases

The average air movement velocity of all summer cases was similar to the average velocity in the rainy season, 2.79 m. s^{-1} in summer, and 2.65 m. s^{-1} in the rainy season. The maximum and minimum velocity in summer was 3.49 m. s^{-1}, and 1.21 m. s^{-1} consequently, while the velocity in rainy season was 4.54 m. s^{-1}, and 1.24 m. s^{-1} respectively. On the 1st floor, the wind could not impinge directly on the measurement locations' focus building in summer and rainy season because of the obstruction of two nearby-building layers. However, at the 7th floor level, in both summer and rainy season, the wind could blow directly on the focus building in some cases resulting to the air movement on the attacked façade of focus building had a higher velocity than the initial wind speed.

6.4.2.4.1 Summary of two nearby building layer cases for summer

Regarding the CFD simulation results in Section 6.2.1, the air movement at opposite orientation (with same wind speed) behaved the same. The simulation for summer (south wind) will be applied but with opposite orientation to winter (north wind).

In this season, the wind mainly flows from the south direction. With 4 m.s^{-1} initial wind speed, the average air movement velocity of all cases was 2.79 m. s^{-1}. The maximum and minimum air movement velocities were 3.49 m. s^{-1} and 1.21 m. s^{-1} respectively. From CFD result of air movement of two layer of nearby buildings, air flow pattern can be categorised mainly into 2 groups, which are

- 3-storey buildings on the first nearby building layer. This includes B1 and B2.
- 8-storey buildings on the first nearby building layer. This includes B3 and B4. (see Figure 6- 43)

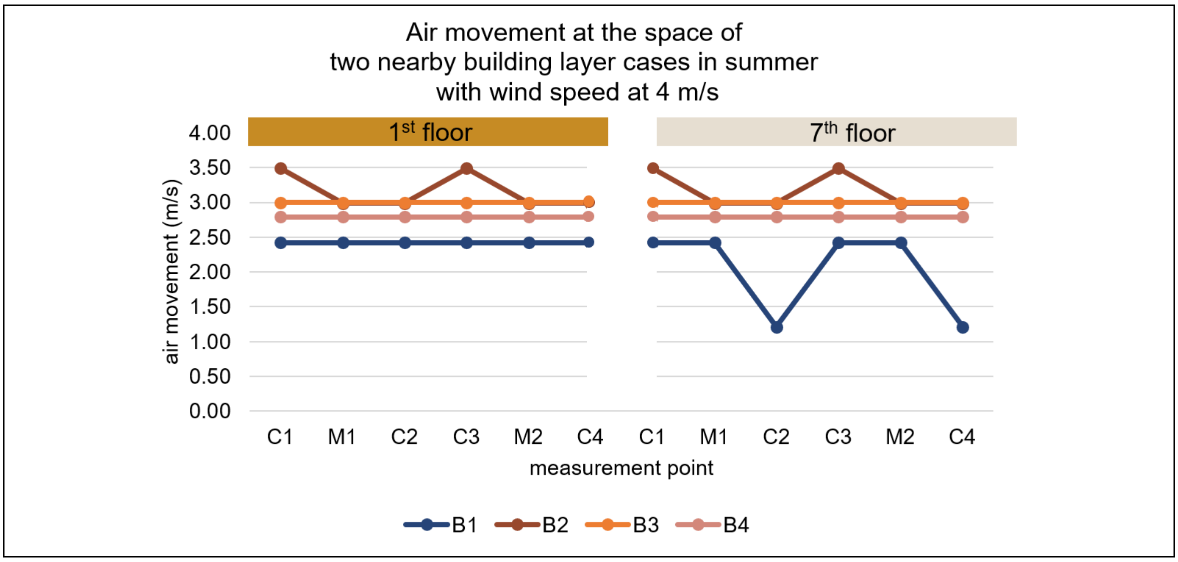


Figure 6- 43 Air movement at the space of two layer of nearby buildings cases in summer with wind speed at 4 m.s^{-1}

6.4.2.4.2 Summary of two nearby building layer cases for rainy season

In this season, the wind mainly flows from the south-west direction. With 4 m.s^{-1} initial wind speed, the average air movement velocity of all cases was 2.65 m. s^{-1}. The maximum and minimum air movement velocities were 4.54 m. s^{-1} and 1.24 m. s^{-1} respectively. From CFD result of air movement of two layers of nearby buildings, air flow pattern can be categorised mainly into 2 groups, which are

- 3-storey buildings on the first layer of nearby building. This includes B1 and B2.
- 8-storey buildings on the first layer of nearby building. This includes B3 and B4. (see Figure 6- 44)

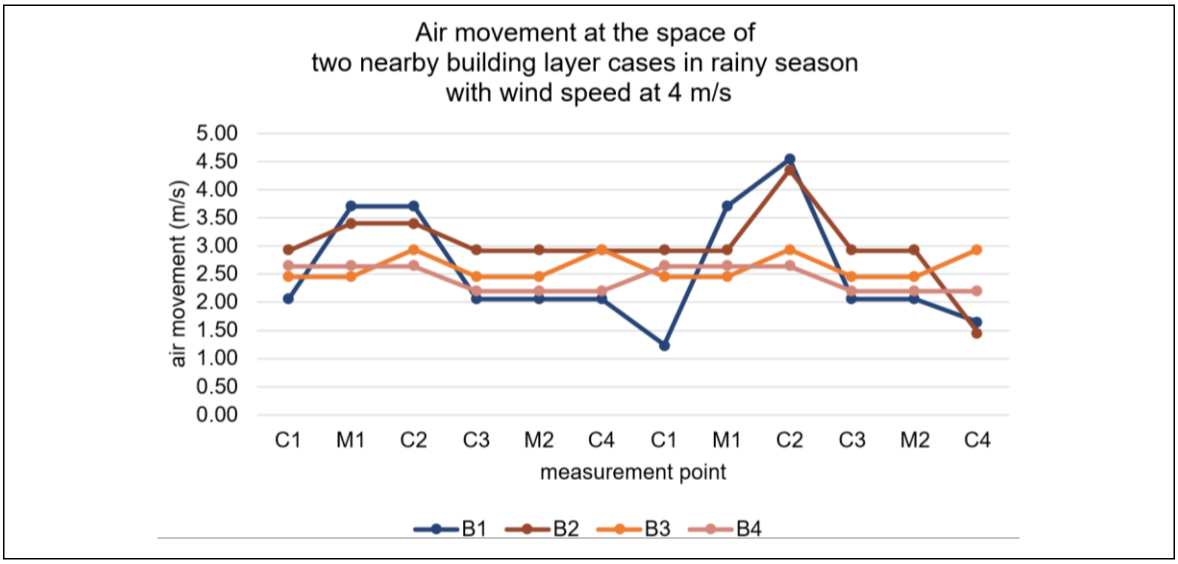


Figure 6- 44 Air movement at the space of two layers of nearby buildings cases in rainy season with wind speed at 4 m.s^{-1}

3-storey buildings on the first nearby building layer

The difference between B1 and B2 involves the second nearby building height, e.g., the second layer buildings of B1 are 3-floor buildings while B2 are 8-floor buildings. The air movement of B1 and B2 behaved similar flow pattern even there was a difference in the building height of the second layer. On the 1st floor, the air movement at C2 and M1 had an equivalent velocity; then, the air movement reduced when flow through C1. The movement at all eastern measurement points in each case remained at a similar velocity. On the 7th floor, the wind impinged on C2 affecting both cases had the highest air velocity; in the meantime, the negative pressure occurred at the C4, which reduced the air movement, bringing about the lowest velocity at this point.

8-storey buildings on the first nearby building layer

The distinction between B3 and B4 relates to the second nearby building height, for example, the second layer buildings of B3 are 8-storey buildings while B4 are 3-storey buildings. The air movement on the1st and 7th floor in each case behaved similar flow pattern. For example, the air movement in B4 at C1, M1, C2 had similar velocity both the 1st and 7th floor level. Although the air movement between B3 and B4 at each measurement point had a different velocity, the velocity had a minor difference which varied between 0.19 and 0.74 m. s^{-1}.

Referring to the less different air movement velocity in summer and rainy season, the next CFD investigation of three nearby buildings layers will explore only in summer.

6.4.3 Three layers of nearby buildings

(Further details regarding the methodology can be found in Chapter 3.5.3.3)

Measurement points were illustrated in Figure 3-18 and Figure 3-22. The 8 different possibilities of focus building surrounded by different range of 3 and 8 floor buildings is illustrated in Figure 6- 42.

The analysis of the 8 different possibilities will be divided into three groups regarding the different heights of nearby buildings, which are the focus building surrounded by all 3-storey building (Section 6.4.3.1), surrounded by a mixture between 3-storey and 8-storey buildings (Section 6.4.3.2), and surrounded by all 8-storey buildings (Section 6.4.3.3). Table 6- 14 shows the summary of air movement in the street canyon of focus building with three layers of nearby buildings during summer.

Table 6- 14 summary of air movement in summer for three layers of nearby buildings

nearby buildings of		Average air speed ($m.s^{-1}$)				air speed ratio top floor : bottom floor)		comparison to initial wind speed (%)	
		corners on windward side		corners on leeward side		corners on windward side	corner on leeward side	windward corners	leeward corner
		1st floor	7th floor	1st floor	7th floor				
all 3-storey buildings	D1	1.95	1.17	1.95	1.95	0.60	1.00	-61.0%	-51.3%
mixture 3-storey and 8-storey buildings	D2	2.22	2.22	3.10	3.10	1.00	1.00	-44.5%	-22.5%
	D3	2.86	2.38	2.86	2.86	0.83	1.00	-34.5%	-28.5%
	D4	2.92	2.92	2.92	2.92	1.00	1.00	-27.0%	-27.0%
	D5	2.14	2.14	2.14	2.14	1.00	1.00	-46.5%	-46.5%
	D6	2.20	2.20	2.20	2.20	1.00	1.00	-45.0%	-45.0%
	D7	2.89	2.89	2.89	2.89	1.00	1.00	-27.8%	-27.8%
all 7-storey buildings	D8	2.90	2.90	2.90	2.90	1.00	1.00	-27.5%	-27.5%

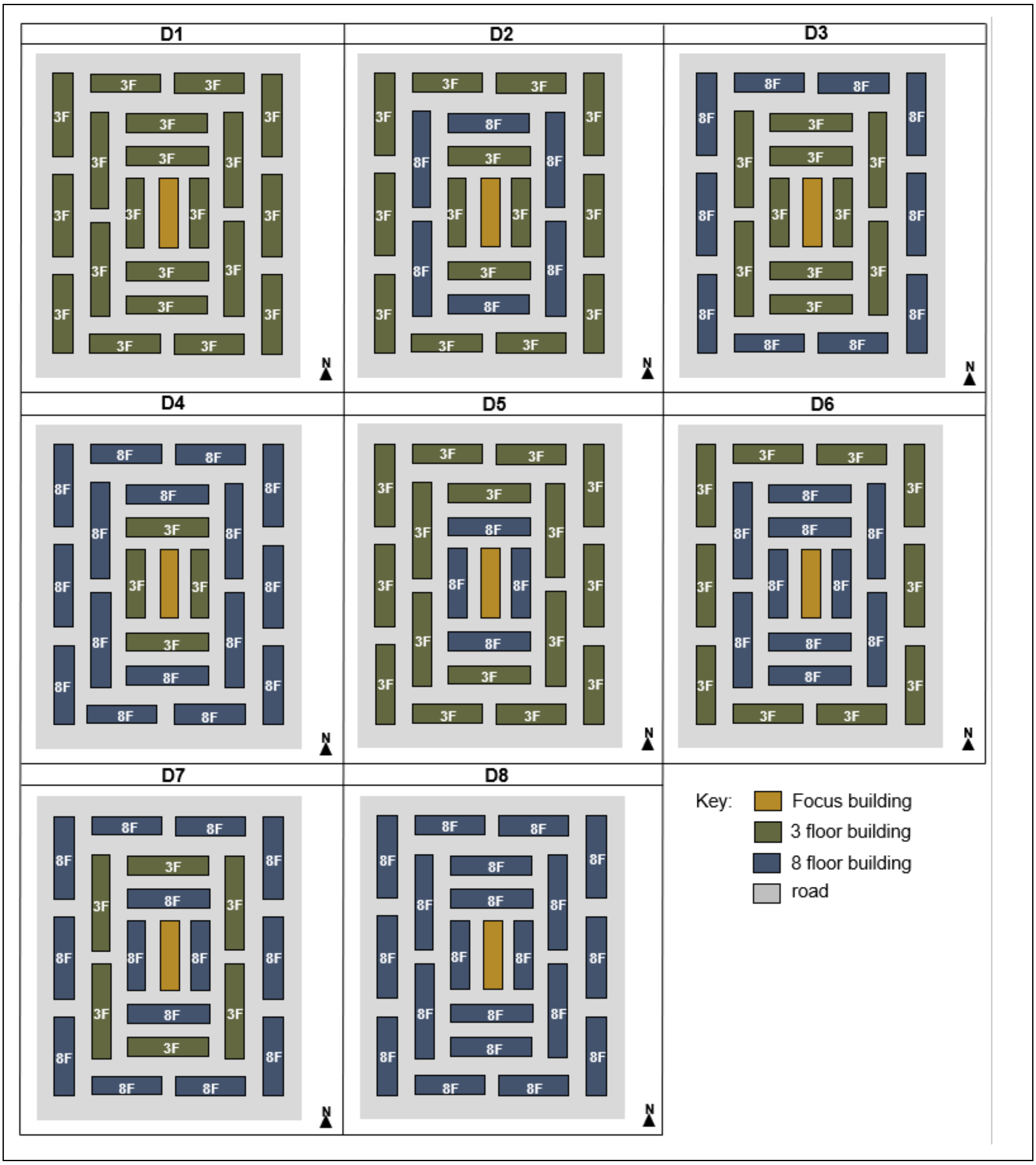


Figure 6- 45 schematic of three nearby-buildings layer cases
(Source: Author)

6.4.3.1 surrounded by all 3-storey buildings

This can apply for Case D1.

The focus building was surrounded by three nearby-building layers with 3-storey buildings. The wind could not impinge directly on the focus building on the 1st floor resulting to the air movement on this floor level remained a similar velocity. The air movement at all measurement points was approximately 2 m. s^{-1}, which was around 50% lower velocity than the initial wind speed. However, the wind encountered straight on the south façade of the focus building at 7th floor level affecting the negative pressure occurring at both the south corners of the focus building (C2 and C4). The air movement at such corners was the lowest velocity, which was 1.17 m. s^{-1} and was 70.5 % lower velocity than the initial wind speed. The air movement at other measurement points was approximately 2 m. s^{-1}.

6.4.3.2 surrounded by a mixture between 3-storey and 8-storey buildings

This can apply for 6 cases, which are D2, D3, D4, D5, D6 and D7. Air movement of three nearby-building layers vary between 1.2 $m.s^{-1}$ and 3.2 $m.s^{-1}$. The different pattern of airflow depended on the first layer of nearby building height, which are

3-storey buildings on the first layer of nearby buildings

On the 1st floor, the air movement of all measurement points in case D1, D3 and D4 remained stable, while the air movement in case D2 fluctuated. On7th floor, the air movement of all cases fluctuated except case D4.

8-storey buildings on the first layer of nearby buildings

On both the 1st and 7th floor, the air movement at the same measurement points behave the same flow pattern.

6.4.3.3 surrounded by all 7-storey buildings

This can apply for Case D8.

The focus building is located in the middle of all three layers of nearby buildings with 8-storey buildings. The air movement at all measurement points of the focus building remained the same velocity with 2.9 m. s^{-1}, which was 27.5% lower velocity than the initial wind speed.

6.4.3.4 Summary of the air movement at the space of three nearby building layer cases

The focus building was surrounded by three nearby-building layers The wind could not impinge directly on the focus building on the 1st floor. Especially in the case of the building surrounded by at least one 8-storey building on the windward area (all cases except D1), the air movement maintained a relatively stable speed. The air movement at all measurement points was range approximately from 2 to 3 m. s^{-1}, which was around 25%-50% lower velocity than the initial wind speed. Additionally, the wind tends to be obstructed mainly by the first and the second nearby buildings if the first and second layer of nearby buildings of the focus building are 8-storey buildings. However, in scenario of D1, the wind encountered straight on the south façade of the focus building at 7th floor level affecting the negative pressure occurring at both the south corners of the focus building (C2 and C4). The air movement at such corners was the lowest velocity, causing the air velocity reduced up to 61% from the initial wind speed. (see Table 6- 14)

In this season, the wind mainly flows from the south direction. With 4 m.s^{-1} initial wind speed, the average air movement velocity of all cases was 2.54 m. s^{-1}. The maximum and minimum air movement velocities were 3.10 m. s^{-1} and 1.17 m. s^{-1} respectively. From CFD result of air movement of two nearby-building layer, air flow pattern can be categorised mainly into 2 groups, which are

- 3-storey buildings on the first layer of nearby buildings. This includes D2, D3 and D4. (see Figure 6- 46)
- 8-storey buildings on the first layer of nearby buildings. This includes D5, D6 and D7. (see Figure 6- 47)

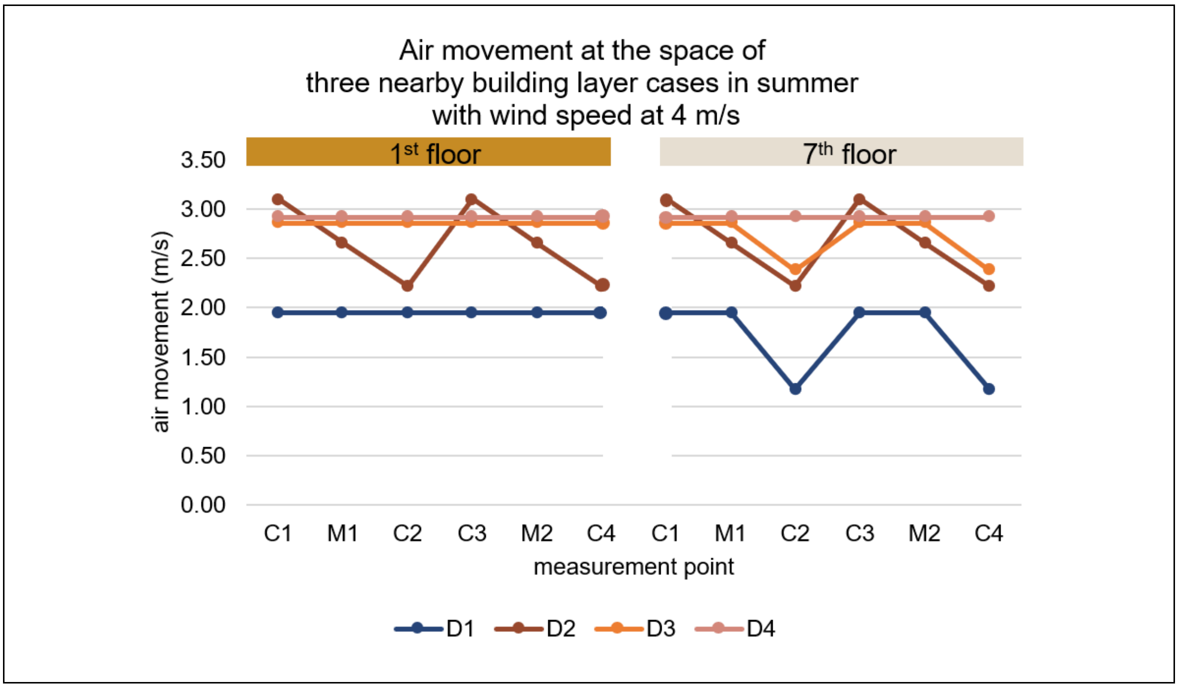


Figure 6- 46 Air movement at the space of three layers of nearby buildings cases in summer with wind speed at 4 m.s^{-1}

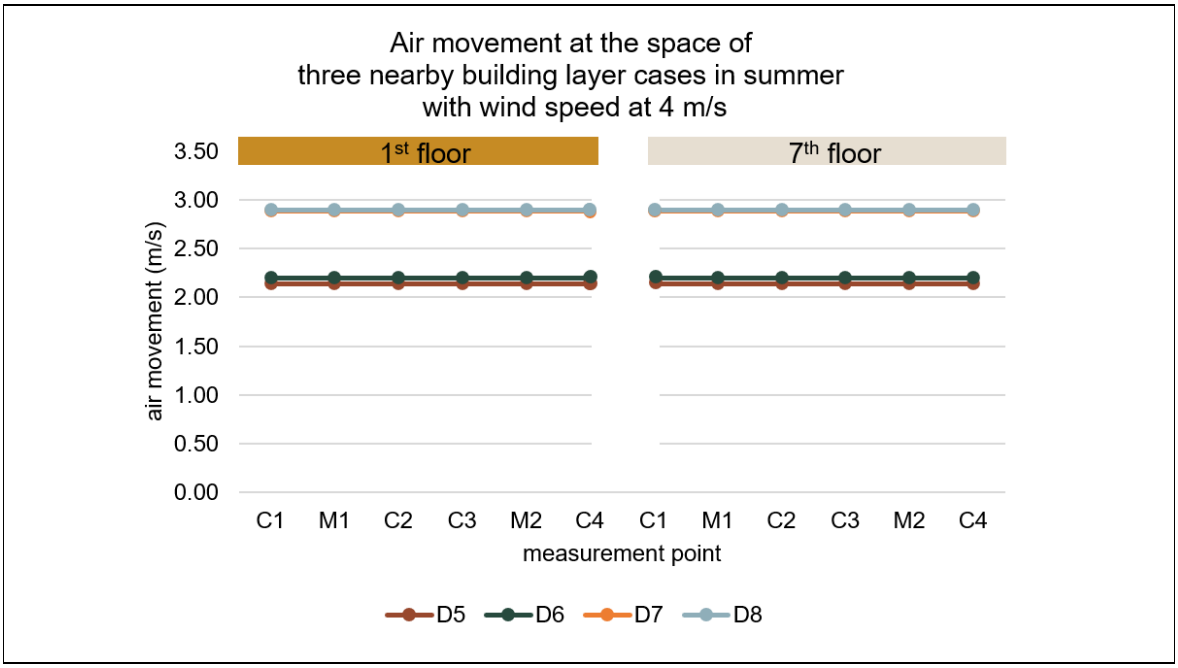


Figure 6- 47 Air movement at the space of three layers of nearby buildings cases in summer with wind speed at 4 m.s^{-1}
(Only data for 3 cases clearly visible due to similarities between certain layouts e.g. D8 is visible which covers similar data for D7)

- Comparing between case D1 (surrounded by all 3-storey buildings) and D2
  The difference between case D1 and D2 is 0 and 1 adjacent 8-floor buildings on the second nearby buildings layer. In case D1, the second layers building is 3-storey buildings whereas the buildings' layer in case D2 is 8-storey buildings. On the 1st floor, the air movement in case D1 was stable, while the air movement in case D2 had a lower velocity at the south corners and had a higher velocity at north corners of the focus building because of the rebound effect.
- Comparing between case D1 (surrounded by all 3-storey buildings) and D3
  The apparent difference of case D1 and D3 is relevant to the third layer of nearby buildings' height. There were 0 adjacent 8-floor storey buildings in case D1 whereas the third building layer of case D3 is 8- storey buildings. Although the air movement velocity at each measurement point of case D1 and D3 were different, both cases' flow pattern was similar. On the 1st floor, the air movement at all points remained stable. On the 7th floor, the wind encountered directly on the south façade of the focus building, which brought about the south corners in both cases had a lower velocity than the other points.
- Comparing between case D3 and D4

The second layer of nearby buildings height between case D3 and D4 is different. The second layer of case D3 is 3-storey buildings, whereas the layer in case D4 is 8-storey building. On the 1st floor, the air movement of both case D3 and D4 had a similar velocity with approximately 2.9 m. s^{-1}. However, only case D3, the wind could impinge directly on the south façade of the focus building on the 7th floor influencing the negative pressure occurring at the south corners, which affected such corners had a lower velocity comparing to other measurement points.

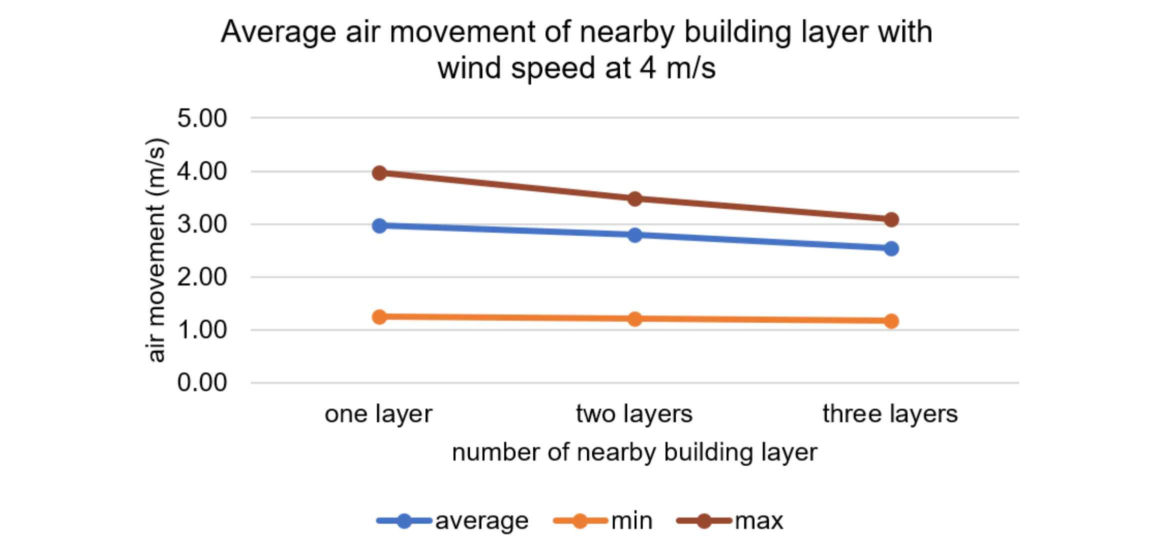
- Comparing between case D5 and D6

  The distinction between case D5 and D6 relates to the second nearby-building layer height. The second layer's height in case D5 is 3-storey buildings, whereas the height of such layer in case D6 is 8-floor buildings. Even the buildings at the second layer had a different height, the air movement at all measurement point had a similar velocity, which was around 2.17 m. s^{-1}, 45% lower velocity than the initial wind speed.

- Comparing between case D7 and D8 (surrounded by all 8-storey buildings)

  The obvious distinction between case D7 and D8 is the height of the layer of nearby buildings in the second layer. The height of the second layer of nearby buildings in case D7 is 3-storey buildings, contrastingly the height of the buildings in case D8 is 8-storey buildings. The air movement of all measurement points of both cases had a similar velocity with 2.9 m. s^{-1}.

Increasing the obstructions' layers affects reducing air movement velocity. The average air movement of one-nearby buildings layer was approximately between 25% and 27% lower velocity in comparison to the original wind speed. The average air movement was between 30% and 33% lower velocity than initial wind speed for two-nearby buildings layers, while the average air movement around the focus building in three-nearby buildings layers of was reduced approximately 37% from initial wind speed (see Figure 6- 48). These simplified models' experiments are significant for understanding air movement velocity decreased from more obstruction's layers. Thus, this could reduce more air movement velocity in the actual city centre with many more layers and random building layouts.



(This average is the air movement of C1, M1, C2, C3, M2, C4 on both 1st and 7th floor)

Figure 6- 48 Average air movement of each nearby building layer with wind speed at 4 m.s^{-1}

6.5 Summary CFD sensitivity: outdoor

Several variables impact the air movement on a building surface, including as follow:

Wind direction and wind speed: wind direction significantly influences air movement and pattern around building surface. The building surface on windward side has the highest wind speed as a result of direct wind impingement. The leeward side, on the other hand, impacts the air velocity to be reduced from shelter effect. Eddies and vortices tend to occur at each corner of building. The turbulence flow occurring affects wind direction to be changed from the original wind direction.

Road width and building height: Buildings along side road act as obstruction of wind flow, leading the air to change direction. Original wind flows over the buildings creating skimming flow region in the narrow space between the buildings. Additionally, the obstruction of nearby buildings creates funnelling effect causing the increasing of velocity in the space between building. The presence of skimming flow in the space between such buildings needs to be taken consideration when designing and simulation building. This is due to the potential of external wind significantly impacts on natural ventilation in passive building design. The building design should be ensured wider gaps between buildings. The aspect ratio between the gap to the height of buildings influence both wind patterns and air movement around building facade.

Nearby buildings: Air movement can be reduced up to 60% of the initial wind due to the increasing of nearby buildings layers. In addition, different heights of nearby buildings also affect wind speed and wind direction on building surface. Air movement of an 8-storey building surrounded 3-storey buildings flow more uniformly comparing to the building surrounded by 8-storey buildings. While turbulence flow occurs in the space between the buildings due to the obstruction, the air movement near the building surface flows along the contour of building façade. This indicates that the wind flow pattern is determined by the presence of buildings in viscosity, especially in high density area. The alignment and orientation of building impact the wind direction to be different from the initial wind direction provided by methodological weather data.

External wind impacts the microclimate around building, which significantly impacts on the potential of natural ventilation.

7 CFD sensitivity analysis result: indoor

7.1 Introduction

This chapter provides the results of the CFD sensitivity analysis for indoor environments, focusing on Objective 5 of the research. This objective seeks to investigate key factors influencing natural ventilation in multi-residential buildings. The methodology for this analysis was detailed in Section 3.6.

This chapter is divided into three main sections: validation (Section 7.2), CFD sensitivity exploring in indoor parameters (Section 7.3) and summary (section 7.4).

The validation section provides the comparison between CFD simulation results and monitored data from physical measurements of a middle room of Building A (Figure 3-10). This validation aims to establish a reliable starting point for CFD simulations and to assess the accuracy of CFD models.

The investigation of indoor parameters in CFD sensitivity analysis investigates the effect of various indoor space factors on natural ventilation. The analysis is divided into three stages, which are:

- Stage 1: focusing on establishing the base case for the study (Section 7.3.1)
- Stage 2: expanding on the base case to examine room parameters, such as the presence or absence of a chimney and the sizes of room inlets and outputs (Section 7.3.2)
- Stage 3: investigating chimney parameters related to thermal behaviour in the room and the chimney, which involve different dimensions of chimney inlet and outlet size, chimney width, chimney depth, chimney outlet and different storeys connecting to the chimney (Section 7.3.3)

The summary (Section 7.4) provides summarising and analysis of the findings from stages one to three of the investigation of indoor parameters to propose design options for improving IEQ in multi-residential buildings.

7.2 Validation

The methodology for validation was detailed in Section 3.6.1. To validate simulation model, outputs, such as air temperature, relative humidity and air velocity, were compared against monitored data from physical measurement in actual room in multi-residential building.

Data from monitored room, featuring single-sided ventilation, middle room on the third floor of Building A (described in Section 3.3.3), were selected for this validation process.

i) Inputting Cp data from MacroFlo (detailed in Section 3.6.1.2): This model in DesignBuilder incorporated Cp data from MacroFlo (addressed in Section 3.2.2 and Appendix A).
ii) Inputting microclimate boundary conditions from the Envi-met programme. (described in Section 3.6.1.3): This CFD model in DesignBuilder used microclimate data from Envi-met. The output from Envi-met was used to generate an EPW file, setting the external environment parameters of the CFD model, such as dry bulb temperature, relative humidity, wind speed, and site ground temperature (see CFD results in Figure 7- 1).

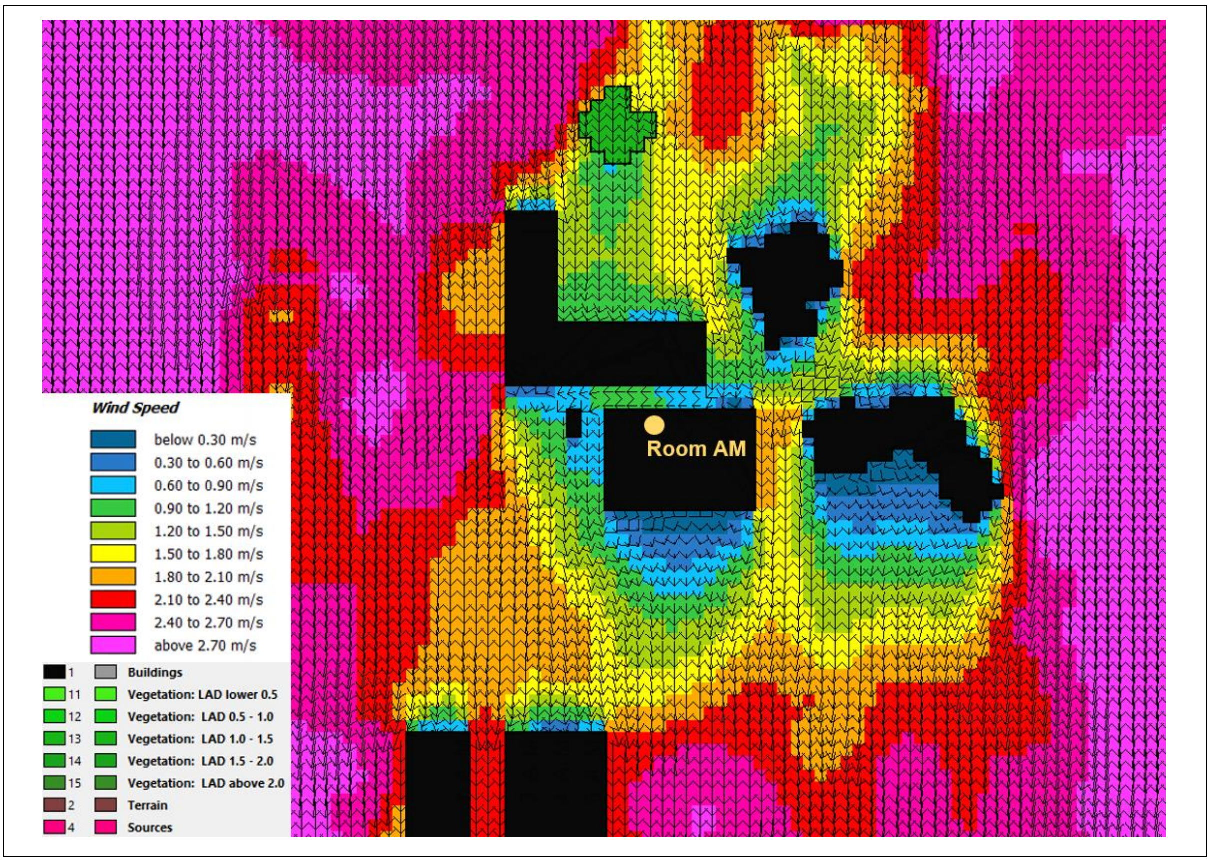


Figure 7- 1 CFD results from Envi-met for Building A and its surroundings at a height of 11 meters from the ground.
(Source: Author)

The comparison of air temperature, relative humidity and air velocity are illustrated in Figure 7- 2, Figure 7- 3 and Figure 7- 4, respectively. To evaluate the accuracy of the CFD model, regression and RSME method were used.

Based on the simulations, indoor air temperatures for case of inputting Cp data from MacroFlo (DB+Cp) ranged from 22.30°C to 25.09°C, with an average of 23.79°C, and for case of inputting microclimate boundary conditions from the Envi-met programme (EV+DB), the range was 22.70°C to 24.89°C, with an average of 23.87°C. These simulated data were consistent with the monitored data, which had an air temperature range of 22.28°C to 24.87°C, with an average of 23.63°C. The Square R values for DB+Cp and EV+DB compared to monitored data were 0.93 and 0.90, respectively. The RMSE values were 0.32 and 0.41, respectively, which were within acceptable limits as described in Section 3.6.1.4. (See Figure 7- 2)

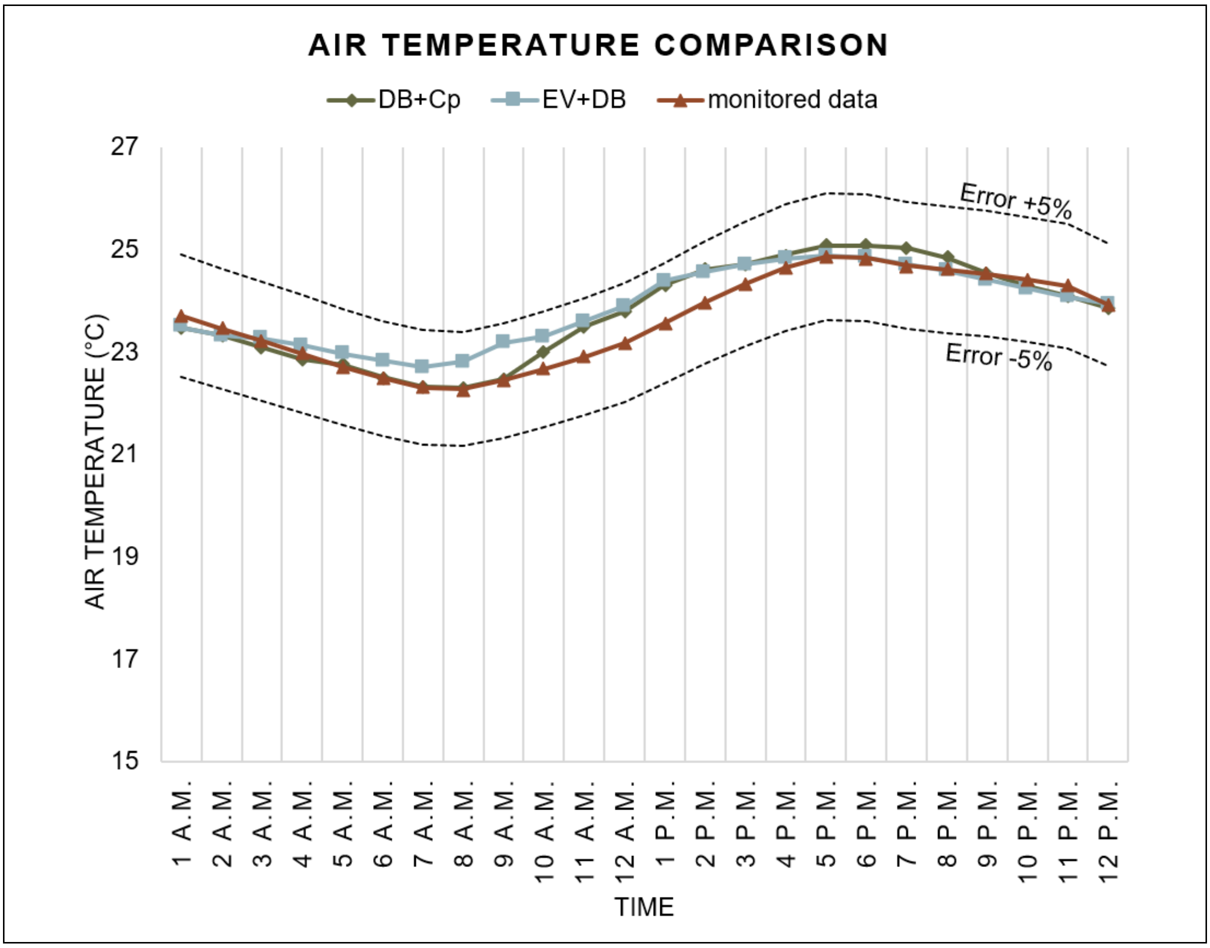


Figure 7- 2 air temperature comparison between physical measurement data, Envi-met and DesignBuilder simulation results

According to the simulations output, relative humidity for case using Cp data from MacroFlo (DB+Cp) varied between 53.81% to 63.46%RH, averaging at 59.65%RH. For case involving microclimate boundary conditions from the Envi-met programme (EV+DB), relative humidity fluctuated between 53.84% to 64.68%RH, with an average of 59.90%RH. These simulated data were relative with the monitored data. Square R values for DB+Cp and EV+DB compared to monitored data were 0.92 and 0.91, respectively. The RMSE values were 1.14 and 1.11, respectively, which were considered acceptable as described in Section 3.6.1.4. (See Figure 7- 3)

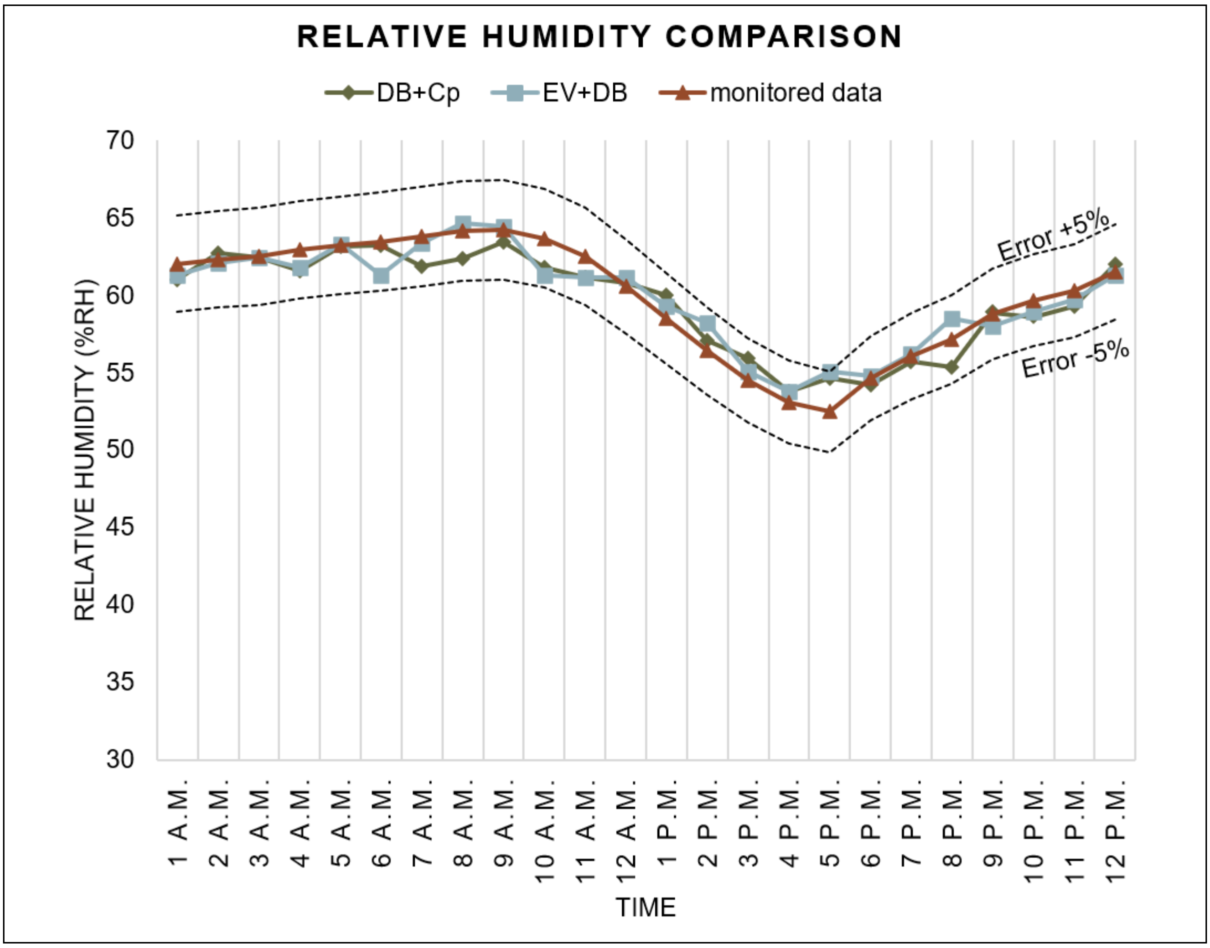


Figure 7- 3 relative humidity comparison between physical measurement data, Envi-met and DesignBuilder simulation results

Minimum and maximum air velocity for case of inputting Cp data from MacroFlo (DB+Cp) were 0.01 $m.s^{-1}$and 0.07 $m.s^{-1}$ and the average of 0.05 $m.s^{-1}$. For case of inputting microclimate boundary conditions from the Envi-met programme (EV+DB), the minimum and maximum air velocity were 0.02 to 0.07 $m.s^{-1}$, with an average of 0.04 $m.s^{-1}$. These simulated data were correlated to the monitored data, with R square of 0.94 for DB+Cp and 0.92 for EV+DB. The RMSE values were at 0.21 and 0.14, respectively, which were within acceptable limits as described in Section 3.6.1.4. (See Figure 7- 4)

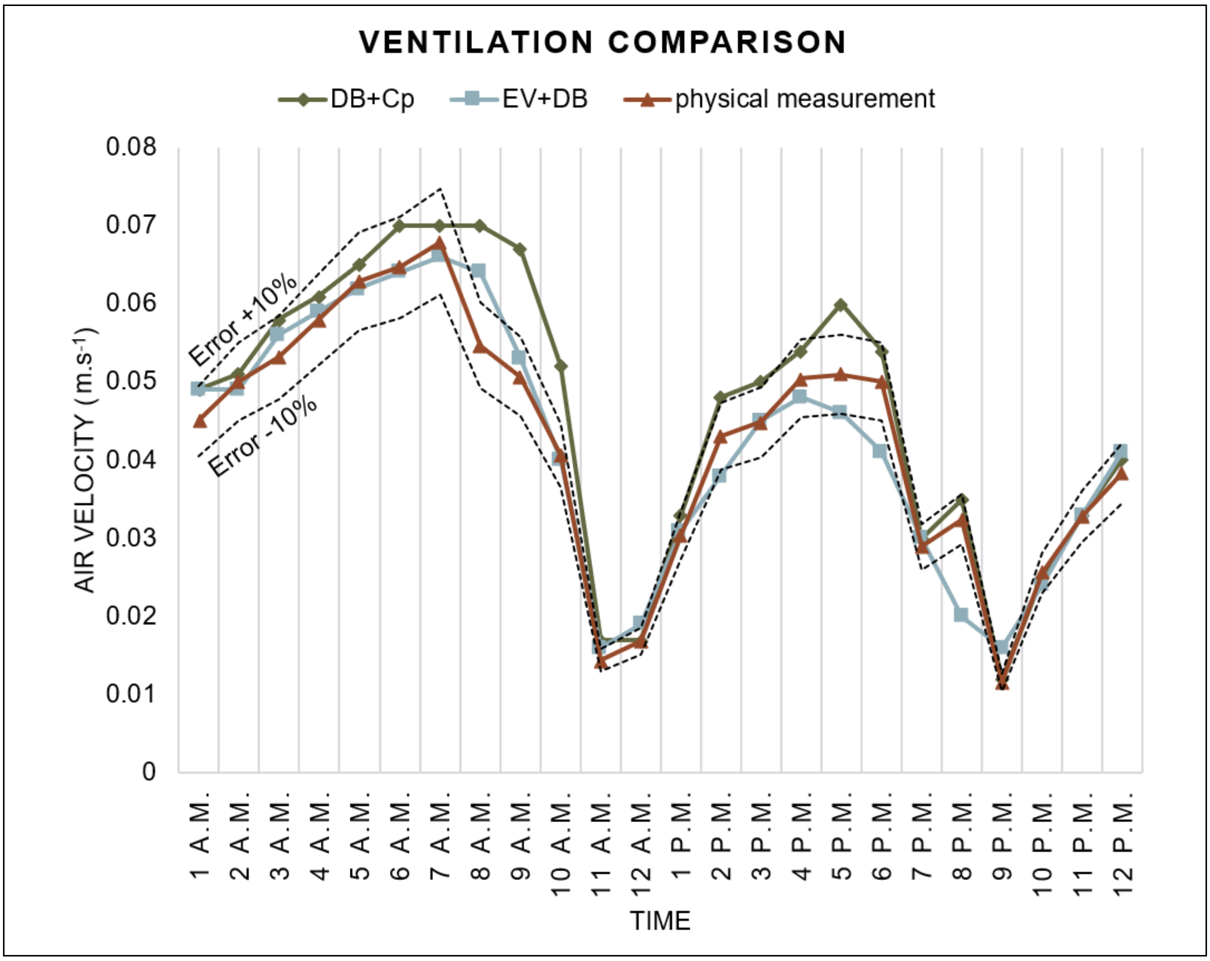


Figure 7- 4 ventilation comparison between physical measurement data, Envi-met and DesignBuilder simulation results

While there are some variations between the simulated and monitored data, these were within an acceptable level. Consequently, using DesignBuilder with input Cp data provides acceptable accuracy and a reliable starting point for CFD simulations and effectively assessing the accuracy of CFD models.

7.3 CFD sensitivity for exploring in indoor parameters

This section provides the results of investigation of indoor parameters in CFD sensitivity analysis investigates the effect of various indoor space factors on natural ventilation. Initially, the study criteria, detailed in Section 3.6.2, identified a thermal comfort range between 22.3 °C and 29.3 °C and 20%RH and 80%RH. The relative humidity considered beneficial for health was defined between 40%RH and 60%RH. The acceptable ventilation in room was set within 0.2 $m.s^{-1}$ to 0.8 $m.s^{-1}$ and the required ventilation rate was 10 $L.s^{-1}$ or 0.01 $m^3.s^{-1}$.

7.3.1 Stage 1: focusing on establishing the base case for the study

In order to establish a base case room, the study divided the exploration of base case into two parts, which were base case building (Section 7.3.1.1) and base case room (Section 7.3.1.2)

7.3.1.1 Base case building

The base case building was established based on the typical building characteristics identified in the findings of the residential perception survey (Chapter 5). This included an 8-storey residential building situated in a dense area, featuring a double-loaded corridor layout.

7.3.1.2 Base case room

According to the minimum requirement of the regulation for the indoor dimension of Building Control Act (2015), this analysis determined that the base case room size should be 20 m^2, with a construction span width of 4 metres and a floor-to-floor height of 2.60 metres. The typical materials used are detailed in Table 3-11. Variations of the room will also be explored to establish the base case room, including Full Balcony (FB) and Half Balcony (HB) (Section 7.3.1.2.1), corner and middle room (Section 7.3.1.2.2), Opening orientation options (Section 7.3.1.2.3) and Room floor (Section 7.3.1.2.3).

7.3.1.2.1 Full Balcony (FB) and Half Balcony (HB)

Figure 7- 5 illustrates a comparison of ventilation between full balcony room (FB) with WC near corridor and half balcony room (HB) with WC located near balcony. The average ventilation rates were approximately 0.07 $m.s^{-1}$ in the corner room and 0.02 $m.s^{-1}$ in middle room. In both the HB and FB rooms, the air velocity was nearly zero, but there were slight differences. The average air velocity in Room HB was found to be 40% lower than in room FB. Room HB had an average air velocity of 0.02 $m.s^{-1}$, while room FB had a slightly higher average of 0.03 $m.s^{-1}$.

7.3.1.2.2 Corner and middle room

The average ventilation was approximately 0.07 $m.s^{-1}$ in the corner room and 0.02 $m.s^{-1}$ in middle room. Notably, ventilation in middle room was 71.4% of the ventilation of the corner room. In the corner room, the ventilation could reach to 0.22 m.s^{-1} due to the extra window.

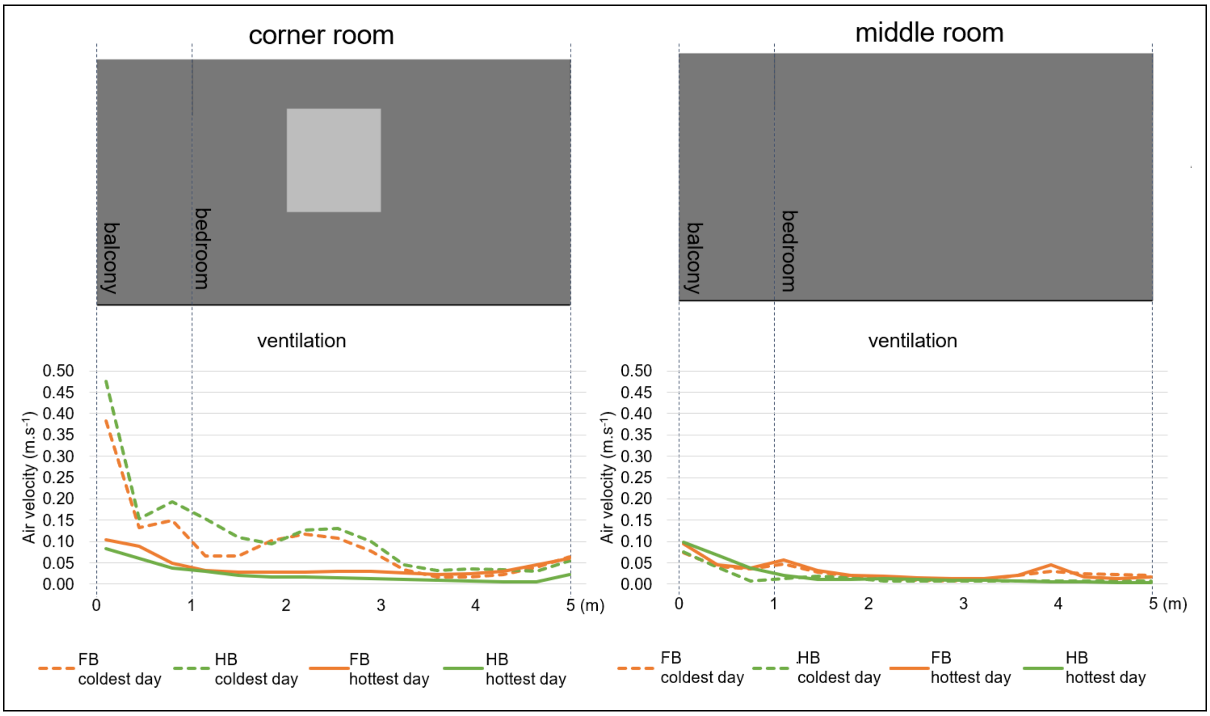


Figure 7- 5 Air velocity comparison between full balcony room (FB) and half balcony room (HB)

7.3.1.2.3 Opening orientation options and room floor

This section focuses various options for opening orientations considering orientations facing north/ south or east/ west. It also examines room heights at different building levels, including 1st, 4th and 7th floor (see Figure 7- 6 Figure 7- 7).

Previous results (Section 7.3.1.2.1 and 7.3.1.2.2) indicated that both half balcony room (HB) and middle room experienced lower ventilation. Therefore, the study further investigates the impact of building orientation on the middle room ventilation by comparing two types of building orientations: those with openings facing north and south (referred to as NS building) and those with openings facing east and west (referred to as EW building).

Figure 7- 6 illustrates location of middle rooms with different opening orientations. In the figure, the abbreviations indicate the specific location and orientation of the middle rooms within the building. The lowercase letter "m" denotes a middle room, while "n,"

"e," "s," and "w" indicate a location that is further north, east, south, or west within the building layout, respectively. The uppercase letters "N," "E," "S," and "W" specify the direction the opening faces. For instance, "msW" refers to a middle room situated further south within the building's layout, with an opening facing west. Similarly, "mwN" denotes a middle room located further west within the layout, with an opening facing north.

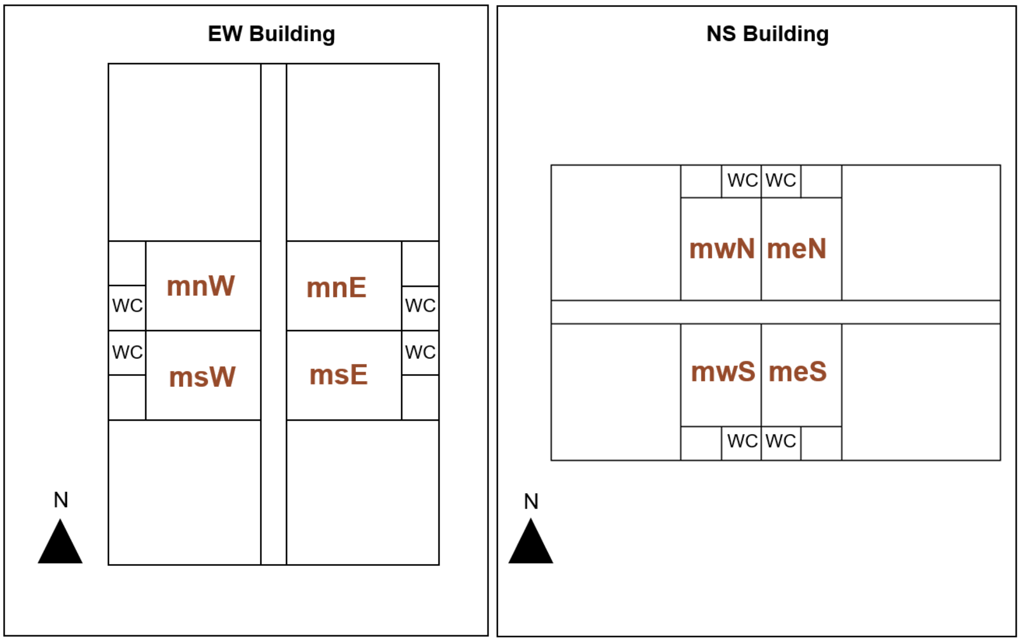


Figure 7- 6 locations of room in different opening orientation options facing north and south (NS Building) or facing east and west (EW Building)

In Figure 7- 7 indicates that ventilation rates remain consistently below the minimum required ventilation rate of 0.2 $m.s^{-1}$ across all floors levels and times of the day. Despite higher floors achieving slightly improved ventilation, they remained lower than the minimum standard. There appears to be a uniform pattern in ventilation rates across the 1st, 4th, and 7th floors, and no significant variation is observed based on the direction in which the rooms face (North, East, West, South). The surrounding buildings were significant influenced on airflow direction. There is little variation in wind direction throughout the simulation. The middle rooms with same opening orientations exhibit similar ventilation. For example, the simulation for room mnW can be applied but with opposite orientation to room msW. Notably, middle room in Building EW with opening facing north (room meN and mwN) had the lowest ventilation in comparison to other rooms facing other directions.

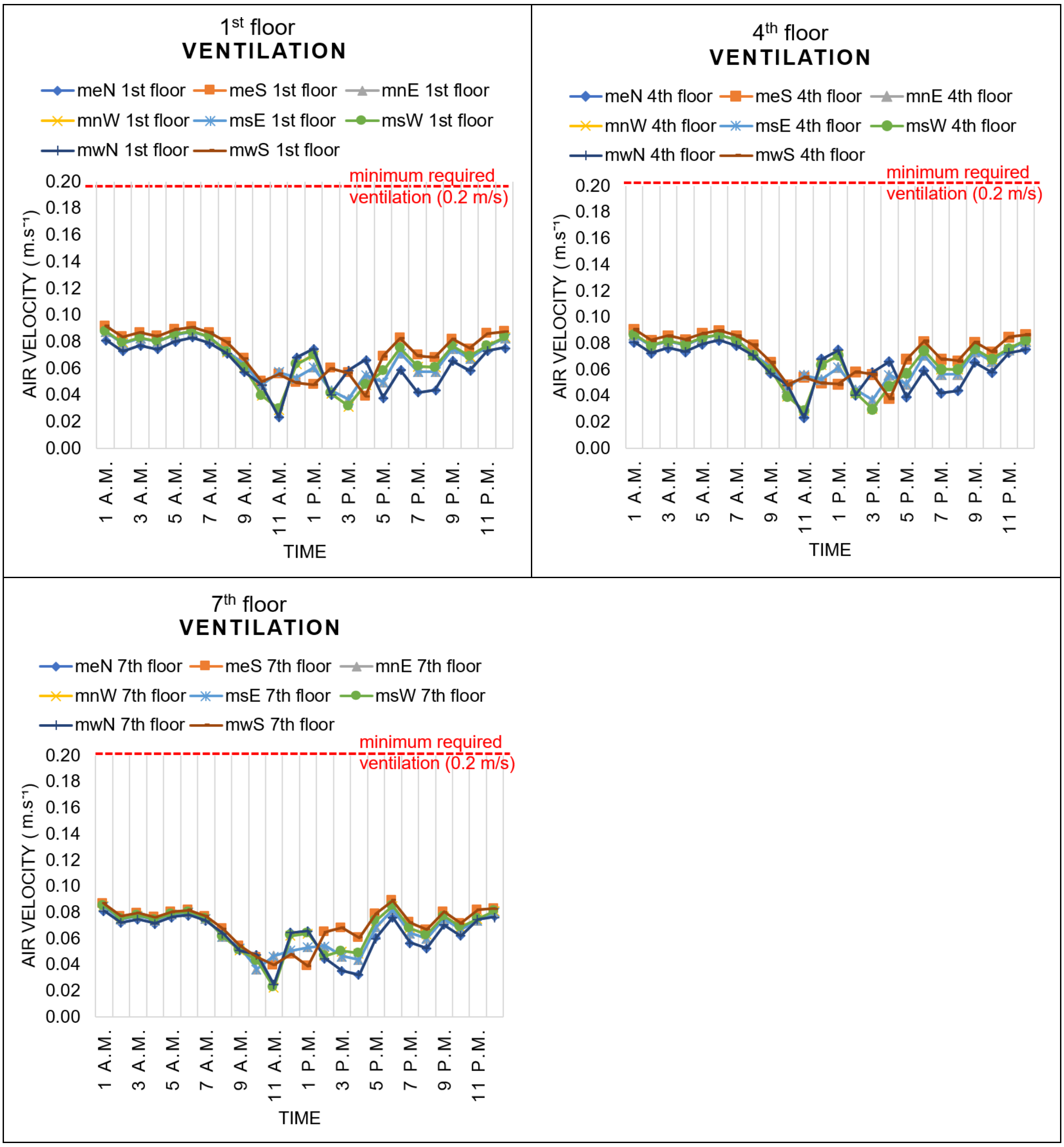


Figure 7- 7 Ventilation comparison of different opening orientation options and room floor

To summarise, the base case for the building in this study is an 8-storey residential structure located in urban area with double-loaded corridor layout. The base case for the room is defined as a Half Balcony (HB) room, located in the middle of the building with its opening facing north. Both the base case building and the base case room will be used as a base model for further exploration in stage 2 and stage 3.

7.3.2 Stage 2: exploring room changes to improve natural ventilation flow

This section provides the EnergyPlus and CFD simulation results of exploring room parameters. Methodology was described in Section 3.6.2.2.

7.3.2.1 Room with and without chimney

Methodology was detailed in Section 3.6.2.2.1.

Figure 7- 8 depicts the hourly average room air temperature at the occupant level (1 meter above the floor) in rooms with and without a chimney. Room with a chimney exhibits lower temperatures than those without. Part (a) of the graph indicates the thermal comfort range. Part (b) indicates the expanded thermal comfort range achievable with air movement between 0.2 and 0.8 m.s⁻¹. On the hottest day, rooms with a chimney remained within this extended comfort range 96% of the time, with an exception at 8 p.m. to 11 p.m. On the coldest day, temperatures in both rooms decrease outside the thermal comfort zone from 12 p.m. to with chimney and 12 a.m. for from 2 a.m. to 11 a.m. for without chimney.

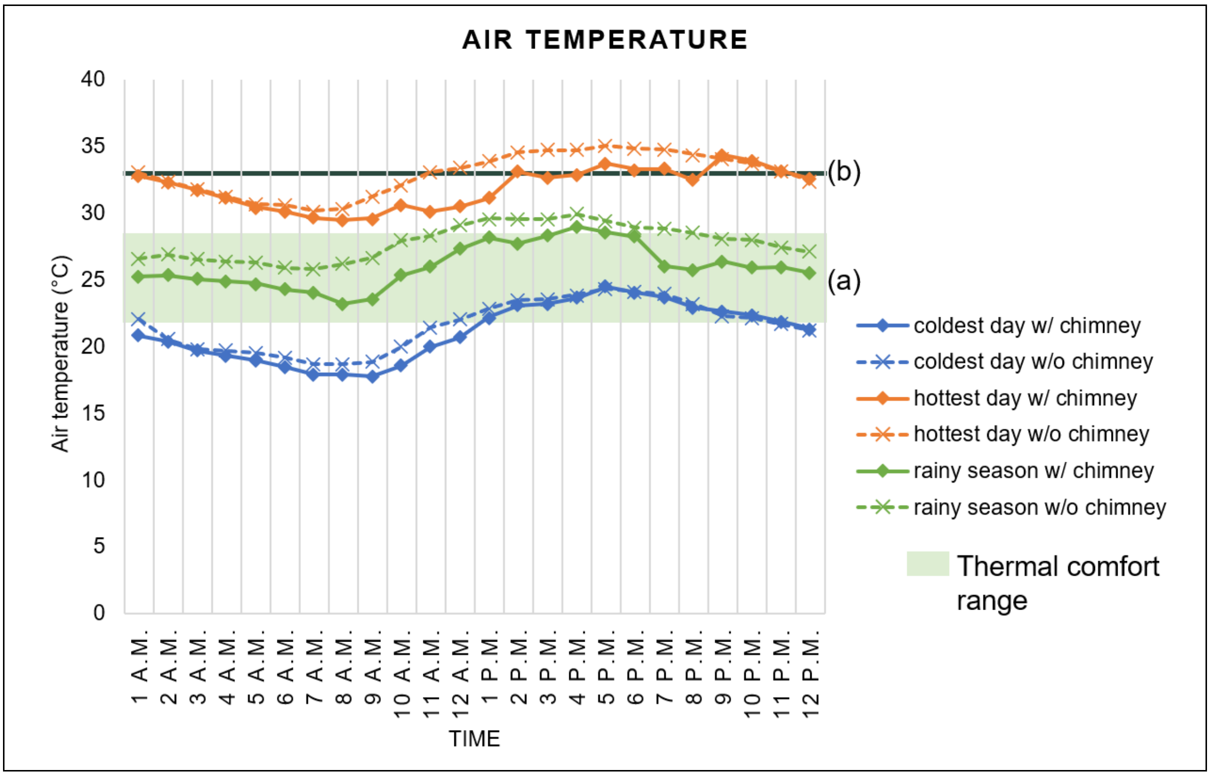


Figure 7- 8 air temperature within room with and without chimney

Figure 7- 9 illustrates the hourly average relative humidity in rooms with and without a chimney. On both the hottest and coldest days, from 11 a.m. to 10 p.m., the rooms

with a chimney have a relative humidity approximately 4%RH lower than those without a chimney.

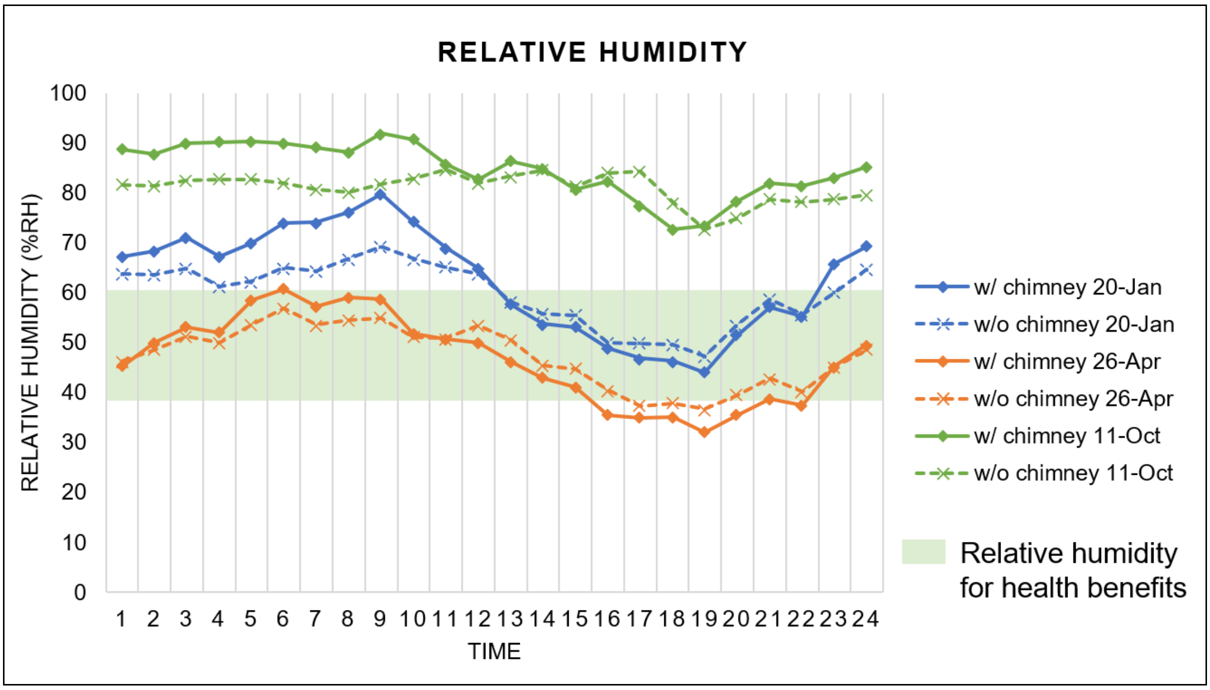


Figure 7- 9 relative humidity within room with and without chimney

The comparison of the average ventilation in rooms with and without a chimney is shown in Figure 7- 10. Rooms with a chimney were shown to enhance greater ventilation. On both the coldest and the hottest days, rooms with a chimney exhibited an increase in average ventilation by 0.20 $m.s^{-1}$ and 0.19 $m.s^{-1}$, respectively, compared to rooms without a chimney. During the rainy season, the rooms with a chimney maintain an average ventilation rate that is 0.11 $m.s^{-1}$ higher than that of rooms without a chimney. Rooms without a chimney have an average ventilation rate of approximately 0.02 $m.s^{-1}$.

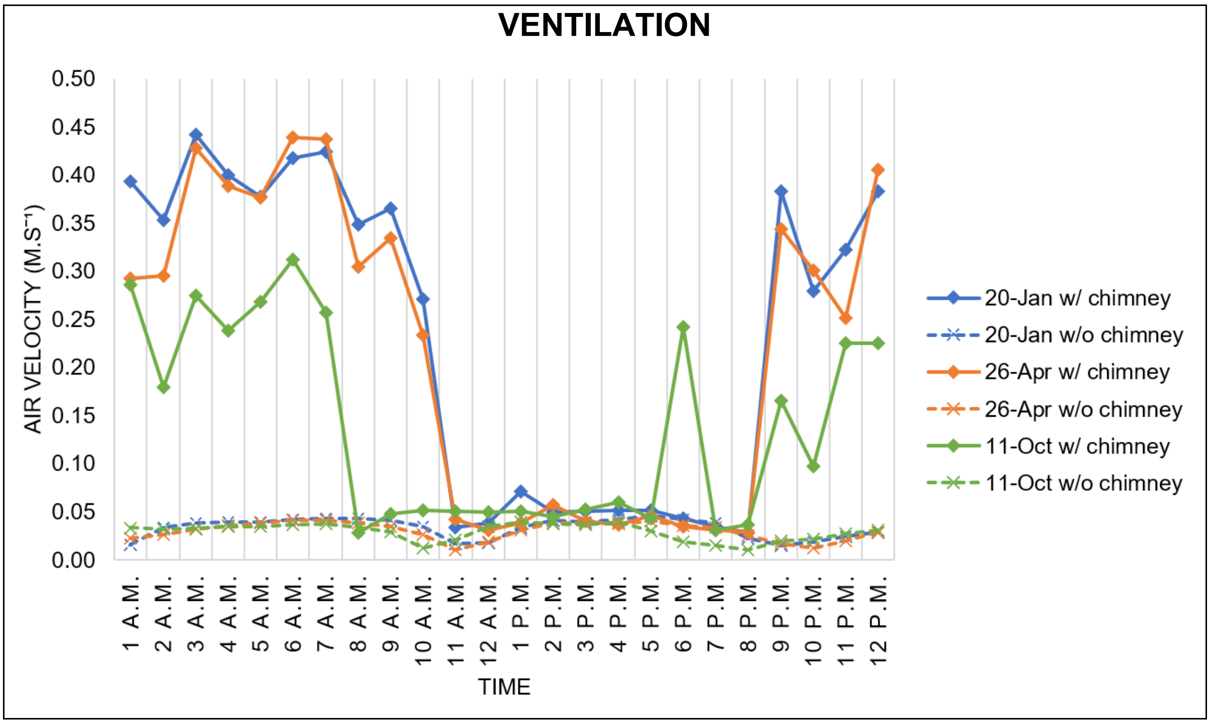


Figure 7- 10 air velocity within room with and without chimney

7.3.2.2 Room inlet and room outlet size

Methodology was described in Section 3.6.2.2.2.

Air temperature resulting from different room inlet and outlet sizes is shown in Figure 7- 11. A room with a greater room inlet size had a higher temperature but the temperature is still lower than the external temperature.

Air temperature in room with the same outlet area but different dimensions was similar. For example, a room with inlet size of 1.0 x 1.1 with outlet size of 1.0 x 0.3 and room with inlet size of 1.0 x 1.1 with outlet size of 0.3 x 1.0 had temperature of 26.85°C and 26.85°C, respectively. The room with narrow outlet size (the outlet width is lower than 0.5 m) offers a greater flexibility in multi- storey room design.

The relationship between temperature and outlet size is illustrated in Figure 7- 12. A positive correlation exists between the outlet area and the average ventilation rate (R square above 0.95). The increase of room outlet area is associated with higher air temperature.

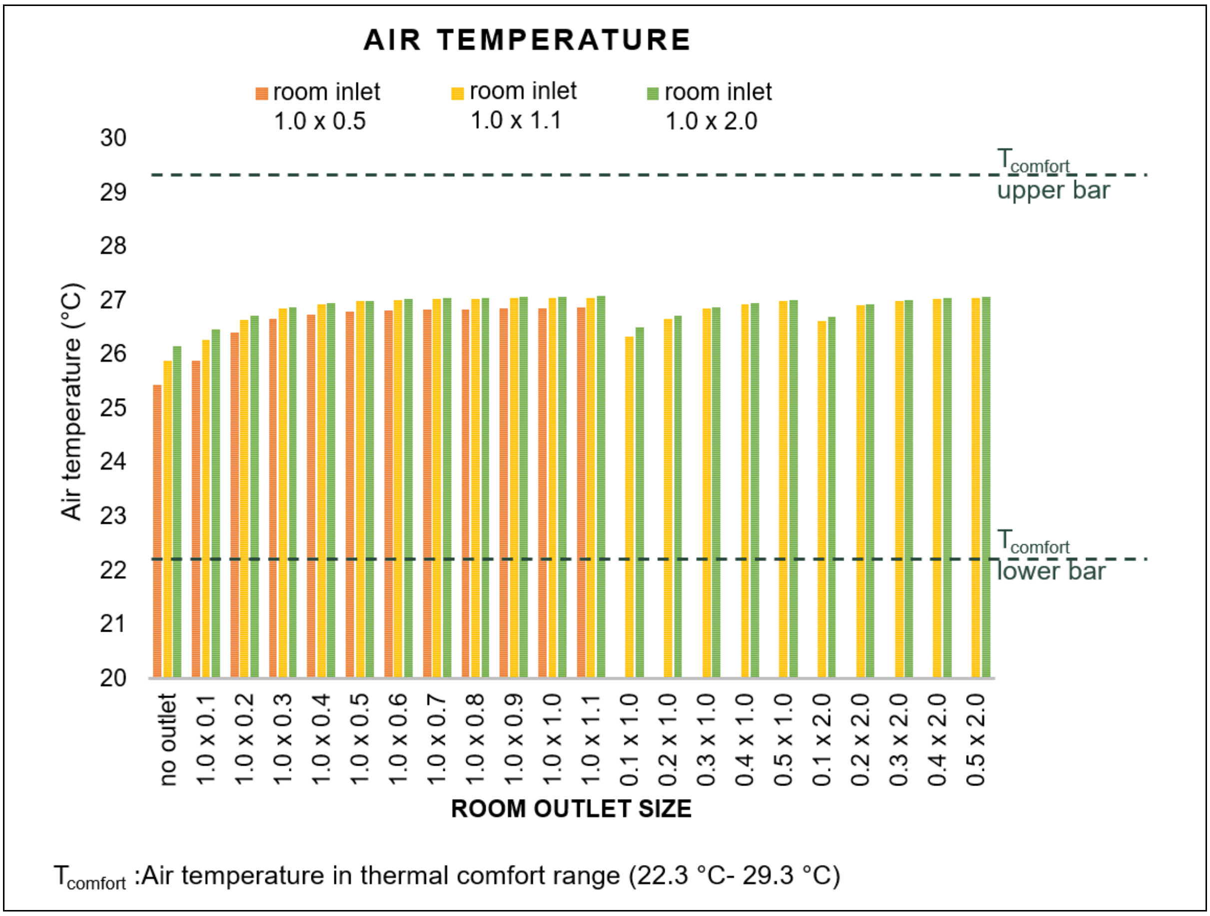


Figure 7- 11 temperature within room with different room inlet and outlet sizes

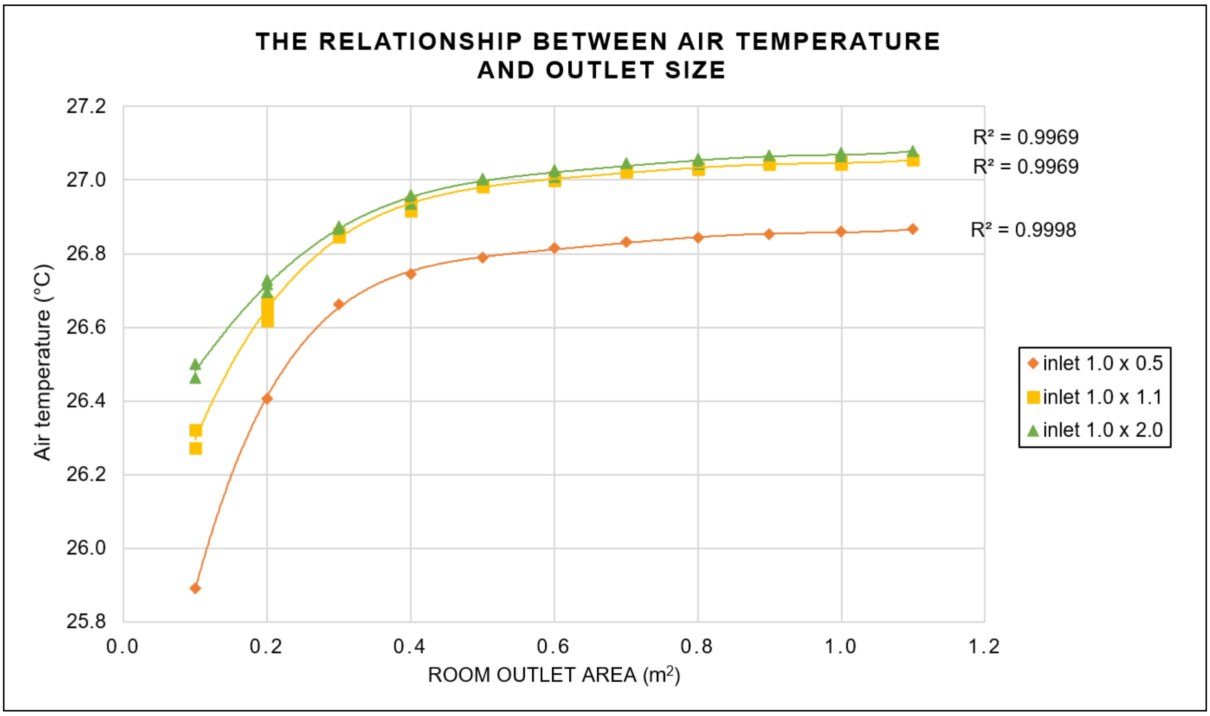
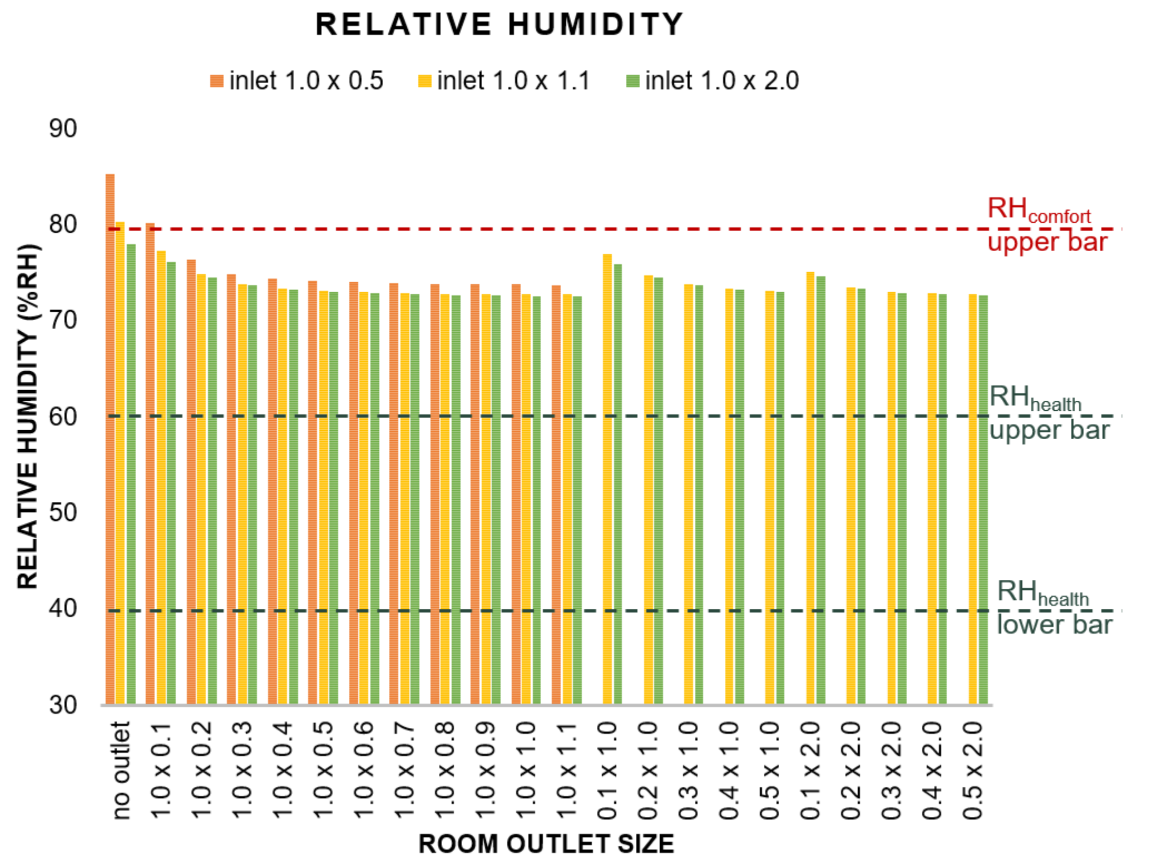


Figure 7- 12 relationship between temperature room outlet size

The relative humidity in rooms with varying inlet and outlet sizes was found to be inversely correlated with temperature, as illustrated in Figure 7- 13 and Figure 7- 14.

A greater inlet size influenced room to have a lower relative humidity. In contrast, the lower inlet size could enhance the room to have higher relative humidity. The room without room outlet (no chimney) had relative humidity more than 10% of the external relative humidity. For example, room with inlet of 1.1 x 0.5 had approximately 85.34%RH, which is a 21.9% increase of external relative humidity.

A room with the same room inlet and outlet area but different outlet dimensions had a similar relative humidity.



$RH_{comfort}$:Relative Humidity in thermal comfort range (20%RH-80%RH)
Rh_{health} :Relative Humidity for health benefits (40%RH-60%RH)

Figure 7- 13 relative humidity within room with different room inlet and outlet sizes

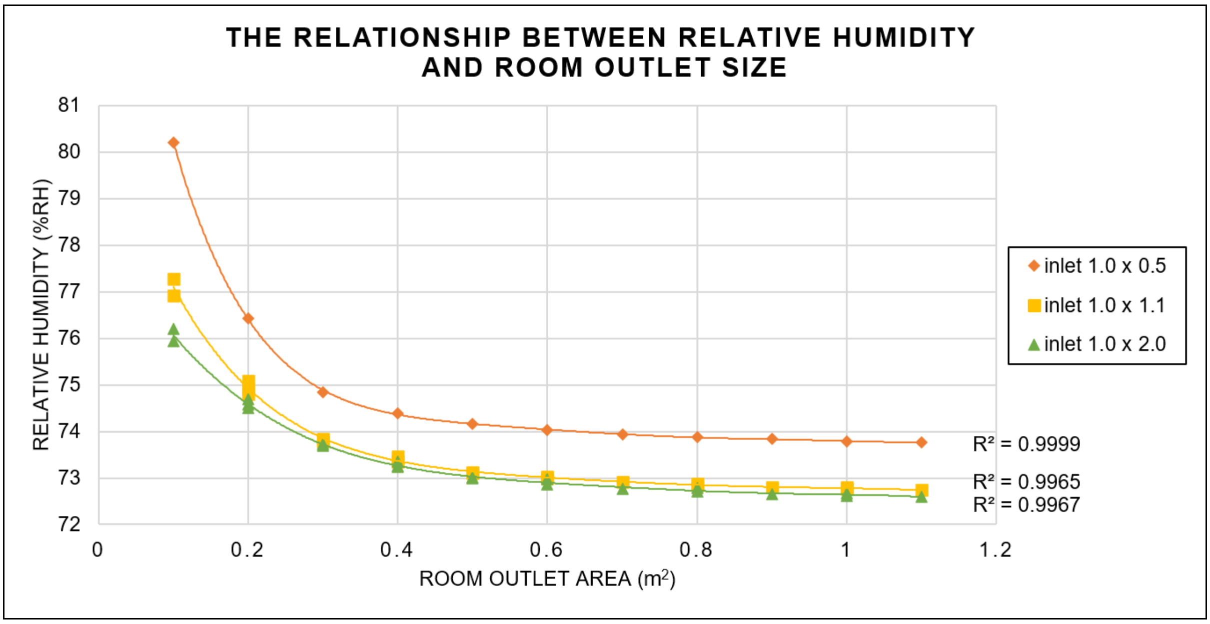


Figure 7- 14 relationship between relative humidity and room outlet size

Figure 7- 15 illustrates the average ventilation of room with different inlet and outlet sizes. An optimal range of outlet area appears to be around 0.3 m² for inlets measuring 1.0 x 1.1 m and 1.0 x 2.0 m. This range is significant as it can achieve the minimum required ventilation rate. Additionally, for these larger inlet sizes, the ventilation rate's increase appears to be uniform across the presented outlet size range.

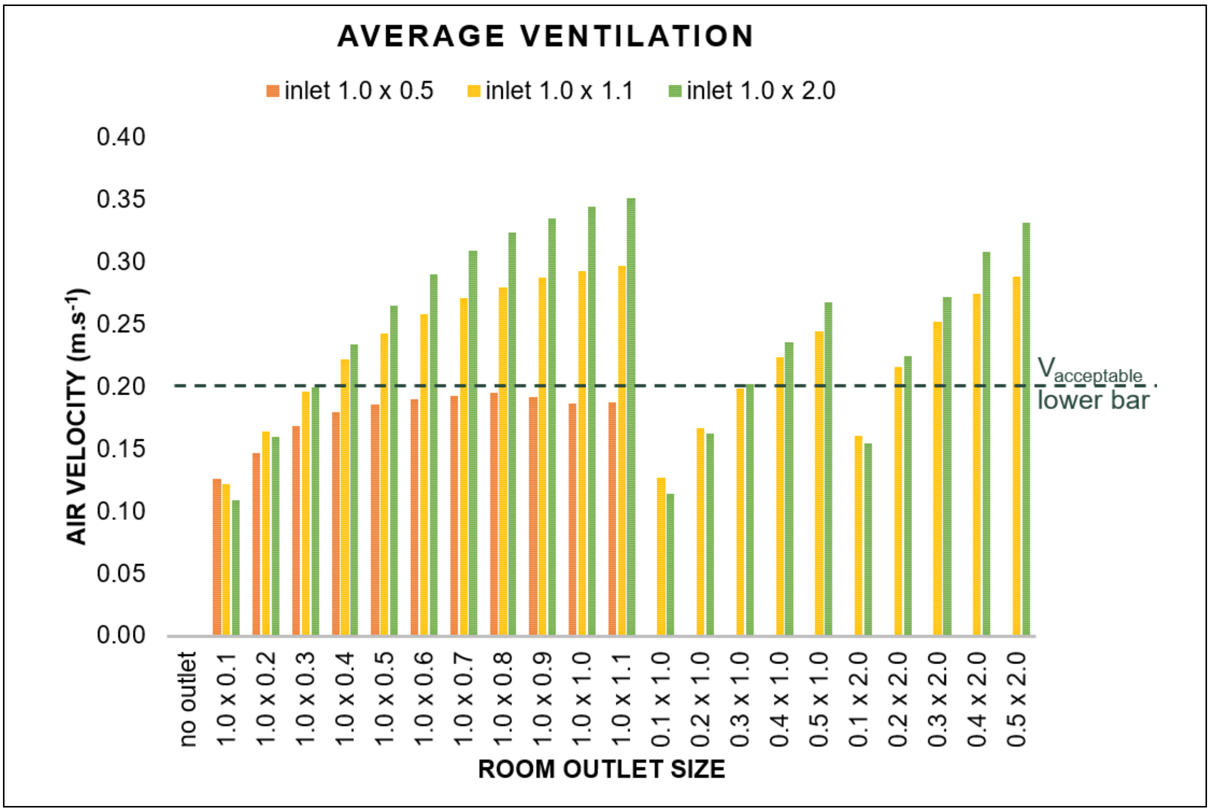


Figure 7- 15 average ventilation within room with different room inlet and outlet sizes

Figure 7- 16 illustrates the relationship between average ventilation and outlet size, considering three different inlet sizes: 1.0 x 0.5 m, 1.0 x 1.1 m, and 1.0 x 2.0 m. For all three inlet sizes, a strong correlation exists between the outlet area and the average ventilation rate (R square above 0.95). The increase of room outlet area influenced ventilation to increase. Notably, the largest room inlet size of 1.0 x 2.0 m demonstrates the highest ventilation rate as the outlet area enlarges. The larger room inlets facilitate further increase in average ventilation rates.

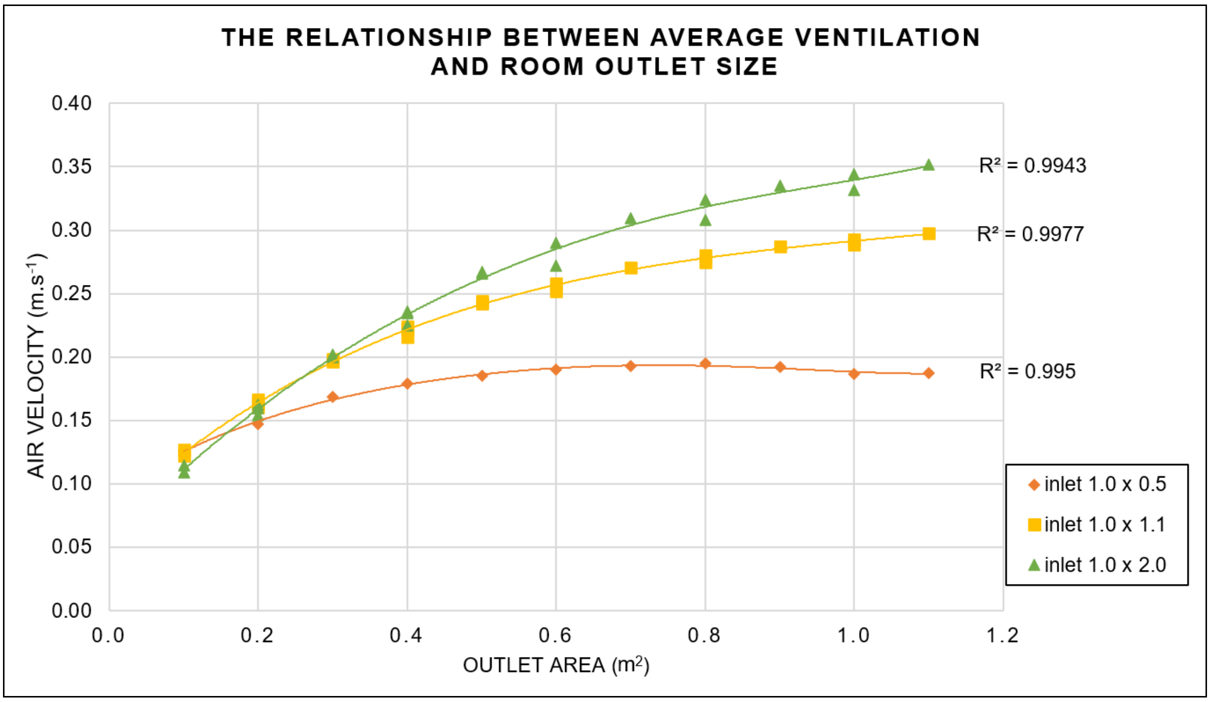


Figure 7- 16 relationship between ventilation and room outlet size

The findings in Stage 2 can be summarised as follows:

- air temperature and ventilation were directly proportional to the inlet and outlet size, while relative humidity was inversely corelated to the inlet and outlet size.
- A room with the same inlet and outlet size but different outlet dimensions resulted in a similar temperature, relative humidity, and ventilation (See Figure 7- 17). The room with narrow outlet was beneficial as it allowed multi-storey buildings to be designed with one chimneys to each room.
- Room with inlet of 1.0m x 2.0m and outlet of 0.3 m x 1.0m was the optimal size. Therefore, this inlet and outlet size will be used as a base case in stage 3.

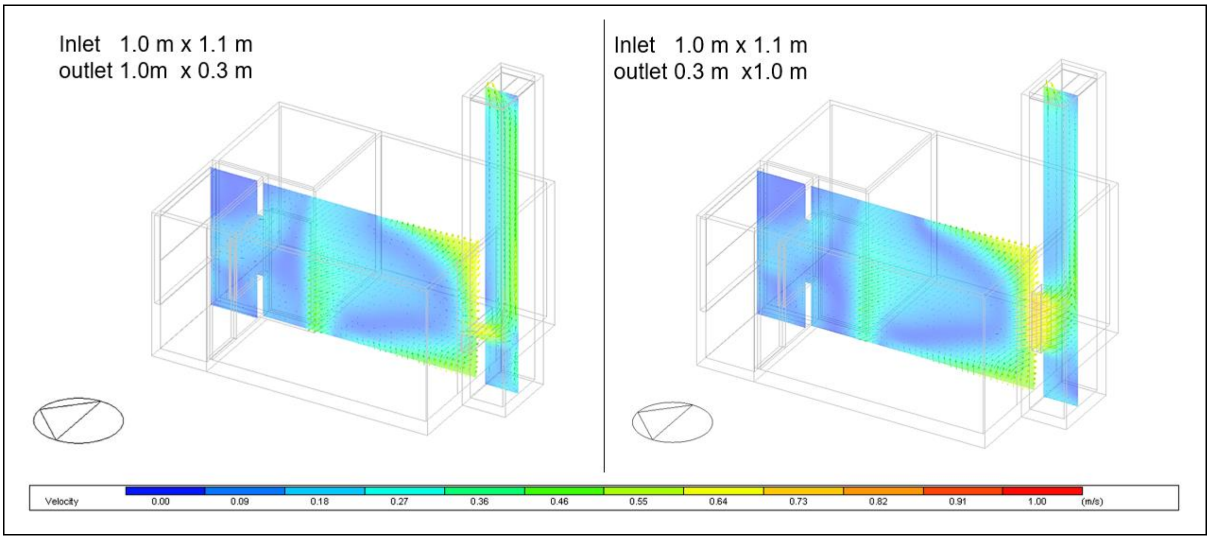


Figure 7- 17 An example of CFD result for exploring room inlet and outlet size

7.3.3 Stage 3: exploration of chimney parameters impact on natural ventilation

This section provides the findings of investigating chimney parameters related to thermal behaviour in the room and the chimney.

7.3.3.1 Chimney width and depth

Methodology was presented in Section 3.6.2.3.1.

The exploration of chimney width and depth was divided into two parts, which were varying width and depth with fixed chimney outlet and varying width and depth with varied chimney outlet dimension (see Figure 3-31).

Figure 7- 18 demonstrated the airflow in chimney between with fixed chimney outlet size (0.3 m x 0.3 m) and varied chimney outlet size. Airflow in chimney with varied chimney outlet size was directly proportioned to the chimney outlet size. The wider outlet size facilitated higher airflow rate through the chimney. In contrast, for the fixed chimney outlet size, the airflow had a negative relationship with chimney width and depth dimension. The optimal chimney depth was analysed to be at 0.3 m. The deeper chimney dimension resulted in lower airflow in the chimney.

The graph shows that varied chimney outlet impacted airflow in chimney more than varying width and depth for fixed chimney outlet size. In other word, chimney outlet size has the most influencer on the airflow in comparison to chimney dimension (width and depth).

Air temperature exhibited a stronger correlation with the dimension of the chimney outlet size than with chimney depth or width, demonstrating a positive relationship with the size of the chimney outlet (see Figure 7- 19). The temperature increase observed is relatively minor, approximately 1%, whereas the increase in airflow increase is significant, approximately 126%, and the air flow has a more significant cooling benefit.

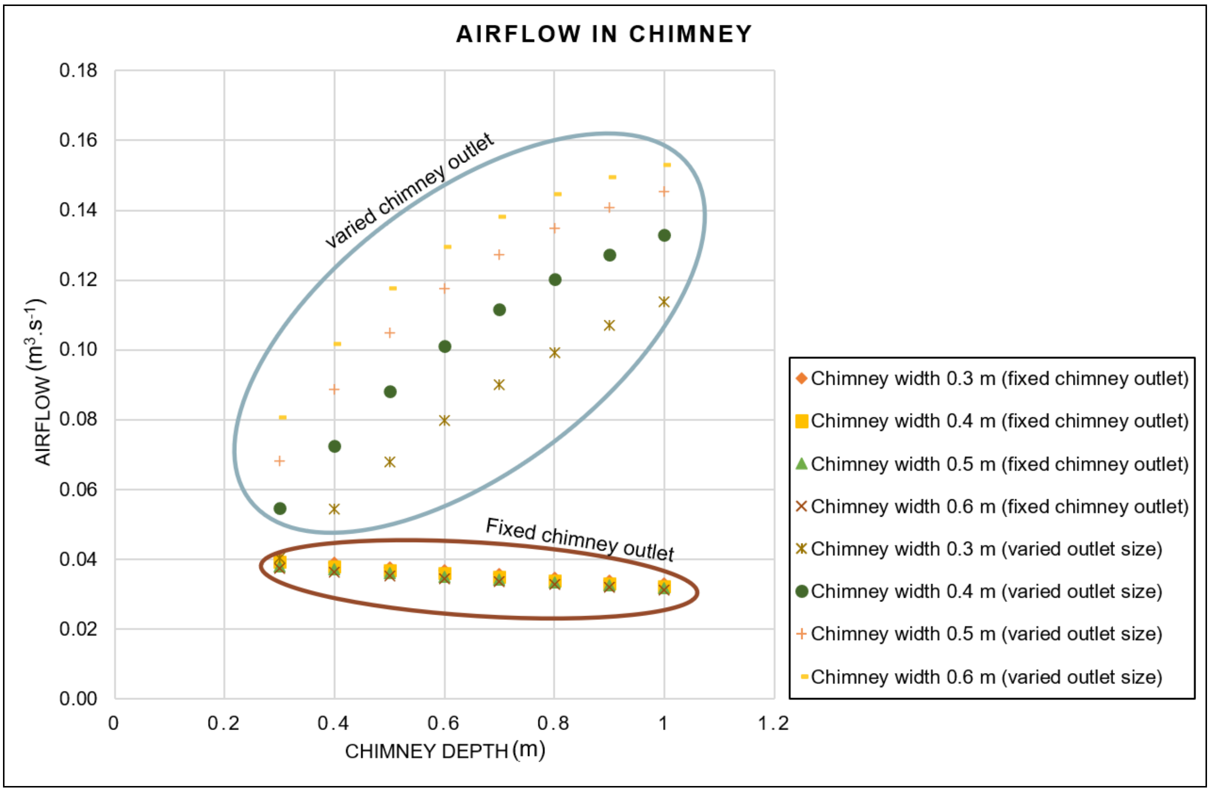


Figure 7- 18 comparison of airflow in chimney between with fixed chimney outlet size and varied chimney outlet sizes

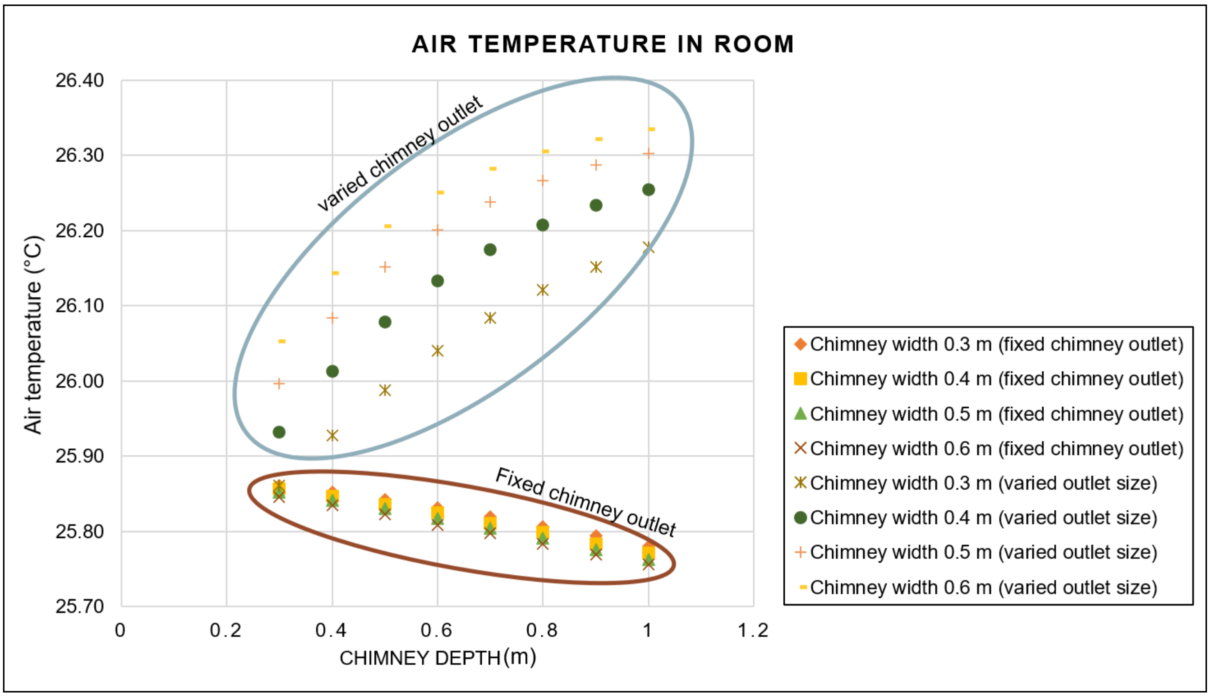


Figure 7- 19 comparison of temperature in room between with fixed chimney outlet size and varied chimney outlet sizes

7.3.3.2 Room outlet location

Methodology was explained in Section 3.6.2.3.2.

Rooms with varying outlet locations (see Figure 3-32) had similar temperatures and relative humidity. There was no difference in temperature, relative humidity and airflow between left, centre and right position of the outlet. Lower-positioned room outlet was like to produce higher airflow within the room. Nonetheless, the difference in airflow between upper and lower outlet locations is marginal, less than 0.005 $m^3.s^{-1}$ (see Figure 7- 20).

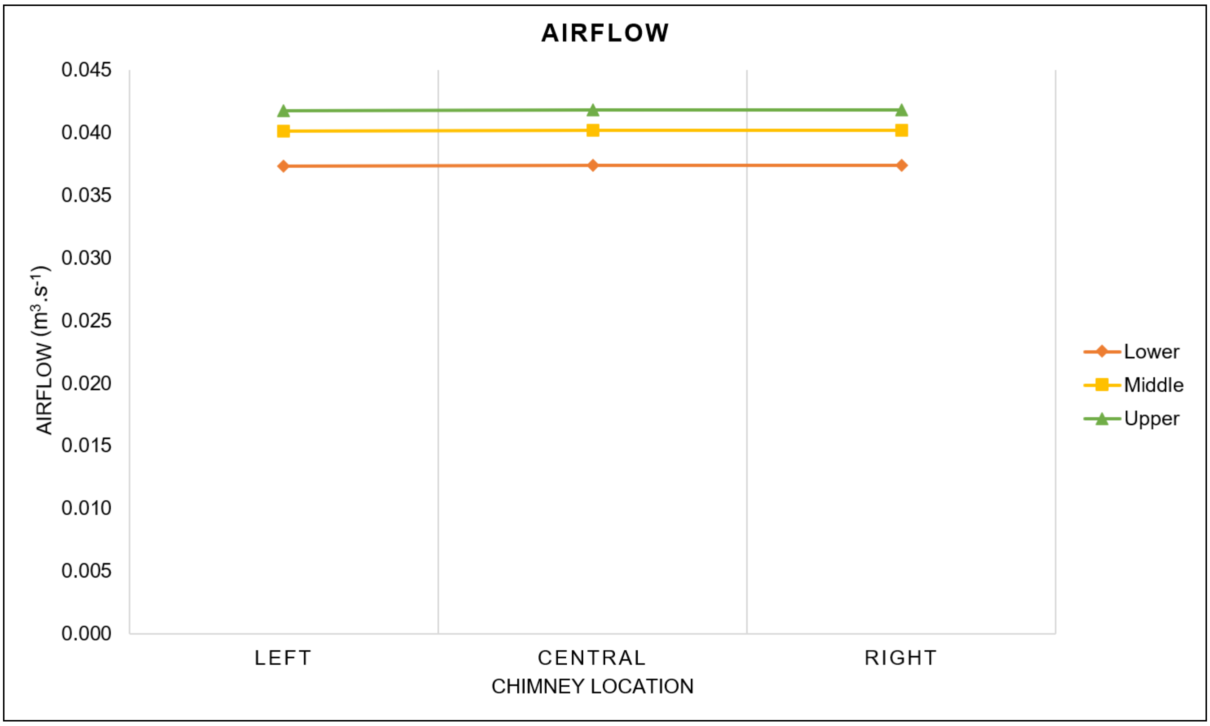


Figure 7- 20 airflow in chimney related to different room outlet location

7.3.3.3 Chimney materials

Methodology was described in Section 3.6.2.3.3.

A room with an insulated solar chimney achieved the highest airflow and the lowest vapour pressure. The air velocity at occupant level in such a room was approximately 0.31 m.s^{-1}, which higher than the air velocity in a room with a standard chimney, 0.20 m.s^{-1}. (See Figure 7- 21 and Figure 7- 22)

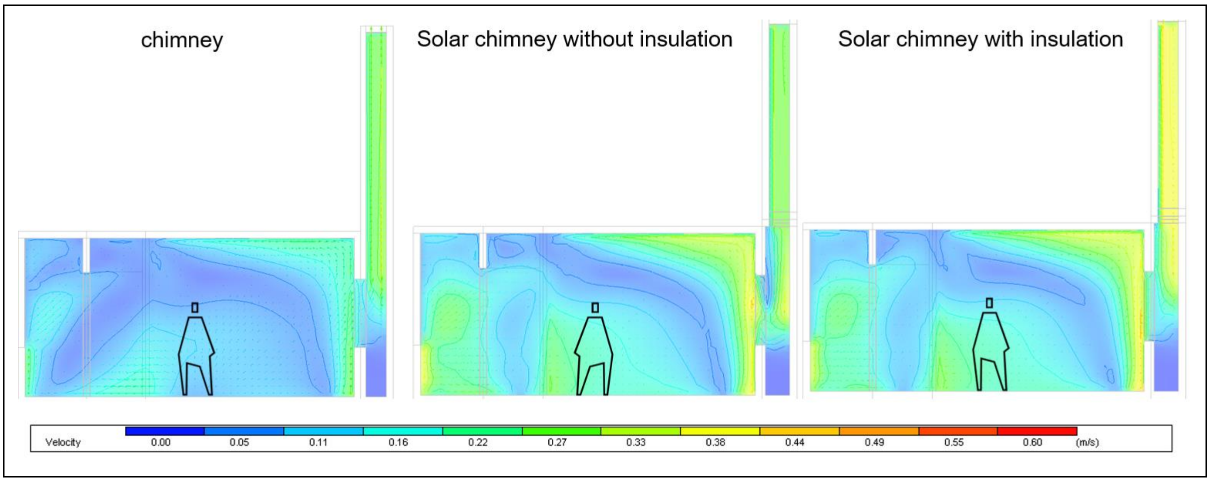


Figure 7- 21 ventilation regarding different chimney materials

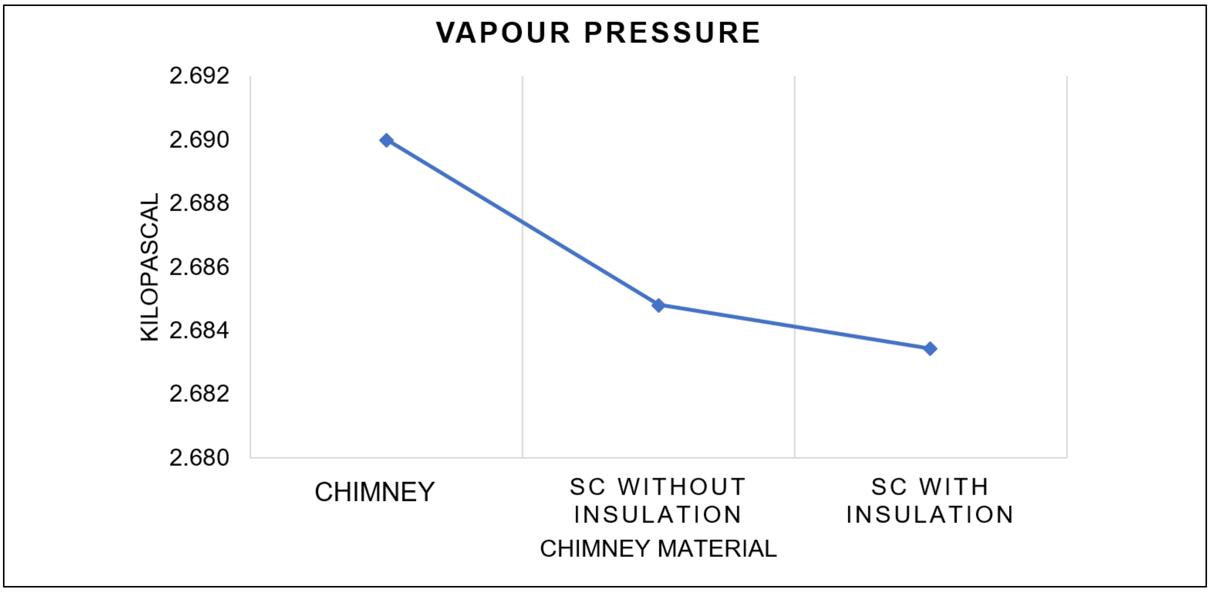


Figure 7- 22 vapour pressure regarding different chimney materials

7.3.3.4 Chimney design

7.3.3.4.1 Trimmed chimney

Methodology was detailed in Section 3.6.2.3.4.1.

The different internal angle in chimney (see Figure 3-33) affected different ventilation within the room (see Figure 7- 23). Room with 45 degree trimmed chimney could enhance the room to reach 0.35 $m.s^{-1}$ on occupant level, which was above the required ventilation as stated criteria of the study. In addition, there was 75% increase in ventilation compared to a room with untrimmed chimney.

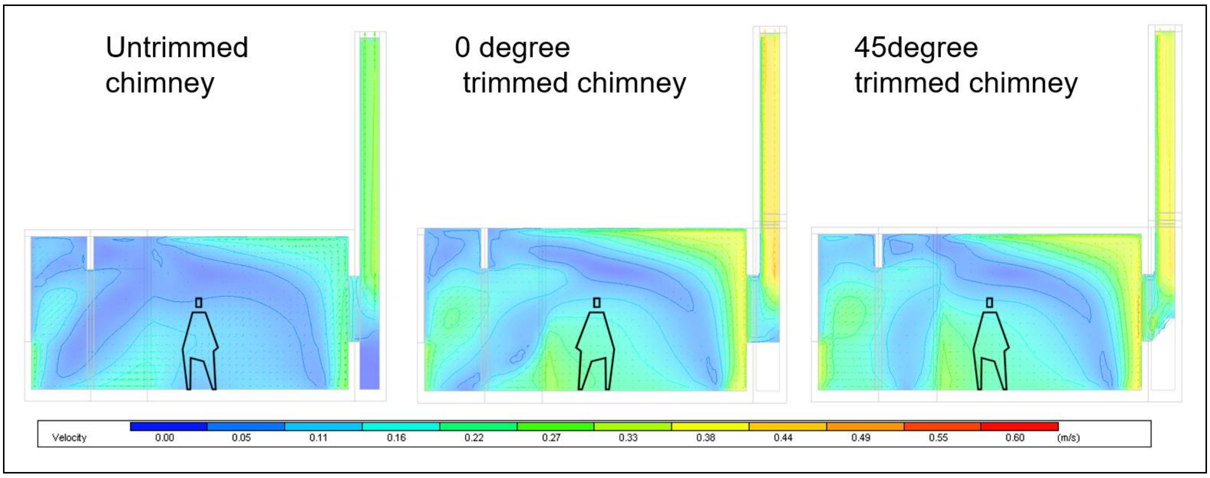


Figure 7- 23 CFD results regarding different internal angle of chimney

7.3.3.4.2 Room with and without grille and mosquito wire

It is common practice to prevent insects and small pests entering the building by installing mosquito wire mesh (to prevent insects and small pests) and similarly to prevent children/small animals entering the duct accidentally by installing grilles. These opening barriers (see Figure 3-34) potentially affect the flow rate entering the room.

The airflow and vapour pressure were analysed for rooms with and without grille and mosquito wire installed over their openings. According to simulation results, the airflow in rooms with grilles and mosquito wire is reduced by about half compared to rooms without these barriers (See Figure 7- 24). This significant reduction in airflow underscores the need to consider the balance between pest prevention and adequate ventilation when designing building openings in tropical climates.

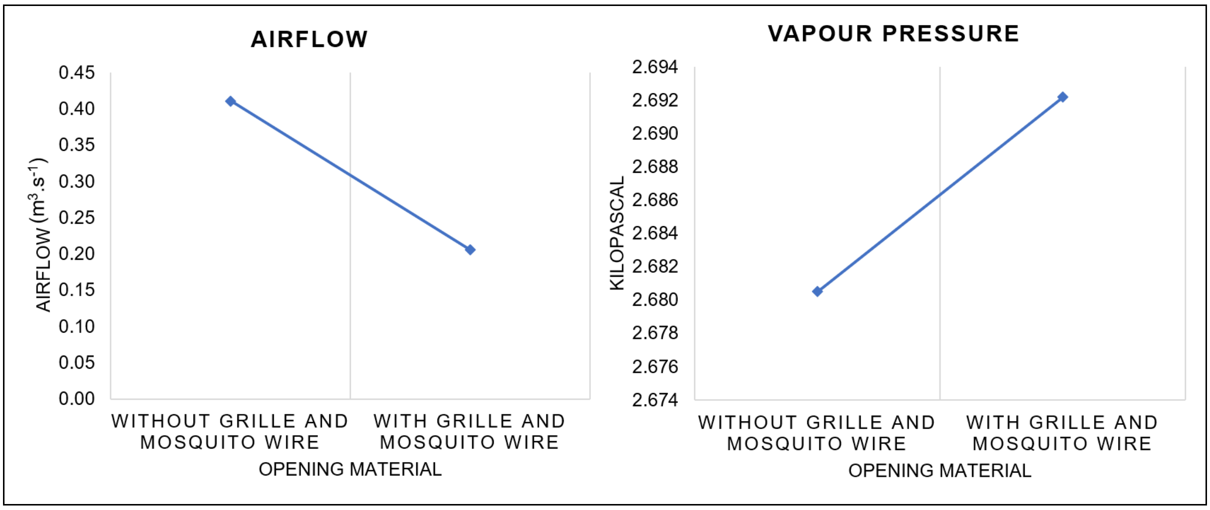


Figure 7- 24 Airflow and vapour pressure between room with and without grille and mosquito wire

7.3.3.5 Chimney outlet style

Referring to the findings in Section 7.3.3.1, chimney outlet significantly affects room ventilation more than the chimney's depth and width. The focus of this part is to investigate the effect of the chimney outlet's location and size (H) (see Figure 3-35).

Based on the finding in Section 2.4.3.1, it is recommended that solar chimney should be oriented southward to maximize sunlight exposure.

A comparative study was conducted on chimney outlets facing south, facing both north and south, and multi-chimneys oriented north and south. The CFD results, illustrated in Figure 7- 25, show that rooms with multi-chimneys facing both north and south achieved the highest ventilation rates, reaching 0.38 $m.s^{-1}$ at the occupant level.

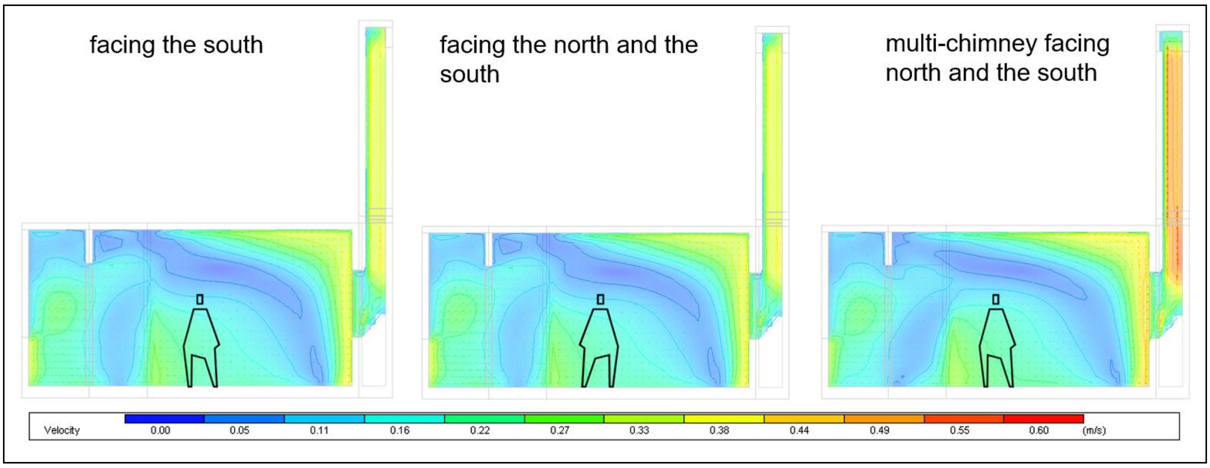


Figure 7- 25 CFD comparison between chimney outlet location

The study further explored multi-chimneys facing both north and south to investigate the impact of chimney height (H) on ventilation. CFD results, as shown in Figure 7- 26, indicate that an increase in the chimney's outlet height correlates with increased ventilation within the room. Figure 7- 27 reveals that airflow reaches its peak when the chimney aperture height (H) is 1.1m. Meanwhile, vapour pressure was at its lowest with the chimney aperture height (H) also at 1.1m. Therefore, it is suggested that a chimney with an aperture height (H) of 1.1m is optimal.

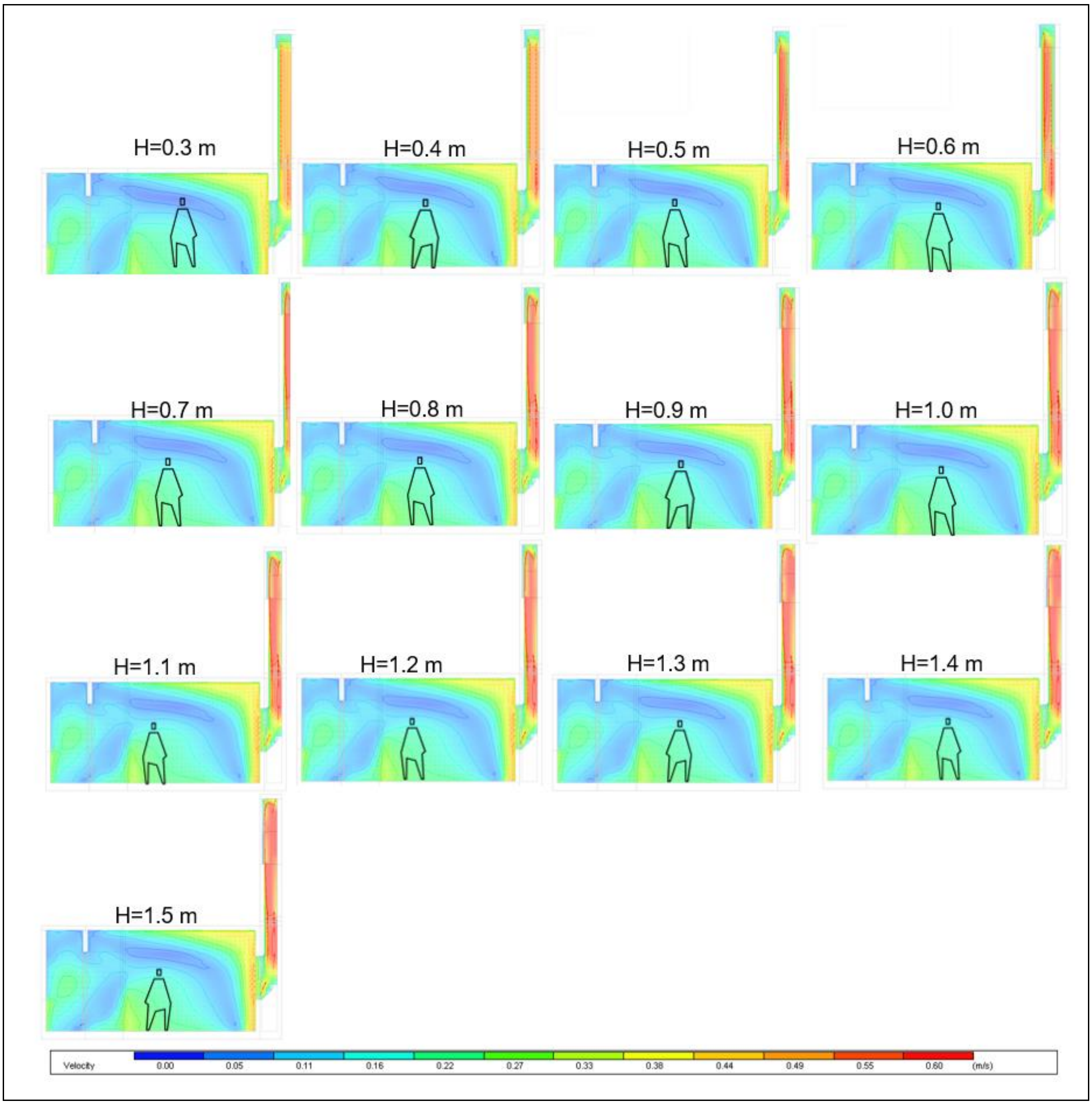


Figure 7- 26 CFD results of different chimney outlet size (H)

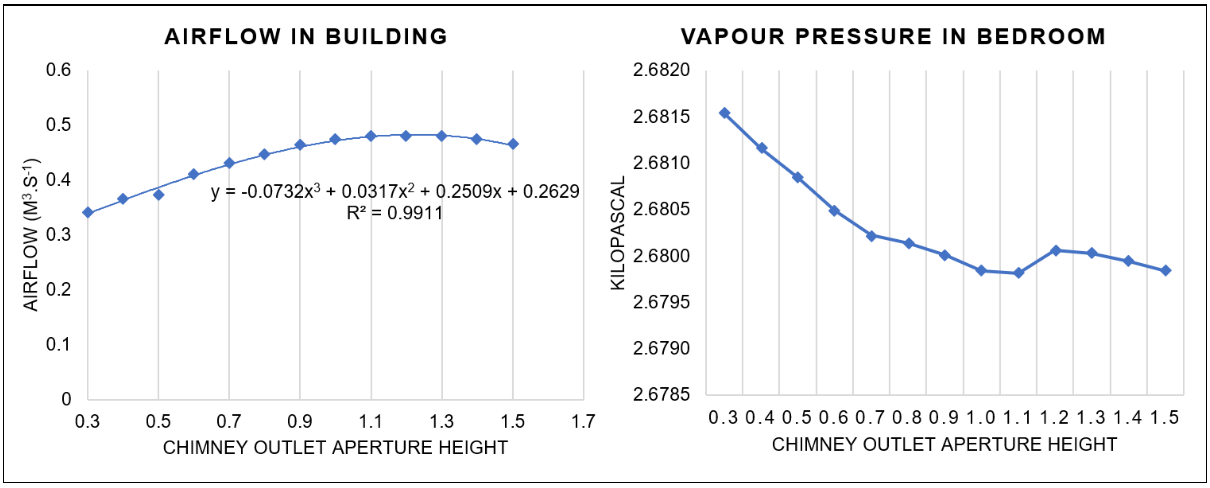


Figure 7- 27 airflow and vapour pressure of different chimney outlet size

7.4 Summary CFD sensitivity: indoor

The study finding establishes an understanding of factors influencing natural ventilation in multi-residential buildings.

Stage 1: Base case for building and room were identified. An 8-storey residential building located in urban area with double-loaded corridor layout was identified as building base case. Half Balcony (HB) room, located in the middle of the building with its opening facing north was defined as base case room.

Stage 2: key findings of exploring room

- Air temperature and ventilation showed directly proportional to the room inlet and outlet size, while relative humidity had an inverse corelation.
- Room with the same inlet and outlet size areas but different outlet dimensions showed comparable temperature, relative humidity, and ventilation, enabling architectural design flexibility in integrating chimney.
- The optimal configuration was found with a room inlet size of 1.0m x 2.0m and outlet of 0.3 m x 1.0m.

Stage 3: key findings of exploring chimney.

- Relative humidity was affected chimney width and depth. The optimal chimney depth was identified as 0.3m. Chimney outlet size was found to be the most significant factor influencing airflow.
- Different room outlet locations showed minor temperature variations, but lower outlet locations had marginally higher ventilation.
- Solar chimneys increased ventilation by 47% and reduced vapour pressure by 3% compared to standard chimneys.
- A trimmed chimney at a 45-degree angle improved room ventilation.
- The maximum airflow was achieved with a chimney aperture height of 1.1m.
- Additional features like grilles and mosquito wire on openings halved the airflow compared to rooms without them.

8. Validating design options for improving internal environment quality within thermally free- running apartments

8.1 Introduction

This chapter presents the result and analysis of interviews conducted with built environment professionals (BEPs) in Thailand. This chapter responds to objective 7 of the research about validating a design option to improve the indoor environmental conditions (focusing on natural ventilation) in residential apartment block in Thailand. The design options evaluated using CFD sensitivity analysis were presented in Chapter 7. The proposed design options were then used to solicit BEPs' thoughts, perceptions and judgements on the concepts.

The research employed semi-structured interviews with the BEPs to explore their opinions regarding indoor environmental quality (IEQ) in multi-residential buildings. The purpose of the interviews was twofold: first to understand current issues related to IEQ, BEPs' experience and knowledge in relation to current multi-storey buildings and second to validate the practicality of the proposed design options. The BEPs were questioned about the feasibility of implementing proposed options, to consider any potential obstacles or challenges, and possible solutions. The interviews were conducted online via Zoom Meeting. This interview involved approximately 30-60 minutes. With the consent of the BEPs, interviews were audio-visual recorded and once the recording had been transcribed, the audio-visual recording was discarded to maintain confidentiality.

The methodology for the interviews was detailed in Section 3.7. The data collected were transcribed verbatim and then analysed using Thematic Analysis via NVivo programme. The analysis incorporated several coding techniques, including initial, open, axial, and selective coding. These coding techniques provided the data's systematic organisation, pattern and theme identification, resulting in a thorough and robust study.

This chapter is divided into two main sections: engagement with BEPs (section 8.2), Summary (section 8.3)

8.2 Engagement with Thailand's built environment professional (BEP)

This section presents the results and analysis obtained from interviewing Thailand's BEP. This section is structured into two parts, which are:

Part one (Section 8.2.1): establish context of the expert's experience and knowledge in relation to current multi-storey residential building and passive design.

Part two (Section 8.2.2): focuses on specific questions about strategies and design options to improve natural ventilation in thermally free-running multi-residential buildings in Thailand.

8.2.1 Part one: establish context of the expert's experience and knowledge

This part is to explore the context of the BEPs' experience and knowledge regarding the current multi-residential buildings and passive design.

8.2.1.1 Demographic information of participants

17 interviews were set as the minimum sample size in Section 3.7.1. The research achieved a total of 21 interviewees and ensured equal representation, for architects, engineers and academics. Figure 8- 1 illustrates the distribution of the panel of BEPs across three categories, architects, engineers and academics. The architect group included both architects and interior architects. The engineer group comprised of construction engineers and mechanical engineers. The academics group consisted of two professional backgrounds: architect- and engineer-based. The academics were from diverse institutions. Most of them have research background about ventilation system in building in Thailand context.

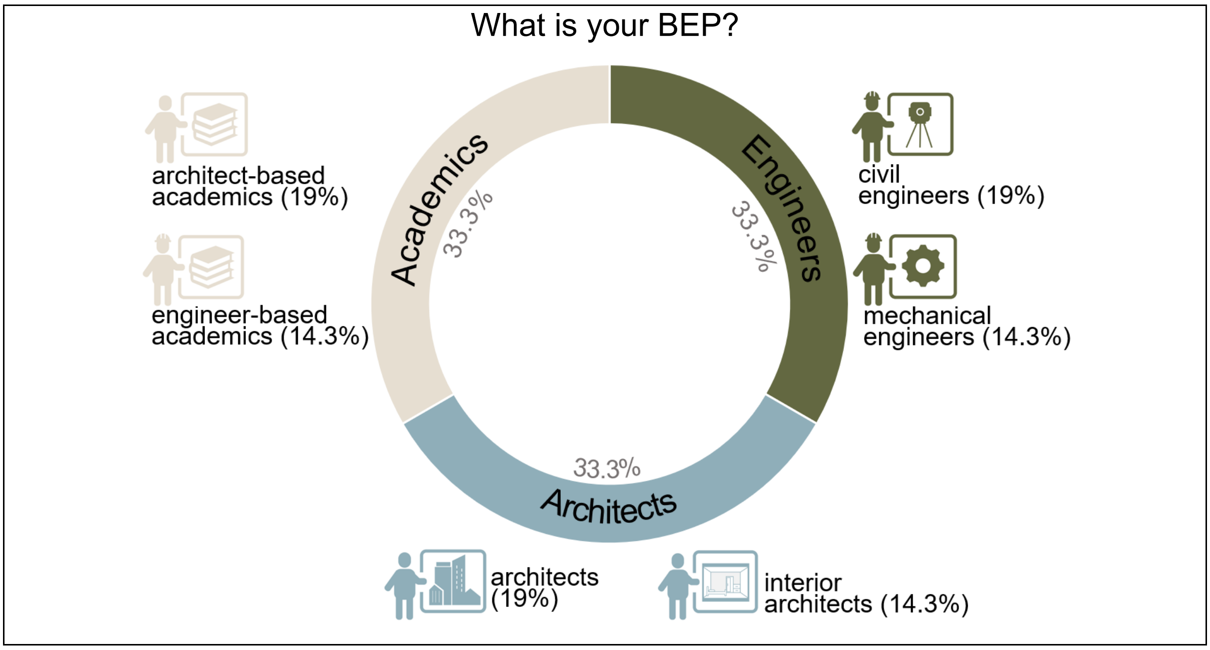


Figure 8- 1 Demographic information of participants

8.2.1.2 Issue of IEQ

Exploring the IEQ issues and obtaining BEP's thought is crucial for understanding the challenges faced in multi-residential building in Thailand. Engaging BEPs enables to gain insights from their knowledge, experiences, and direct interactions with building occupants. This can help to reflect the existed issues, identify solutions and shed light on the challenges.

Questions asked were **"What (if any) indoor environmental quality problems exist in free-running multi-storey residential buildings in Thailand?" and "What design solutions do you think could be implemented to solve these issues(s)?"**

The word cloud presented in Figure 8- 2 demonstrates the top 50 most commonly mentioned issues of IEQ in multi-residential buildings from the interviews. In the word cloud, words with higher frequencies appear more prominently, providing a visual representation of the overall concerns raised by the BEPs regarding IEQ. This word cloud effectively highlights the most frequently occurring words related to the topic from the whole dataset 1784 words. For example, ventilation (85 occurrences, 4.76%), room (80 occurrences, 4.48%), design (62 occurrences, 3.48%), and humidity (38 occurrences, 2.13%).

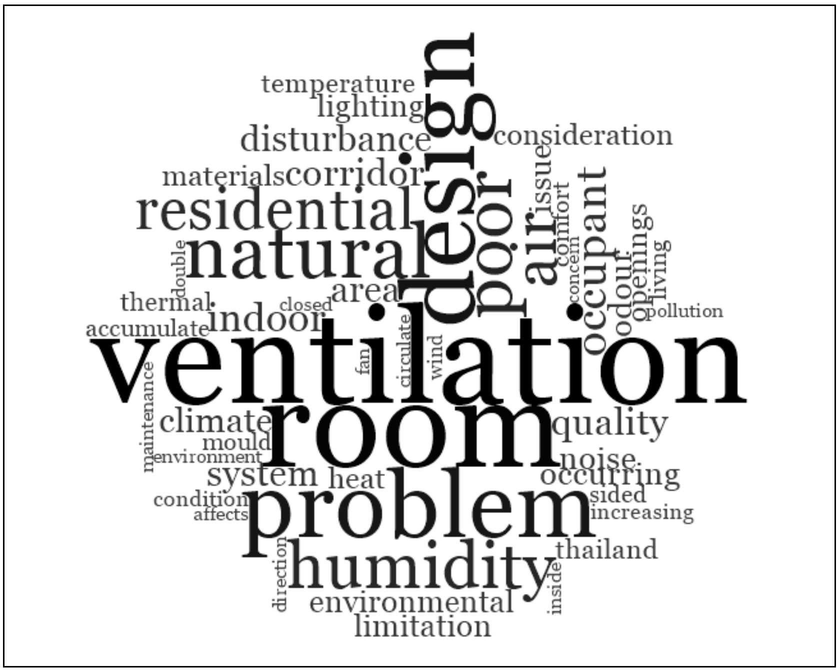


Figure 8- 2 word cloud of current issue occurring in multi-residential buildings in Thailand

Despite the limitation of word clouds, they provide a basic understanding of frequently raised issues in multi-residential buildings in Thailand. Word clouds visualise word frequency, but they may not necessarily indicate the importance of words within the context. However, comprehend the significance and context of specific issues and design solutions in greater detail, further analysis through coding process and thematic analysis were required.

The coding process and thematic analysis were used to identify and refine of key themes and pattern of the interview data and to provide valuable insights into the IEQ issues and potential solutions proposed. The data from the interviews was encoded in four stages including initial coding, open coding, axial coding, and selective coding.

- <u>Initial coding:</u> keywords related to IEQ issues in multi-residential buildings were extracted from Chapter 5 (Residential's questionnaire). The analysis revealed that the five key factors influencing the occupants' satisfaction with IEQ are natural ventilation, relative humidity, natural lighting, temperature, and room privacy. The derived five key factors were used to initially highlight and capture words from the transcript.
- <u>Open coding</u>: new nodes were generated as the transcripts revealed additional issues relating to IEQ in the building. This was carried out with an open mind

and enabled new codes to be developed without any constraint on the number. The transcribed data were systematically categorised into individual nodes and subsequently analysed. Consequently, 157 nodes indicating the IEQ problems and 72 nodes representing the solution were generated.

- Axial coding: The objective of axial coding was to develop coherence by connecting and combining topics in order to find significant connections between individuals. The individuals were sought out for profound connections. As a result of this technique, the issue nodes formed 17 nodes, while the solution nodes were sorted into 11 nodes. This systematic grouping enabled more organised representation of the interconnections and interdependencies among the identified issues and solutions.
- Selective coding: As an outcome of selective coding, two core codes indicating the issues occurring in multi-residential buildings in Thailand were investigated. In addition, four core codes were identified as the solutions. This process was achieved through a careful examination of the sub-issues and sub-solutions, totalling 12 examinations of issues and 9 examinations of solutions This in-depth analysis led to a more comprehensive and coherent understanding in the relationships among the issues and solutions, contributing understanding of the complex dynamics regarding IEQ in multi-residential buildings. (see Table 8- 1)

Table 8- 1 issues and solutions in relation to IEQ derived from coding in nVivo

issues	sub-issues
IEQ problems	poor natural ventilation
	high humidity
	odour in building
	noise disturbance
	mould growth occurrence
	poor natural lighting
	high temperature
	unable to achieve thermal comfort
	indoor air pollution from cooking
OEQ problems	outdoor weather
	air pollution
	urban heat island
suggested solution	**sub-suggested solution**
leveraging building design for providing optimal IEQ	designing double-sided ventilation
	designing single loaded corridor
	designing ventilation shaft
	facilitating proactive maintenance practices
	increasing natural ventilation
	integrating climate and site consideration in building design
	integrating IEQ knowledge in building design
	prioritizing IEQ consideration at the early stage of design
	selecting appropriate material
establishing building code for promoting natural ventilation in building design	establishing ventilation standards, IAQ guidelines, thermal comfort requirements, and acoustic control standard.
utilizing active HVAC systems	using fan or air-conditioner

Two core issues and sub-issues of IEQ and four core solutions suggested by the BEPs are presented in Table 8- 1. Two core issues are described in Section 8.2.1.2.1 and Section 8.2.1.2.2. Three core solutions suggested from the BEPs are described in detail in Section 8.2.1.2.3 to Section 8.2.1.2.5.

8.2.1.2.1 Issues: Indoor Environmental Quality (IEQ)

All BEPs unanimously recognised the existence of IEQ issues in multi-residential buildings in Thailand. The existing IEQ issues had been either observed or experienced by BEPs throughout their work. Nine sub-issues were raised regarding IEQ including poor ventilation, high humidity, odour in room and building, poor natural lighting, high temperature, pollution from cooking, noise disturbance, occurrence of mould growth, and inability to achieve thermal comfort.

To simplify BEPs identification and referencing, abbreviations have been allocated based on three groups of BEPs. For example, “AC- #” represents each of the 7 academic participants, “AR- #” represents each of the 7 architect participants, and “EN- #” represents each of the 7 engineer participants”. The abbreviation can assist in acknowledging particular BEP groups and their opinions without revealing personal information.

76.2% of BEPs substantiated that poor ventilation is a prevalent issue in multi-residential building in Thailand, especially natural ventilation. This is mainly due to the common practice of building with single-sided ventilation, resulting in challenge to provide individual rooms with adequate natural ventilation. AC-01 mentioned that poor ventilation indeed entails a significant challenge for IEQ in multi-residential buildings. The presence of a double-loaded corridor design, in which the room units are located on both sides of a corridor, can exacerbate the ventilation problem. Double-loaded corridors rooms have a limitation of opening area, resulting in difficulty of achieving natural airflow. AC-02 also pointed out that poor natural ventilation is the main problem in multi-residential building. Multi-residential building in Thailand is typically designed with limited room floor space and single-sided opening, which tends to have inadequate ventilation. AR-13 stated that “Poor ventilation is a prevalent issue in multi-residential buildings, especially double-loaded corridors building.” Additionally, AR-05, AR-02, AR-04 and EN-02 also emphasised the limitation of ventilation associated with single-sided ventilation. AR-07 stated that the building with double-loaded corridor design is characterised by its narrow and long corridor layout, where residential units only receive natural light and ventilation from only on one side.

62% of BEPs, indicated that poor ventilation commonly resulted in excessive humidity levels within the building. AR-13 stated that “Excessive indoor humidity is not only hazardous to occupants’ health, but also to building components. The presence of dampness can promote mould growth in the building. The limitation of ventilation lead to high humidity levels. AC-01 expressed “Providing adequate natural ventilation in multi-residential buildings can help to prevent humidity accumulation and then improve IEQ”. AR-03 also mentioned that high humidity problem in the residential units mainly come from poor ventilation. EN-01 highlighted that multi-residential units tend to experience high humidity during rainy season. Mould can emerge in the area with poor natural ventilation and lighting. AC-04 raised concern about the issue of high humidity leading to mould growth in rooms, especially in the WC.

In addition, over 40% of those interviewed acknowledged receiving concerns from occupants regarding odour from high humidity levels in the buildings. AC-02 “Many apartments’ rooms were designed with limited opening, relying on only natural ventilation and having WC located within the room. This room type can contribute to moisture accumulation within the rooms, then generate a damp environment in the building. I have experienced living in a studio room with single-sided ventilation with full room wall opening, but ventilation potential remains insufficient. As a result, certain areas, such as WC, wardrobe surfaces and room corners, become excessively humid, mould growth”. EN-01 mentioned the residential unit can experience odour from dampness in sanitation systems. EN-02 stated that "Based on my experience working on construction project sites, there have been issues with odour disturbances between rooms and within rooms, mainly due to poor ventilation that allows odours to occur”. AR-04 also mentioned that “I have heard about odour issue arising in their rooms from high humidity experienced by occupant after use.” EN-03 highlighted that high humidity and rainwater leakage are another concern in multi-residential building. Humidity level, exacerbated by substantial rainfall, becomes problematic when the building lacking climate consideration in its design. In the past, traditional buildings in Thailand were thoughtfully designed with climate consideration, but modern buildings are typically influenced by Western styles that may not be suitable with Thailand’s climate. Additionally, building located in dense areas tends to have high humidity and mould occurrence within the indoor area.

Another noted issue from 20 % of the BEPs is high air temperature within the buildings. HVAC systems e.g., air conditioners in buildings can be used to significantly reduce room air temperature. However, the benefits of natural ventilation are limited to supplying fresh air, reducing air temperature towards outside temperature and being more conducive to well-being of human body. Additionally, it is important to consider that active HVAC system consumes energy and contributes to other environmental issues.

Additional opinions related to IEQ, for instance:

EN-11: “The primary issue in Thailand is the lack of clear standard and regulations in Thailand governing air ventilation matters or IEQ. Even if many engineers and architects are willing to integrate environmental consideration into building design, the final decision is depended on the developer. Construction cost reduction often affect the building design to meet only the minimum legal requirements. However, the lack of IEQ standard in Thailand result in a neglect of efficient air circulation in building, which is essential for comfortable living conditions. In addition, high humidity issue in the building is easily spotted, which also reflect to the need for comprehensive legislation and guidelines regarding minimum ventilation requirements for enhancing IEQ in multi-residential buildings.”

AC-02 “The limitation of room opening also results in less natural lighting within the room”.

AR-13 However, solutions for providing more ventilation are often costly and time-consuming. Investors may hesitate to invest in solutions; therefore, the burdens are putted on the occupants to discover their own solutions. Prioritising providing proper ventilation in sustainable solutions can result in not only having healthier and more comfortable living spaces for occupants but also optimising overall building performance.”

EN-10: “Noise disturbance is primarily concerned for multi-residential building design due to the proximity of many dwelling rooms within the building. However, the developers tend to prioritise budget consideration over noise disturbance issue. For instance, reduction of construction cost by compromising sound absorbent material quality in the building can lead to increased occurrences of noise disturbance.

AR-18: “multi-residential buildings designed with narrow and elongated corridor restricts natural lighting and ventilation accessing to the room, as they can access only from single side. The limitation of opening leads the building and its room to have insufficient natural air circulation and lighting. In particular, multi-residential rooms with WC located close to the corridor side often do not provide adequate ventilation or exhaust fans, resulting in high humidity and dampness.

The lack of proper air movement and moisture control create an unpleasant odour in the interior space. Improving ventilation and incorporating exhaust fans in such areas can enhance IEQ for occupants.

8.2.1.2.2 Issues: Outdoor Environmental Quality (OEQ)

Three OEQ issues, namely air pollution, outdoor weather and urban heat island, have been identified by the BEPs as significant factors to IEQ. Enhancing IEQ in the context of severe OEQ has become a significant challenge. The crisis of air pollution is prevalent approximately 1-2 months per year in Thailand, which significantly impact IEQ and alter occupant behaviour. Similarly, outdoor weather conditions also have an impact on IEQ. For example, building opening allow outdoor moisture to transfer inside the building and increase the indoor moisture level. Furthermore, urban heat island effect is another OEQ concern that can influence IEQ.

AR-05: "Air pollution crisis occurs in Thailand for approximately 2-3 months due to wildfires and burning agriculture waste."

AC-19: "Thailand has had a serious environmental challenge in recent years due to pollution of 2.5 micrometre particulate matter (PM2.5). During the air pollution crisis, occupants have increasingly embraced a tendency towards enclosure and reliance on closed systems. While some individuals can afford active HVAC systems to mitigate the IEQ, lower-income groups often struggle to afford such solutions. Consequently, the enclosed living spaces obstruct fresh air to circulate into rooms, leading to the increasing of carbon dioxide accumulation."

AR-14: "The lack of climate consideration in building design has resulted in a reliance on active HVAC systems, notably air conditioner, which emit excess heat into the environment. This cumulative heat contributes to raise temperature throughout the city. This eventually cause in the formulation of urban heat island effect. This environmental challenge exacerbates the situation for building occupants, which leads them to rely further on active HVAC systems to cope with the intensified heat. However, this perpetuates a cycle of adverse OEQ and IEQ impacts."

BEPs identified three main reasons contributing to the issues occurring in multi-residential buildings:

- Neglect of climate considerations in building design: 61.9% of respondents pointed out that climate consideration in building design may not receive sufficient attention, particularly in country with inadequate building code and regulation. Several negative consequences might arise in the building, such as poor IEQ, increased reliance on active HVAC system, reduced occupant wellbeing and comfort etc. EN-01 noted that "Buildings are sometimes designed without taking into account Thailand's climate, incorporating designs from Western countries. This lack of local climate consideration can lead to poor IEQ". AC-02 mentioned "Numerous multi-residential buildings designed without integrating climate considerations into their design are faced with the IEQ issues". AR-05 also stated that "One of critical issue is the lack of climate consideration in building design, for example the failure to consider building orientation in layout design. Eventually, this issue has significant direct and indirect consequences on IEQ problems". AC-03 recommended "considering local climate should be incorporated into the initial stages of residential building design".
- Profit-driven building: 57.1% of the BEPs mentioned that the primary concern from developers is to maximise their profits, leading to construction cost reduction. This results in compromising building design, materials, and other building components, which ultimately impact IEQ. AR-03 noted that "The building is profit-driven because investors prioritise cost-effectiveness as the most important factor. The maximisation of construction area for maximum benefits, resulting in a narrow gap to other buildings that can cause poor IEQ". EN-03 stated that "According to my work experience, many developers choose to decrease the cost of building construction by using lower-quality materials, which affects the thermal performance".
- Lack of building codes: 33% of BEPs highlighted the inadequacy of building regulations that mandate minimum standards and requirements for IEQ in Thailand. Establishing building codes and standards is vital to maintaining adequate IEQ and promoting sustainable building practices in multi-residential developments. EN-04 addressed that "When developers aim to cut construction costs, the building design often only meets the minimum requirements of the building codes. However, because there are no building codes particularly

addressing IEQ, it leads to the neglect of IEQ issues in buildings, such as inadequate ventilation, high indoor humidity and temperatures".

8.2.1.2.3 Solution: leveraging building design

To achieve optimum IEQ, 81% of the BEPs suggested leveraging building design to incorporate IEQ strategies practically. This integration should also encompass climate and site considerations to tailor the design to local conditions. In addition, prioritizing IEQ is essential to consider in the early process of building design. For example, using appropriate materials that are suitable for the local climate and site conditions. Building designed with climate consideration has positive impact not only on the building's overall performance and sustainability but also on occupant wellbeing.

60% of BEPs addressing increasing natural ventilation is important to further enhance IEQ. This can be achieved through increasing opening areas and locations to facilitate fresh air movement. Single-loaded corridor layout design can also promote better air circulation in the building from double-sided ventilation. Another solution is integrating ventilation shafts in building design especially in building with limited opening area to enhance airflow throughout the building.

8.2.1.2.4 Solution: Regulating building code for IEQ

Establishing building codes regarding IEQ can have a profound impact on wellbeing and comfort for all occupants, regardless of their financial resources. In other word, these codes can be particularly beneficial for low-income residents who may be disproportionately affected by substandard living conditions. The BEPs (20 %) mentioned that the building code can ensure buildings design and construction meeting the minimum requirement for occupants' well-being and sustainability. The building code could be developed to include various aspects of IEQ, such as ventilation standards, IAQ guidelines, thermal comfort requirements, and acoustic control. As previously mentioned in Section 8.2.1.2, EN-04 addressed that when developers aim to cut construction costs, the building design often only meets the minimum requirements of the building codes. However, because there are no building codes particularly addressing IEQ, it leads to the neglect of IEQ issues in buildings, such as inadequate ventilation, high indoor humidity and temperatures. AC-01 recommended that establishing building codes specifically addressing IEQ can potentially enhance residential building to achieve minimum requirement of IEQ.

8.2.1.2.5 Solution: utilising active HVAC system

Mechanical equipment, such as fan, air conditioner etc., can serve as a second option to support occupants to achieve thermal comfort when natural ventilation is not feasible or outdoor weather conditions are unfavourable (noted by 23.8% of the BEPs). AC-01 stated that “Regarding the limitation of natural ventilation, active energy systems, such as fans or air conditioners can provide occupants with thermal comfort, increased ventilation. However, the systems demand maintenance and are not sustainable”. AR-05 mentioned that “As a result of lack of climate consideration in building design, occupants tend to rely on active HVAC systems to deal with IEQ issue.” Initially, the building should prioritise climate considerations and maximise the use of natural resources, such as natural lighting, natural ventilation, and fresh air. The natural resources offer benefits not only to promote optimal IEQ, but also to reduce reliance on building energy consumption.

8.2.1.3 Natural ventilation

Question addressed were **“Do you think natural ventilation is important in thermally free running building in Thailand? If yes - what benefits do you think natural ventilation brings? If no - are there specific issues that you associate with natural ventilation?”**

All BEPs (100%) agreed that natural ventilation is important in thermally free-running building in Thailand. BEPs addressed five key benefits and identified two key challenges associated with providing natural ventilation in multi-residential building in Thailand. AR-02 noted that “Natural ventilation is essential for thermally free-running buildings. When a building lacks sufficient openings for natural ventilation to circulate, resulting in moisture accumulation within rooms and causing health risks for occupants”. AC-04 added that “Natural ventilation offers thermal comfort conditions for occupants”. AC-01 emphasised that “Natural ventilation is beneficial to occupant well-being as it corresponds to human body temperature”. EN-01 stated that "Air conditioning system are not inherently superior. While the air conditioning system can reduce the temperature inside the building, it may not maintain suitable humidity levels for thermal comfort. Natural ventilation, on the other hand, provides a more refreshing environment”.

The five main benefits of providing natural ventilation are: building cost reduction, energy use reduction, enhancing indoor air circulation improving IAQ, promoting occupant well-being and sustainable benefits.

On the other hand, while it is acknowledged that natural ventilation is highly beneficial and desirable for the building, it cannot be accommodated in all circumstances. Two main challenges have been raised: outdoor environment and optimizing construction cost (see Table 8- 2).

Table 8- 2 benefit and issues associated with natural ventilation

advantage	cost reduction	construction cost reduction from optimizing wall construction
		lower maintenance costs
	energy used reduction	
	indoor air circulation improving IAQ	mitigating humidity accumulating in material
		mitigating indoor air humidity accumulation
		mitigating indoor CO2 accumulation
		mitigating indoor heat accumulation
		mitigating indoor pest infestation
		providing fresh air
	promoting occupant well-being	suit for the human body
	sustainable benefits	
challenges	outdoor environment	wind and solar obstruction in dense urban environment
		wind unpredictability
		people need active HVAC system occasionally
	developer optimizing construction expenses	building space limitation
		neglect climate consideration in building design

8.2.2 Part two: focuses on specific questions about strategies and design options

This part focuses on specific questions about strategies and design options to improve natural ventilation in thermally free-running multi-residential buildings in Thailand. Initially general approaches to improve natural ventilation are considered (Section 8.2.2.1), then the specific concept of a solar chimney (Section 8.2.2.2), finally BEPs explore the pros and cons of potential design options to identify the most appropriate design to take forward (Section 8.2.2.3).

8.2.2.1 Improve natural ventilation in building

The BEPs were questioned to deliver opinions and suggestions to develop building features in the provided multi-residential building plan. (see Figure 3-37)

The suggested features are divided into two main scopes, which are the whole floor layout and the residential unit. (see Figure 8- 3 and Figure 8- 4 respectively).

For the floor layout, BEPs proposed 3 options for the whole floor layout design, which were:

Two options for developing a floor layout design to increase natural ventilation

- expanding the width of the corridor. Due to the venturi effect, a long and narrow corridor obstruct the flow of outdoor air entering the building.
- increasing the sizes of building apertures to enhance the circulation of the external air into the corridor.

and one option for minimise nuisance noise. BEPs suggested the improvements not only in terms of natural ventilation but also broadening the scope of recommendations to include IEQ for the whole floor layout. BEPs concerned the issue of noise disturbance in the corridor. Therefore, they recommend integrating sound insulation or noise-controlling materials used on the corridor walls can minimise nuisance noise. This is because this building type accommodates living spaces for multiple families.

Figure 8- 3 illustrates proposed features for developing floor layout in following details (a) the existing situation, (b) corridor area (c) expanding the width of the corridor, (d) increasing the sizes of building apertures to enhance air circulation (e) integrating sound insulation or noise-controlling materials.

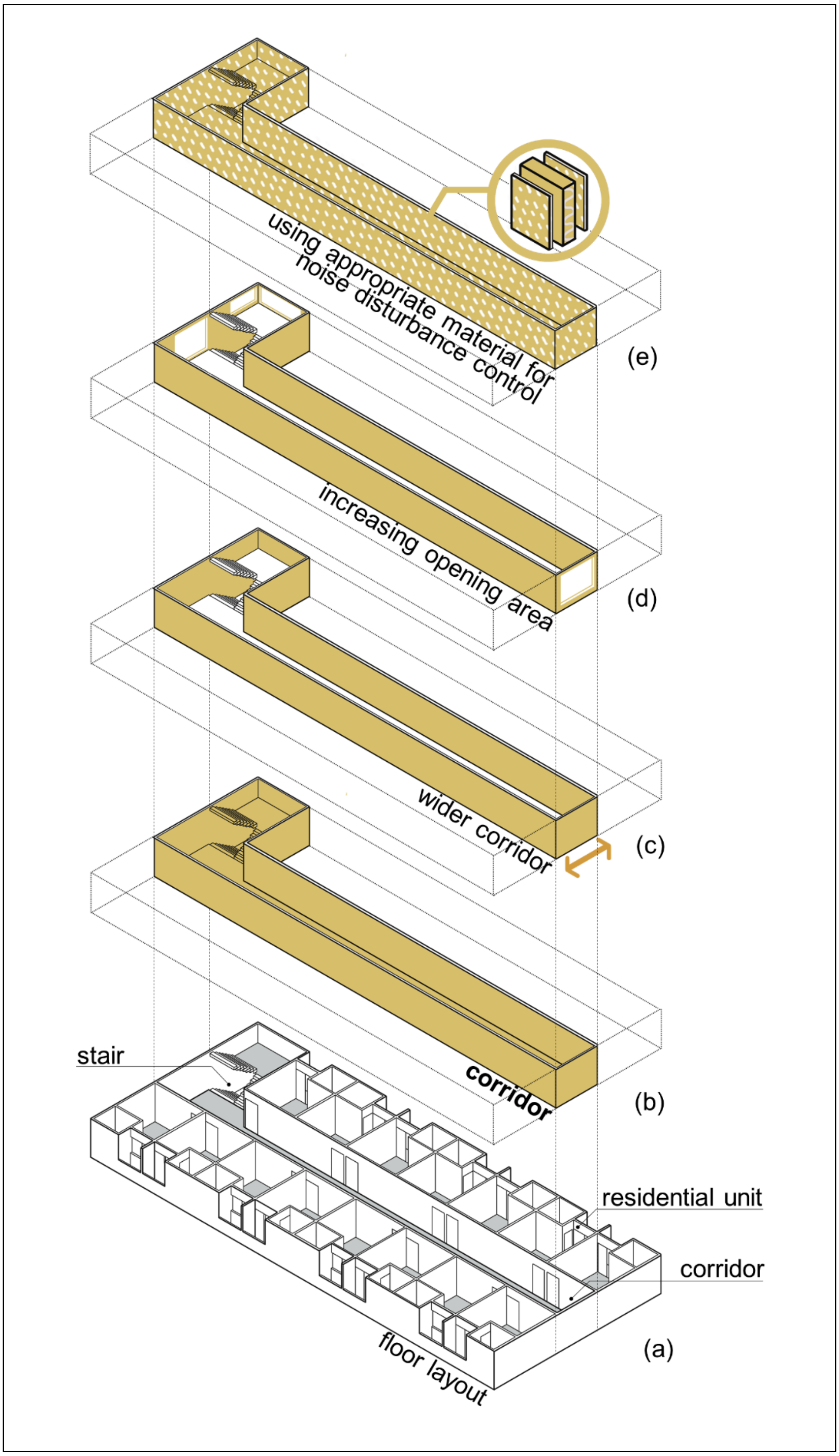


Figure 8- 3 suggested features for floor layout
(Source: Author)

For the scope of the residential unit, there are various suggestion regarding improving natural ventilation at the room components within the unit (Figure 8- 4). The primary concept involves increasing the size of the room apertures in order to increase fresh air to circulate into the room. The suggestions for each room's components in the residential unit are detailed as below:

<u>bedroom</u>

- 52.4% of BEPs recommended that the room should maximise the opening on the wall between the bedroom and the balcony to enhance air inflow (Figure 8- 4 (a)). This opening is typically designed with window size of 1.0 x 1.2 m. AR-01 suggested that adding additional window on wall at the occupant's living area can improve natural ventilation and keep privacy. EN-03 noted that the opening can be maximised and integrated with the balcony door. This can involve designing a slide door and awing door.
- The room should be designed with double sided ventilation (Figure 8- 4 (b)). A majority of 95.2% of BEPs addressed that adding additional window along with the bedroom wall connecting to the corridor can increase airflow into the room. However, 38% of the BEPs expressed concerns regarding potential noise disturbances resulting from such additional opening. They also highlighted that this opening may affect resident's privacy. For example, AC-07 raised the possibility of the danger of intruder entering the room via this opening. AR-08 pointed out the possibility of light pollution from corridor might cause nuisance for occupant.
- Due to the limitations imposed by the available wall space for creating opening, stack ventilation is an alternative option for improving natural ventilation. The stack ventilation involves such as ventilated chimney (Figure 8- 4 (c)) and ceiling ventilation (Figure 8- 4 (d)) (suggested by 23.8 % of BEPs). EN-12 pointed out that while ventilation chimney could be beneficial for IEQ, it requires more vertical building space which could potentially impact the property construction cost.

<u>for balcony</u>

- Wall balcony can block natural ventilation as it creates vortex occurring near the balcony wall (Figure 8- 4 (e)) (AC-16). Railing balcony can encourage the air to flow into the internal space more than wall balcony (AC-07). Additionally, EN-10 also pointed out that the many buildings have mould growth on the inner balcony wall, especially during rainy season. This phenomenon occurs because the wall obstructs the airflow and allows dampness to accumulate inside this area, leading conducive environment for mould to emerge.

for WC

- Providing natural lighting within WC. The opening for natural lighting could be used for additional ventilation (Figure 8- 4 (f)).
- WC should be designed with isolating wet and dry zone. In many economical residential buildings in Thailand, WC are typically designed without separating wet and dry zone (Figure 8- 4 (g)). When the resident uses the WC, the entire space becomes wet and exacerbates humidity levels with less ventilation. This causes a certain time of dampness which encourages mould growth in the room.
- Due to the limitation of the room opening, providing sufficient ventilation becomes challenge. Active HVAC system, particularly an exhausted ventilation fan can increase inflow of fresh air and reduce humidity accumulation built up in room (Figure 8- 4 (h)).

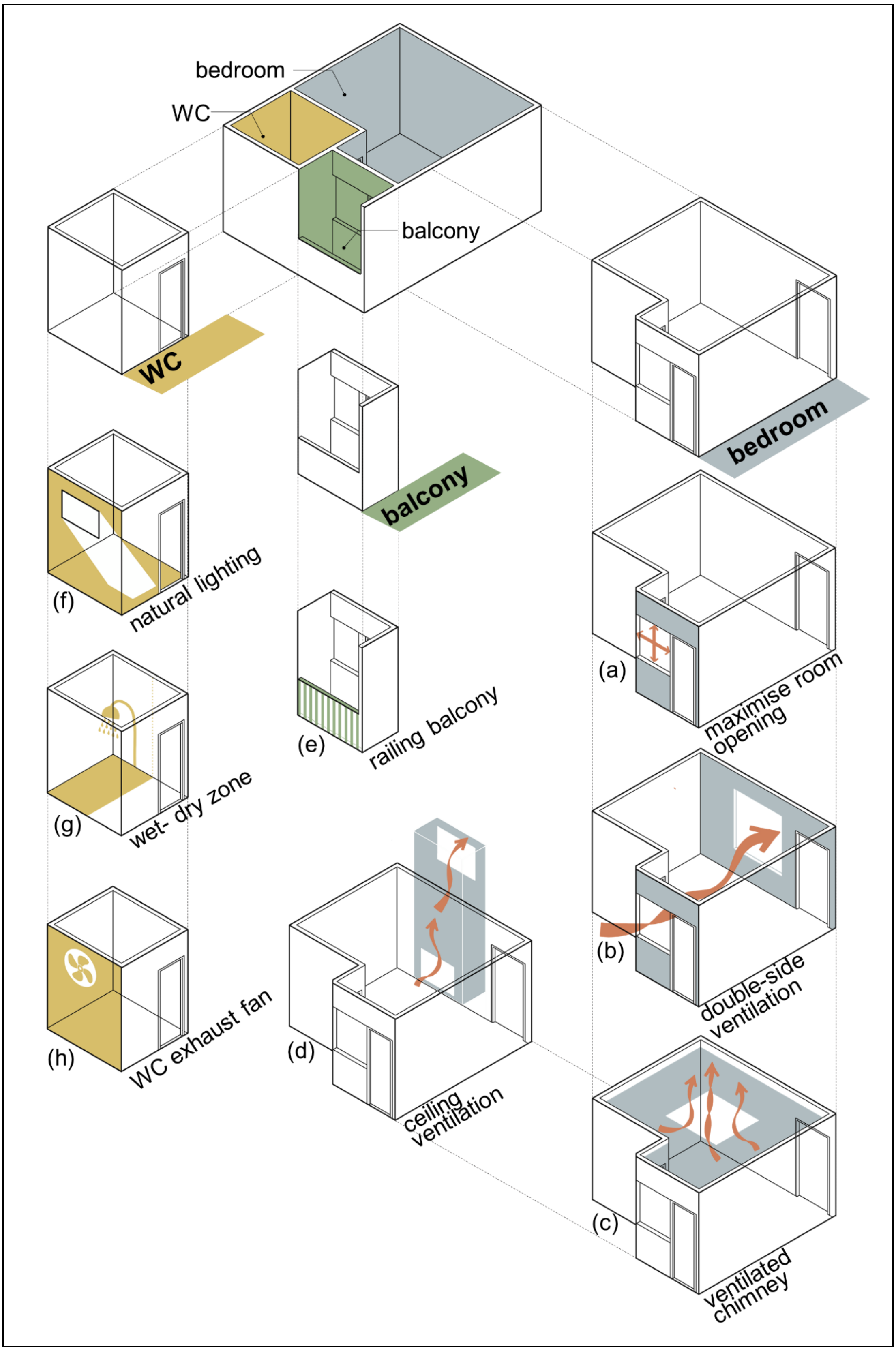


Figure 8- 4 suggested features for room planning
(Source: Author)

8.2.2.2 Solar chimney

The BEPs were asked two questions about solar chimney "**What opportunities and obstructions do you see in integrating solar chimney with multi-residential building in relation to natural ventilation, building design, energy, and construction?**

For obstruction, what additional system should be used to assist solar chimney in relation to natural ventilation, building design, energy, and construction?"

All BEPs (100%) recognise the opportunities of integrating solar chimney with multi-residential building. 72% of BEPs indicated a strong possibility of the integration to building design. Additionally, 50% of BEPs noted that the integration is not complex and not difficult to construct.

However, ten concerns were raised such as, cost effectiveness, the limitation of building space, the challenges of the outdoor environment etc. (see Table 8- 3)

Table 8- 3 opportunity and obstructions of solar chimney in multi-residential building

opportunities	enhancing property value through SC integration
	high possibility for integrating SC in multi-residential building design
	improving IAQ
	incorporating solar-driven ventilation system in building
	integrating SC as integral building structure
	lower maintenance costs
	optimizing construction cost
	promoting health and well-being of occupant
	providing privacy
	save energy and energy cost
	sustainable solution
	the ease of SC construction
obstructions	addressing concerns of cost-effectiveness
	addressing concerns of noise disturbance through SC
	addressing concerns about ventilation performance
	addressing concerns related to unwanted animal intrusion
	addressing concerns related to water leakage
	building space limitation
	challenges of outdoor environment
	the need for architects in considering and knowledgeable about SC

8.2.2.3 Design options

The BEPs were asked to provide their opinions regarding opportunity, feasibility, challenge, concern on design options of each component of the room, which include:

- Balcony type: Room with solid wall balcony and Room with railing balcony
- Room inlet size: Room with window size 1.0 x1.1 m and Room with window size 1.0 x 2.0 m
- Room with and without chimney: Room without chimney and Room with chimney
- Chimney design: One chimney connected to multi-rooms and One chimney connected to only one room
- Room outlet design: Room with horizontal room outlet and Room with vertical room outlet

The coding process and thematic analysis were used to identify key themes and pattern during this stage. The opinions provided from the BEPs were encoded in four stages including initial coding, open coding, axial coding, and selective coding.

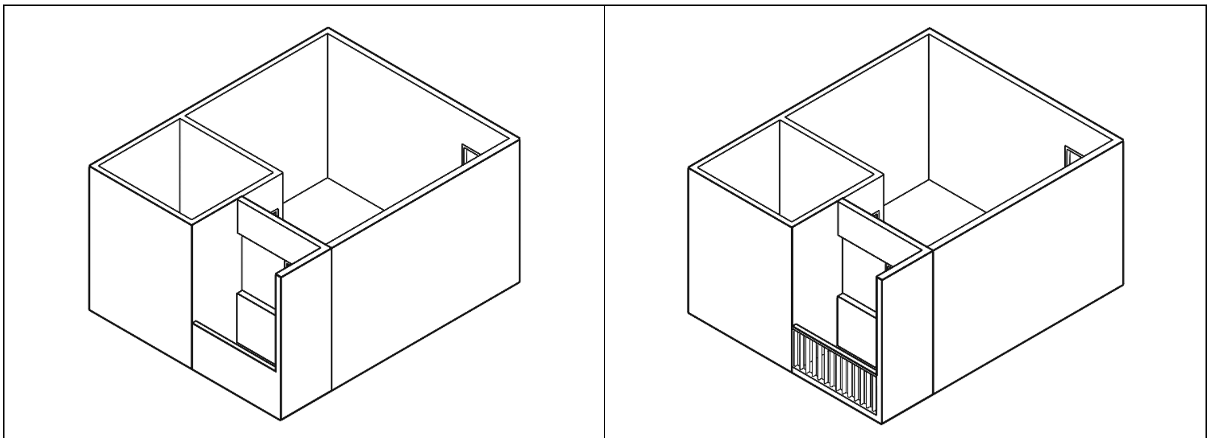
- Initial coding: the 12 keys IEQ issues derived in Section 8.2.1.2 were utilised to initially capture and extract words from the transcripts.
- Open coding: new codes were emerged as the transcripts indicating further aspects. The transcripts were also systematically categorised into individual nodes and subsequently analysed. As a result of the open coding, 106 nodes were generated for all design options.
- Axial coding: axial coding process was used to organize and connect prior codes. This involves the exploration of data to establish a coherent code, which helps to understand the relationship between individual nodes. The prior nodes were grouped to be 15 nodes.
- Selective coding: the nodes derived from axial coding were refined and categorised to identified themes. Three themes were established regarding the BEP opinions on the design options, including design and construction, IEQ and occupant wellbeing.

Key themes, sub-themes, available data regarding to the BEPs' opinions and perspectives of the design options are shown in Table 8- 4.

Table 8- 4 key themes, sub-themes and available data related to BEPs' opinion on design options derived from coding in nVivo

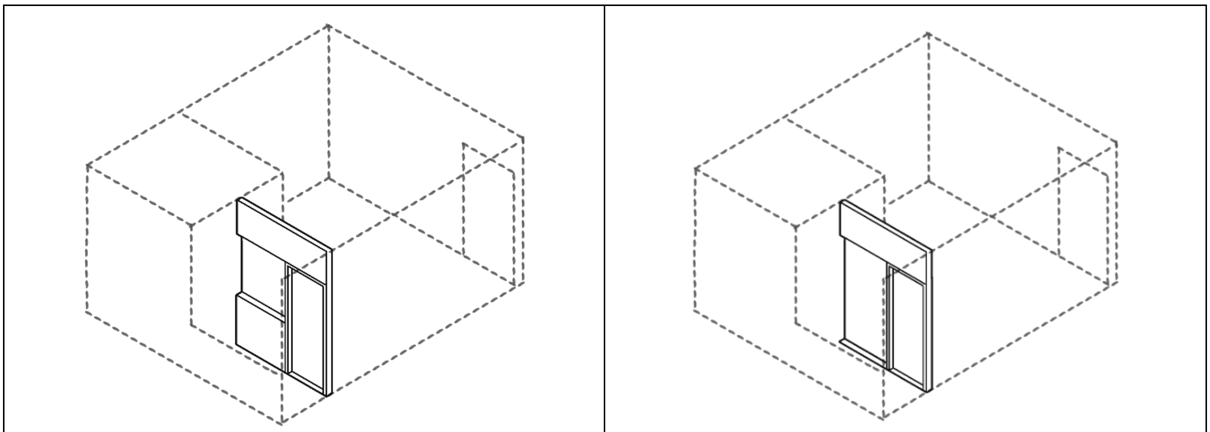
key themes	sub-themes	Design options				
		balcony type	room inlet size	room with and without chimney	chimney design	room outlet design
design and construction	aesthetic	X	X	O	O	X
	construction cost	X	X	O	X	X
	construction process	X	X	X	X	X
	flexible design options	X	X	O	X	X
	maintenance	X	O	O	X	O
	space planning	O	X	O	X	X
IEQ	humidity level	X	X	O	X	O
	natural lighting	X	X	O	O	O
	natural ventilation	X	X	X	X	X
	temperature	X	X	X	X	X
occupant wellbeing	noise nuisance	O	O	X	X	O
	odour nuisance	O	O	O	X	O
	privacy	X	X	X	X	O
	safety	X	O	O	X	O
	visual connection	X	X	O	O	O
*X-available data and O- no data mentioned from BEPs						

The study listed all possibly situations to compare each design option (Figure 8- 5 - Figure 8- 9). A total of 20 cases were developed (see Table 8- 5). Each case was assigned a score based on the corresponding sub-themes using a binary rubric. A score of 1 was assigned to the advantages, positive opinions or perceiving a significant potential in implementing the option, whereas a score of 0 was assigned for some concerns, negative viewpoints or indicating cons in the design options.



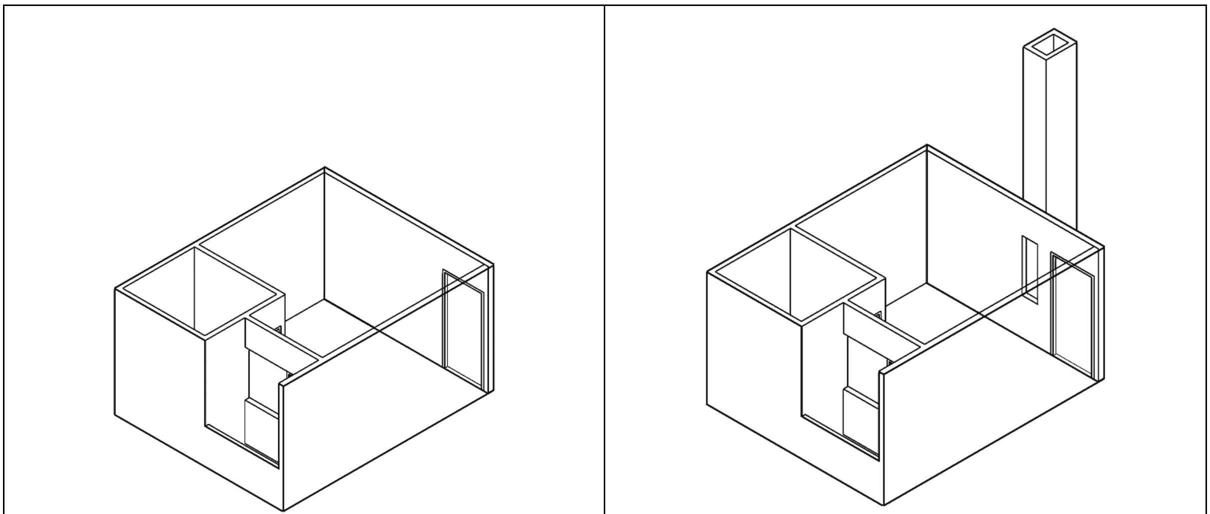
a) Room with solid wall balcony | b) Room with railing balcony

Figure 8- 5 different balcony type
(Source: Author)



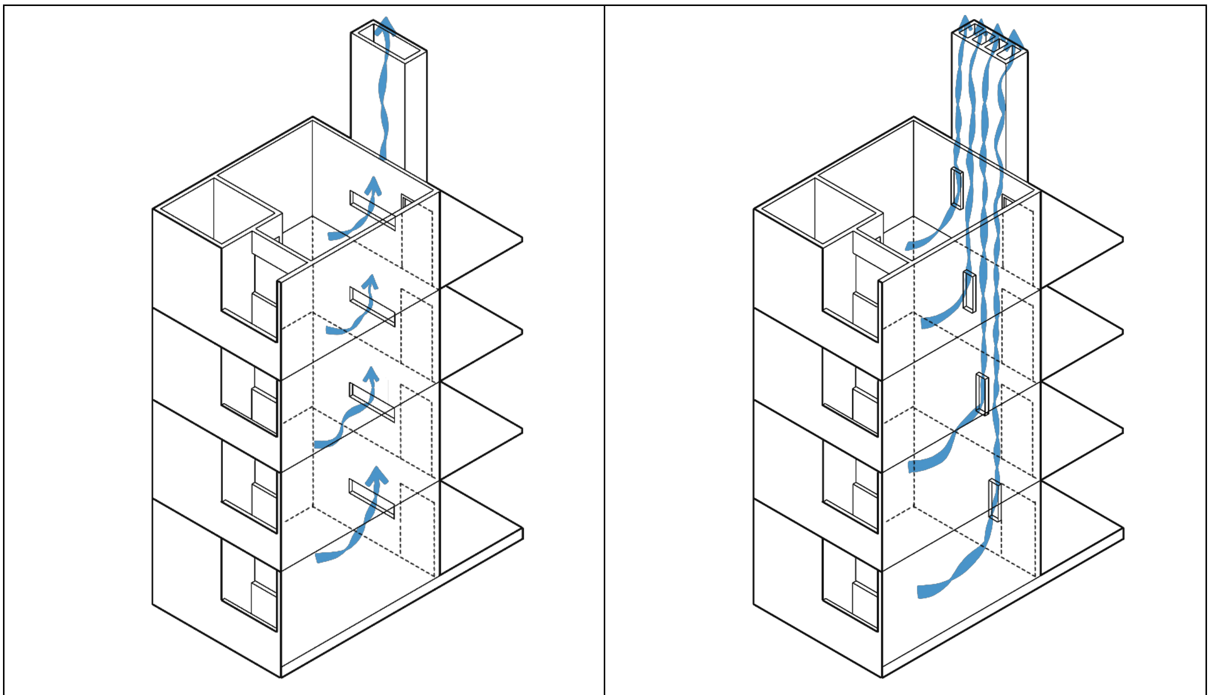
a) Room with window size 1.0 x1.1 m | b) Room with window size 1.0 x 2.0 m

Figure 8- 6 room inlet size
(Source: Author)



a) Room without chimney | b) Room with chimney

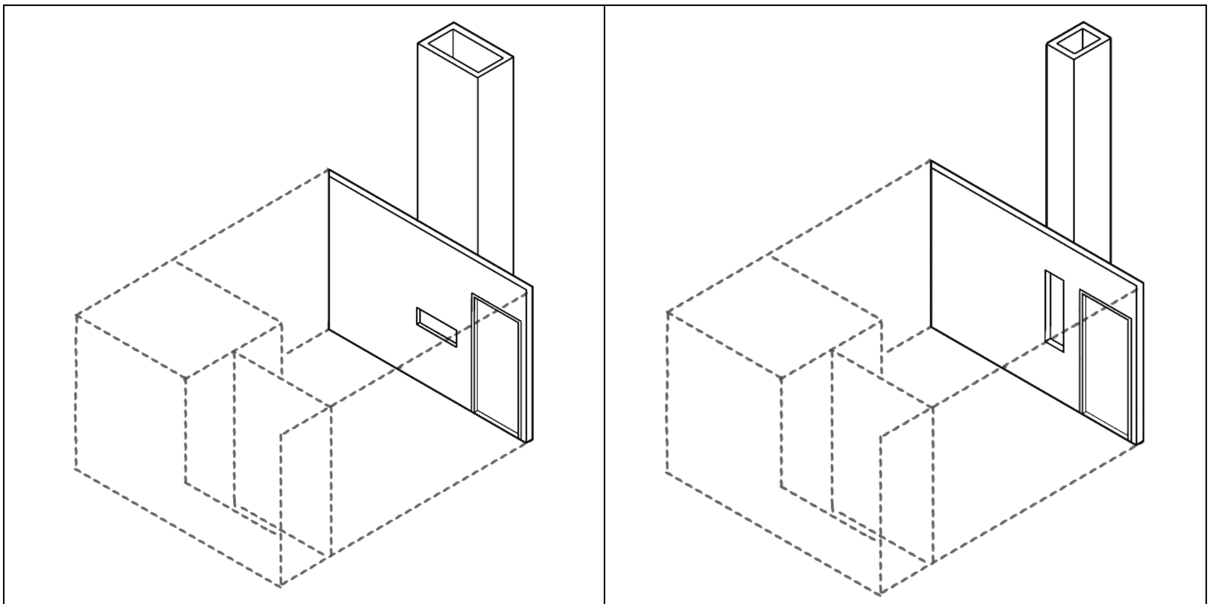
Figure 8- 7 room with and without chimney
(Source: Author)



a) One chimney connected to multi-rooms

b) One chimney connected to only one

Figure 8- 8 chimney design
(Source: Author)

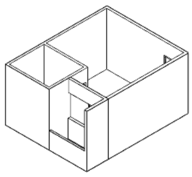
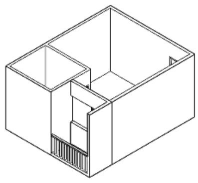
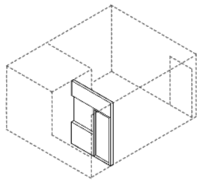
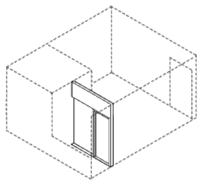
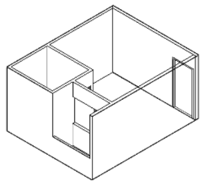
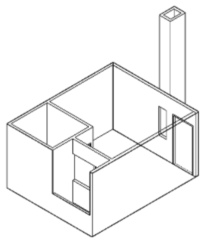
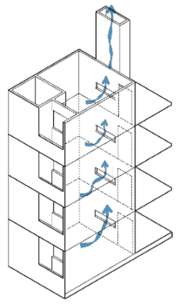
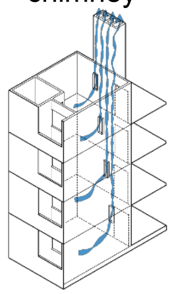
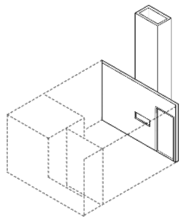
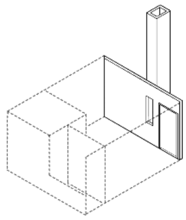


a) Room with horizon room outlet

b) Room with vertical room outlet

Figure 8- 9 Room outlet design
(Source: Author)

Table 8- 5 possibilities of design options

	balcony type	room inlet size	room with and without chimney	chimney design	room outlet design
	 a) wall  b) railing	 a) 1.0 x1.1 m  b) 1.0 x 2.0 m	 a) without chimney  b) with chimney	 a) one chimney  b) multi chimney	 a) horizon  b) vertical
case 1	wall	1.0 x1.1 m	without chimney	-	-
case 2	railing	1.0 x1.1 m	without chimney	-	-
case 3	wall	1.0 x 2.0 m	without chimney	-	-
case 4	railing	1.0 x 2.0 m	without chimney	-	-
case 5	wall	1.0 x1.1 m	with chimney	one chimney	horizon
case 6	wall	1.0 x1.1 m	with chimney	multi chimney	horizon
case 7	railing	1.0 x1.1 m	with chimney	one chimney	horizon
case 8	wall	1.0 x 2.0 m	with chimney	one chimney	horizon
case 9	railing	1.0 x1.1 m	with chimney	multi chimney	horizon
case 10	wall	1.0 x1.1 m	with chimney	one chimney	vertical
case 11	wall	1.0 x 2.0 m	with chimney	multi chimney	horizon
case 12	wall	1.0 x1.1 m	with chimney	multi chimney	vertical
case 13	railing	1.0 x 2.0 m	with chimney	one chimney	horizon
case 14	railing	1.0 x1.1 m	with chimney	one chimney	vertical
case 15	railing	1.0 x 2.0 m	with chimney	multi chimney	horizon
case 16	wall	1.0 x 2.0 m	with chimney	one chimney	vertical
case 17	railing	1.0 x1.1 m	with chimney	multi chimney	vertical
case 18	wall	1.0 x 2.0 m	with chimney	multi chimney	vertical
case 19	railing	1.0 x 2.0 m	with chimney	one chimney	vertical
case 20	railing	1.0 x 2.0 m	with chimney	multi chimney	vertical

Positive response on all cases were calculated as percentages based on the sub-themes defined in Table 8- 4. The resulting percentage for key themes overall evaluation show in Table 8- 6. Case 20 demonstrated the highest overall percentage

(81%). The room in Case 20 had a railing balcony, window size 1.0 x 2.0 m, one chimney connected to only one room and vertical room outlet. Case 20 room was identified as 100% for the IEQ and 82% for Occupant Wellbeing, and 67% for Design and Constructions. Some concerns were raised regarding construction cost and process in this case. Contrastingly, the lowest overall percentage was typical room design, Case 1 (23%). The room in this case was the scenario of room with wall balcony, window size 1.0 x 1.1 m, and without chimney. There were 45%, 29% and 0 % for Occupant Wellbeing, Design and Construction and IEQ, respectively. In particular, all cases of room without chimney exhibited the overall percentage lower than 50%, even the cases designed with larger inlet size.

When Case 4 and 5 were compared, the former case was the room with railing balcony, inlet size of 1.0 x 2.0 m and without chimney, while the latter case was a room with wall balcony, inlet size of 1.0 x 1.1 m, with chimney connected multiple rooms. Even though Case 5 had a chimney, the overall percentage was lower than Case 4. Several concerns were raised regarding Case 5, particularly in relation to IEQ. This was because the room was designed with the wall balcony which could block fresh air intake in comparison to room with railing balcony. Additionally, this scenario had smaller inlet size.

Table 8- 6 percentage distribution in key themes and overall of each design options

	Design and construction	IEQ	Occupant wellbeing	Overall
case 1	29%	0%	45%	23%
case 2	29%	27%	36%	30%
case 3	38%	27%	55%	38%
case 4	38%	53%	45%	45%
case 5	57%	13%	45%	40%
case 6	38%	33%	82%	47%
case 7	57%	40%	36%	47%
case 8	67%	40%	55%	55%
case 9	38%	60%	73%	53%
case 10	76%	27%	45%	53%
case 11	48%	60%	91%	62%
case 12	57%	47%	82%	60%
case 13	67%	67%	45%	62%
case 14	76%	53%	36%	60%
case 15	48%	87%	82%	68%
case 16	86%	53%	55%	68%
case 17	57%	73%	73%	66%
case 18	67%	73%	91%	74%
case 19	86%	80%	45%	74%
case 20	67%	100%	82%	81%

In addition, BEPs were asked to make a decision between a and b of each design option in order to apply into their future projects. 85.7 % of BEPs chose railing balcony. Room inlet size of 1.0 m wide and 2.0 m high were chosen by 95.2% of the BEPs. All BEPs (100%) preferred to have room with chimney. Regarding chimney design, 81% of BEPs chose one chimney connected to only one room, while 19% preferred one chimney connected to multi-rooms. 90.5% of the BEPs selected vertical room outlet.

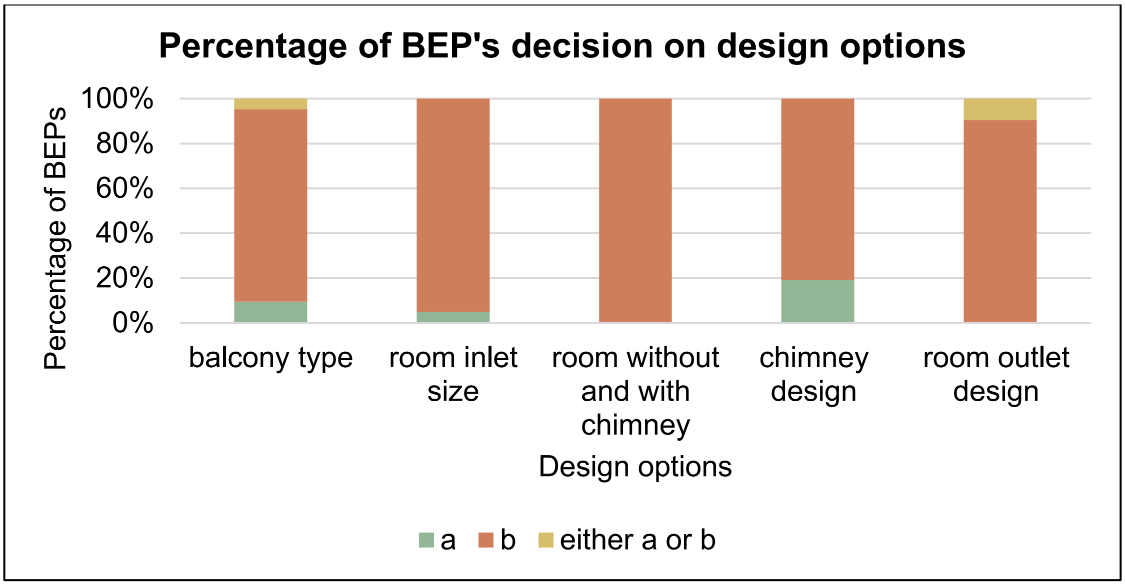


Figure 8- 10 Percentage of BEP's decision on design options

8.3 Summary Validating Design Options

The findings from Part 1, exploring the expertise and knowledge of BEPs in the context of current multi-residential buildings, revealed several IEQ issues such as poor ventilation, high humidity, odour in building, high temperature and mould growth occurrence in the buildings. The majority of BEPs suggested that improving building design could significantly enhance IEQ, with a focus on increasing natural ventilation, and incorporating climate and site considerations into building design. BEPs emphasised the need of natural ventilation in thermally free-running buildings in Thailand. However, in circumstance of OEQ crisis, achieving adequate natural ventilation can be challenging. Active HVAC system becomes a viable option; nonetheless, it poses a significant challenge for economically disadvantaged occupants in terms of both purchasing and operational costs.

In Part 2 of the study, the research focused on strategies and design options. BEPs emphasised the need for redesigning building layout and room features to optimise natural ventilation, including suggestions for double-sided ventilation and ventilated chimneys. BEPs address strong possibility for integrating solar chimney with the design. Regarding proposed 20 design options, BEPs opinions focused on three main topics, which were 1) design and construction, 2) IEQ and 3) occupant wellbeing. For example, an optimal option (a room with a railing balcony, window size of 1.0 x 2.0 m, one chimney connected to only one room, and a vertical room outlet) had the highest overall percentage indicating a great potential for implementation (81%). Conversely, the original room feature (a room with a wall balcony, window size of 1.0 x 1.1 m, and no chimney) had the lowest overall percentage (23%). Additionally, all cases of no chimney had overall percentages below 50%, even when some options featured larger inlet sizes. All BEPs reported a preference for rooms with chimneys and a majority selecting the configuration of one chimney connected to only one room.

The comparative analysis between the original room and the optimal case will be discussed in Chapter 9: Discussion.

9 Discussion

9.1 Introduction

This chapter provides discussions of the research findings from previous chapters, including the literature review (Chapter 2), monitoring physical measurement (Chapter 4), occupant perception survey (Chapter 5), CFD sensitivity analysis: outdoor (Chapter 6), CFD sensitivity analysis: indoor (Chapter 7), and validating design options for improving internal environment quality within thermally free- running apartments (Chapter 8). The discussions involve comparing and analysing those findings against relevant theory and previous research to incorporate them into the current knowledge framework.

To summarise, this research has been achieved through three phases of investigation. Initially, the study thoroughly analysed the current situation of apartment dwellings in Thailand context. The research revealed that passive cooling strategies, particularly natural ventilation, could potentially provide significant benefits for Thailand's climate and context. Physical measurements within the multi-residential buildings in Thailand were conducted to understand the current situation regarding IEQ, particular temperature, relative humidity and air speed. Furthermore, the existing conditions, such as building regulation, weather data, and census, were investigated. Due to the limited availability of information about multi-residential buildings in Thailand, the research sought to fill this knowledge gap by conducting resident questionnaires. This exploration established the typology and key features of such buildings. In addition, the relationship between key features of typical buildings and occupants' perceptions with regard to their IEQ were investigated.

The second phase was focused on investigating factors influencing both outdoor and indoor air movement. Outdoor CFD sensitivity analysis was used to explore five factors affecting the air movement around the building, which were wind direction, wind speed, position on building, building height and road width, and different layers of nearby buildings. These insights were then applied to modify the wind direction parameters for the indoor simulation models.

The indoor sensitivity analysis, on the other hand, concentrated on parameters that influence natural ventilation through CFD and BES simulations. This exploration commenced with the initial room parameters and subsequently explored various factors, including the presence or absence of ventilation chimneys, room inlet and outlet sizes, chimney dimensions, room outlet locations, chimney design variations, and different chimney materials. The findings identified the significant indoor factors impacting on ventilation within the indoor space.

The final phase entailed proposing design options to improve IEQ in multi-residential buildings in Thailand. Validation of the design options was sought through engagement with BEPs in Thailand. These experts agreed with the presence of IEQ issues in such buildings and emphasised that enhancing ventilation is essential for improving IEQ. The design options, encompassing considerations of design and construction, IEQ, and occupant well-being, demonstrated substantial potential for future implementation in Thai multi-residential buildings.

This chapter provides discussions of three main topics, including Indoor Environmental Quality Issues (Chapter 9.2), Passive Cooling via Natural Ventilation (Chapter 9.3) and Proposed Design Options (Chapter 9.4).

9.2 Indoor Environmental Quality Issues

Previous research has consistently demonstrated that densely packed urban buildings can significantly obstruct wind flow (Ng 2016; Azizi and Javanmardi 2017) and solar radiation (Mesa et al. 2010; Freitas et al. 2015), affecting thermal comfort both outdoors and indoors, particularly in tropical climates. High residential density in urban areas frequently results in poor indoor environmental quality (IEQ) and inadequate living conditions (Wong et al. 2009). This further causes health risks to occupants. Furthermore, people tend to spend a considerable amount of their time indoors, therefore a healthy IEQ is very important. Many studies reveal that the most vulnerable or disadvantaged populations are frequently located in areas with poorer environmental quality (Santamouris et al. 2014; Abdulaali et al. 2020). Low-socioeconomic groups tend to suffer worse health as a result of inadequate indoor environmental quality.(Evans and Kantrowitz 2002; Jun et al. 2011)

The physical measurement conducted in residential units within multi-residential buildings in Chiang Mai city centre (Section 4.2) provided insightful findings regarding vapor pressure and thermal comfort. The findings from physical measurement are consistent with previous research, indicating that multi-residential buildings located in city centres tend to experience lower IEQ (Chan et al. 2008; Zhang and Yoshino

2010b; Kozielska et al. 2020). Factors such as limited natural ventilation due to closely located buildings (Allard et al. 2009), and urban heat island effect contribute to this diminished IEQ (Ai and Mak 2015). The analysis identifies three primary factors influencing water vapour pressure within the residential units, 1) building environment, 2) room layout and 3) occupant activity. These findings are supported by findings from other studies (Zhang and Yoshino 2010a; Nguyen and Dockery 2016; Wolkoff 2018; Lou and Ou 2019; Pan et al. 2021). The building environment significantly impacts indoor temperature and humidity levels, particularly in passive buildings (Gou et al. 2018). The study reveals that interior design plays a role in determining varying levels of vapour pressure (You et al. 2017). Furthermore, field studies have also established that room layout influences humidity level (Lou and Ou 2019). In addition, occupant activity in room is recognized as another key factors to the variability and uncertainty of vapour pressure within room (Yan et al. 2015). Literature review (Section 2.1) indicated that the thermal comfort for Thailand's climate range between 22.3 to 29.3 °C, with relative humidity within the range of 20% RH to 80% RH (Givoni 1992). The suggested relative humidity range for minimising bioaerosols is 30% to 60% RH (Arundel et al. 1986). Over the data-collecting period, the residential units remained within the thermal comfort range for 30% to 78% of the time. It was observed that the period within the thermal comfort range depended on the building environment, room layout and occupant activity. For example, rooms with a greater number of openings experience had 5% longer period in thermal comfort condition than the rooms with less opening. Thermal comfort can be improved by increasing the number of openings, which has been explored in previous research (Mochida et al. 2005; Daghigh et al. 2009; Mishra and Ramgopal 2013; Wang et al. 2021). However, the use of curtains for privacy within the room obstructs natural ventilation, resulting in a decrease of thermal comfort duration. Residential units managed to achieve the range of optimal relative humidity to minimize bioaerosol for appropriately half of the measurement period.

The expectation of increased air movement with increased number of openings from literature (Mochida et al. 2005; Fan et al. 2021) was tested. Physical measurements were conducted in two rooms: one located in the middle of the building and the other located at the corner of the building with an additional window. When all windows in both rooms were opened, it was observed that the airspeed at the balcony of the middle room was reduced by approximately 90% of the outdoor air movement. Meanwhile the velocity at the balcony of the corner room was decreased by nearly 40% of the outdoor air movement. In addition to the number of openings, the location of a room within a building significantly influences its ventilation (Jiang et al. 2020; Liu et al. 2020). Rooms located at the corners of a building typically have the advantage of being on the windward side, obtaining greater amount direct airflow. In contrast, rooms located in the middle of a building frequently obtained wind that has been redirected along the building's surface (Jiang et al. 2020). When both rooms had all openings fully open including room doors, the air velocity at the balcony of the middle room was approximately 5.6% lower than the corner room. Although the airspeed varied depending on such openings at the balcony, the airspeed in the middle of both rooms was nearly negligible, at almost 0 $m.s^{-1}$. Previous studies have recommended an airspeed of at least 0.2 $m.s^{-1}$ to improve thermal comfort (Szokolay 2012; ASHRAE 2017). In tropical climates, natural ventilation can potentially improve indoor thermal comfort by 36% to 50%. Haase and Amato's study suggested that the ventilation of 0.4 $m.s^{-1}$ is optimal for increasing the rate of evaporative and convective heat loss from the human skin to the environment (Haase and Amato 2009). However, the findings from physical measurement indicate that the actual ventilation in the multi-residential building is unlikely to be sufficient to achieve the desired thermal comfort condition.

The findings from the occupant perception survey (Chapter 5) provide insightful feedback on living conditions in multi-residential buildings in Thailand. The findings are divided into four categories: demographic results, physical environment, occupant activity, IEQ and occupant comfort satisfaction.

In term of demographic results, the participants commonly spent time in their room between 8 to 12 hours during weekdays and 12 to 16 hours during weekends. This pattern indicates that, on average, occupants spend about half of their day in their rooms. Given this substantial amount of time, maintaining a healthy IEQ is crucial for the occupants' health and well-being.

The physical environment findings indicate that participants primarily reside in rooms with single-sided ventilation, which are typically located in the middle of the building. Multi-residential building are often designed with single-sided ventilation due to the compact configurations, but this results in limited ventilation (Farea et al. 2012; Aflaki et al. 2016). This is consistent with previous research, which indicates that room with single opening achieve only 12-23% of the external wind velocity, leading to inadequate IEQ and potentially affecting occupant well-being (DeKay and Brown 2013). Furthermore, two-third of participants lived in buildings located ranging from 0 to 6 metres away from the nearest nearby building. This limited spacing between buildings raise concerns about restricted air movement in urban areas (Fernando et al. 2010; Liu et al. 2015). The physical environment, such as the proximity of nearby buildings and the height of occupants' building, significantly influence indoor air quality perceptions. For example, occupants typically perceive inadequate natural lighting and low natural ventilation when another building is located within a 0 to 3 metre range from their buildings. Occupants perceive air rather humid when the distance to nearby building is smaller. It was additionally found that occupants in buildings located in close proximity nearby building often maintain privacy by keeping curtain closed, which further limits natural ventilation (Foster and Oreszczyn 2001; Yan et al. 2015). Based on the findings of the study, it is recommended that building designs with short distance to nearby buildings should consider balancing privacy needs with maintaining adequate indoor air quality. This might involve innovative building designs that enhance privacy while still allowing for effective natural ventilation.

The findings indicate that most building materials utilised in the typical rooms are porous. These materials display varying degrees of vapor permeance. For example, wood doors and furniture are classified as vapor permeable, implying that moisture can pass through it more readily. Brick walls and concrete walls are considered vapor semi-permeable, which indicate a moderate level of moisture transmission. Toilet floor tiles, on the other hand, are categorised as semi-impermeable, making them less susceptible to moisture damage due to their lesser permeability (BuildingScienceCorporation 2013; Cengel and Ghajar 2015).

These findings of physical environment and typical room materials contribute to modelling in CFD sensitivity analysis and BES analysis.

Occupant activities that generate moisture, such as cooking, washing, and indoor clothes drying, significantly contribute to the perception of stale and humid air, inadequate ventilation, and a higher occurring level of mould. Residential moisture is produced not only through occupant's body but also through various household activities (Yik et al. 2004; Zemitis et al. 2016). Residential activity, room function, usage duration and frequency contribute different level of moisture generation in room. For example, 2,000-3,000 grams, 1,500 grams, 500 grams per day for cooking, drying clothes indoor and washing clothes respectively (Institution 2011). Despite these variations, it is critical that buildings are built to minimise indoor moisture accumulation. Moreover, the findings reveal a significant correlation between human behaviour characteristics and IEQ.

9.3 Passive Cooling via Natural Ventilation

Referring to the necessity of improving thermal comfort and reducing health risk in residential building in Thailand, passive cooling through ventilation is a potential technique to acquire the comfort condition with sustainable environment.

Increasing ventilation in buildings is beneficial for thermal comfort as it enhances convective heat transfer (De Dear and Brager 2002). In addition, this aligns with the findings that ventilation satisfaction significantly influences overall comfort in occupants' rooms (see more details in Section 5.4). Occupants in tropical climates often prefer higher air speed (Sekhar 2016). Based on tropical climates, natural ventilation is a particularly cost-effective strategy to for mitigating physiological effects of high humidity, while maintaining acceptable indoor thermal comfort (Priyadarsini et al. 2004). Natural ventilation can be achieved in buildings by cross ventilation and/or stack ventilation. However, while natural ventilation can improve thermal comfort levels, there are challenges in its implementation (Nguyen and Reiter 2014; Du et al. 2020). For instance, buildings with limited opening options, which may not facilitate sufficient ventilation. The presence of buildings in close proximity in city centre can limit cross ventilation.

The physical measurement findings in the stack area (Section 4.1) reveal an increase in airspeed when two openings are present, one located at a lower elevation and the other at a higher elevation. Therefore, the air velocity in the stack area is rather small, ranging between 0.02-0.05 $m.s^{-1}$. This aligns with previous research that air temperature difference between indoor and outdoor in tropical climate is typically less than 5°C (Yusoff et al. 2010). Stack ventilation has challenges in design and control due to the inherent unpredictability of its driving forces, wind and temperature difference (Khanal and Lei 2011).Therefore, relying solely on stack ventilation might not be sufficient in this climate, highlighting the need for solar induced ventilation strategies to optimise indoor thermal comfort.

Previous studies have established and demonstrated the potential of solar chimney used in tropical climate (Awbi and Gan 1992; Bansal et al. 1993; Nugroho 2009; Punyasompun et al. 2009; Nugroho 2010). As a passive cooling technique, solar chimney uses the buoyant effect to enhance ventilation, particularly in urban areas which suffer from air movement obstructions (see more detail in Section 2.3). The combined radiation and convection inside a solar chimney results in appreciable air movement to improve ventilation (Khanal and Lei 2011).

Various suggestions to develop typical multi-residential building features to enhance fresh air to circulate into building were proposed to BEPs (as detailed in Chapter 8). The majority of BEPs recognize the potential for integrating solar chimney into multi-residential building design. They emphasized that the integrating solar chimney is neither complex nor difficult to construct. However, concerns were raised regarding limitations such as the limitation of building space, the challenges of the outdoor environment etc.

While natural ventilation has its limitations, including pollution and extreme weather (Azam et al. 2018; ChooChuay et al. 2020), it is generally effective for most of the year. A basic design incorporating solar chimneys can provide an optimal solution for buildings while also catering to the socioeconomic situation of the occupants.

9.4 Proposed Design Options

To establish design options that enhance IEQ through passive cooling, it is essential to investigate and comprehend both outdoor and indoor factors influencing ventilation. Understanding of the factors can help to develop explicit modelling for accurately predicting ventilation flow rates and for refining design options. This exploration includes outdoor CFD sensitivity analysis (Chapter 6), indoor CFD and BES sensitivity analysis (Chapter 7) and interview BEPs (Chapter 8).

Previous studies have highlighted the challenges in air movement within urban areas, identifying factors such as drag, accidental release, roughness. The air movement is altered and reduced airflow patterns compared to initial wind based on meteorological data (Cheng et al. 2013; Liu et al. 2015; Ng 2016; Azizi and Javanmardi 2017). The findings of CFD sensitivity: outdoor (Chapter 6) illustrate air movement around building surfaces. The explorations include wind direction and wind speed, road width and building height, and nearby buildings. The results demonstrated that air movement can be reduced by up to 60% from initial wind when the number of nearby building layers increases from one to three, or when the radius of these layers expands by 2.7 times. This finding is consistent with previous research indicating significant decreases in wind speed in high density area (Du et al. 2018). For example, a previous CFD study showed that over 60% reduction in wind speed around focus building due to the presence of high rise buildings (Peng et al. 2018). Another CFD simulation study revealed that pressure was reduce up to 60% when comparing models with a radius of 100m to those with 250m, or when the radius of nearby building layers increased 2.5 times (Lee 2017). Pressure decreases with increased nearby building layers (van Druenen et al. 2019). Furthermore, the layers of nearby buildings were found to have a significant influence on wind characteristics (Lee 2017). Notably, wind direction has been identified as a crucial factor influencing ventilation in buildings. The air movement pattern through and around the focus building is altered due to the impact of urban configurations. In this study, the research explored air movement on focus building facade by considering scenarios with up to three layers of nearby buildings. The result (Section 6.3.3.4) in the research shows the convergence of the average air movement when nearby buildings were increased to three layers. Previous research also suggested that modelling of three layers of nearby buildings within the influence region provides a convergence in airflow rates. An actual urban configuration is non-uniform. Airflow convergence is not only found in the non-uniform of three layers in urban area but also equivalent to that from uniform building arrays (Tong et al. 2016). Therefore, uniform building arrays can generally be applied to non-uniform configurations.

The findings from the CFD sensitivity analysis for indoor, detailed in Chapter 7, initially present a comparative CFD and BES analysis of two room configurations: the original room (without a chimney) and a room equipped with a chimney. As highlighted in Chapter 2 and Section 9.3, the integration of chimney into building design can significantly enhance building ventilation, particular in urban areas where wind availability is limited. The study revealed that a room with chimney could achieve 12.5% thermal comfort during summer compared to a room without chimney. This is similar to previous chimney research observed that percentage of thermal comfort hour during summer in high-rise multi-residential building in tropical climate (Bangkok) increased from 38% to 56%, marking an 18% increase (Prajongsan and Sharples 2012). In addition, the presence of chimney in a residential unit can increase ventilation to nearly 0.2 $m.s^{-1}$, which is a 50% improvement over a room without chimney. However, it is noted that this ventilation rate still does not reach the air velocity appropriate for the elevated temperature. Previous research has indicated that building with solar-induced ventilation can achieve room temperature approximately 4–5 °C lower (Punyasompun et al. 2009). Another study focus on solar chimney integrated into residential building design demonstrated that the chimney could increase indoor air speed up to 0.58 $m.s^{-1}$ higher than the design without solar chimney (Nugroho 2010). Incorporating solar chimney into room design can increase airflow up to nine times in comparison to room without chimney. Solar chimneys are designed to maximize ventilation benefits by optimising solar gain, resulting in a significant temperature difference between indoor and outdoor to produce adequate airflow (Khanal and Lei 2011). These findings confirm that incorporating a chimney into building design can significantly enhance ventilation and thereby increase the hours of thermal comfort in residential units.

Different variations in chimney design are influenced by several factors, including location, climate, orientation, inlet, outlet, chimney depth, and internal heat gains (Harris and Helwig 2007). Consequently, this study investigates various parameters of room and chimney to understand their impact on ventilation (see Figure 3-29, Section 3.6.2.2). It was found that rooms with greater inlet size significantly enhance ventilation. This aligns with prior research which demonstrated that an increase in inlet size improves ventilation (Bassiouny and Koura 2008; Khanal and Lei 2011).There is a direct proportional relationship between air temperature and airflow with the inlet and outlet sizes, whereas relative humidity inversely correlates with these dimensions (Maghrabie et al. 2022). Additionally, a larger outlet area can lead to a greater mass flow rate compared to an inlet of equal size (Shi et al. 2018).

The study (Section 2.4.3.1) identified that the optimal chimney depth is 0.3 m which align with other research (Miyazaki et al. 2006; Khanal and Lei 2011). Air velocity within the solar chimney increases with the depth of the air gap, making it a crucial parameter for ventilation performance in terms of mass flow rate (Chen et al. 2003; Mathur et al. 2006; Khanal and Lei 2011). Despite most research highlighting the importance of air gap for ventilation performance, reverse airflow occurs when the chimney depth is too large (Miyazaki et al. 2006; Lee and Strand 2009). Furthermore, the study discovered that chimney with a 45-degree trim can enhance ventilation at occupant level reaching up to 0.2 $m.s^{-1}$, which is considered acceptable for cooling effect. Previous research has also found that an inclined chimney improve natural ventilation, with an optimal angle of 45 degrees (Bassiouny and Korah 2009). Triangular corner in solar chimney results in higher thermal performance for natural ventilation compared to other configurations (Dhahri et al. 2021).

Various suggestions to develop typical multi-residential building features to enhance fresh air to circulate into building were proposed to BEPs (as detailed in Chapter 8). The majority of BEPs recognise the potential for integrating solar chimney into multi-residential building design. They emphasised that the integration of solar chimneys is neither complex nor difficult to construct. However, concerns were raised regarding limitations such as the limitation of building space, the challenges of the outdoor environment etc.

The study investigated various room and chimney parameters that influence ventilation (Section 7.2.3) in order to develop design options (Section 8.2.2.3). These options were then presented to BEPs for their opinions. As described in Chapter 8, BEP interviewees provided their opinions on 20 design options, focusing on three main themes, which are 1) design and construction, 2) IEQ and 3) occupant wellbeing. The study precisely compared all potential scenarios to evaluate each design option. Within these options, the one with the highest overall BEP satisfaction percentage (81%), the optimal case, involves features such as railing balcony, window size 1.0 x 2.0 m, solar chimney with one chimney connected to only one room and vertical room outlet. In contrast, the original room features, which was used as a baseline for comparison, included wall balcony, window size 1.0 x 1.1 m, and without chimney, resulting in the lowest overall BEP satisfaction percentage (23%). The comparison of features of original room and the optimal case is shown in Figure 9- 1. In term of chimney design, 100 % of BEPs showed a preference for room with chimney. When compared to the original room, the optimal case exhibits a reduction in vapour pressure within the room (see Figure 9- 2). Considering annual hourly weather data, the study discovered that the optimal case could enhance thermal comfort by up to 21.9% longer than the original room. Additionally, the optimal case can maintain a relative humidity within the range of health benefit approximately 5% longer than the original room. During rainy season, the optimal case improves even more significantly. It can provide thermal comfort 42.3% higher than the original room. Furthermore, relative humidity within the health benefit range is achieved approximately 8%, providing a 56% improvement over the original room. Another notable advantage of the optimal case is that it can provide natural ventilation can reliably exceed 0.2 m. s^{-1} and occasionally reach 0.4 m.s^{-1} at the occupant level. This aligns with suggestions by Tantasavasdi et.al (Tantasavasdi et al. 2001), as cited in Aflaki et.al (Aflaki et al. 2015) that indoor air speed in tropical climate condition of at least 0.4 m.$s^{-1}$is necessary to enhance evaporation rate from human skin, thereby achieving thermal comfort for achieving thermal comfort. In contrast, ventilation is insufficient in the original room, at nearly 0 m. s^{-1}. The CFD comparison between the original room and the optimal case are illustrated in Figure 9- 3.

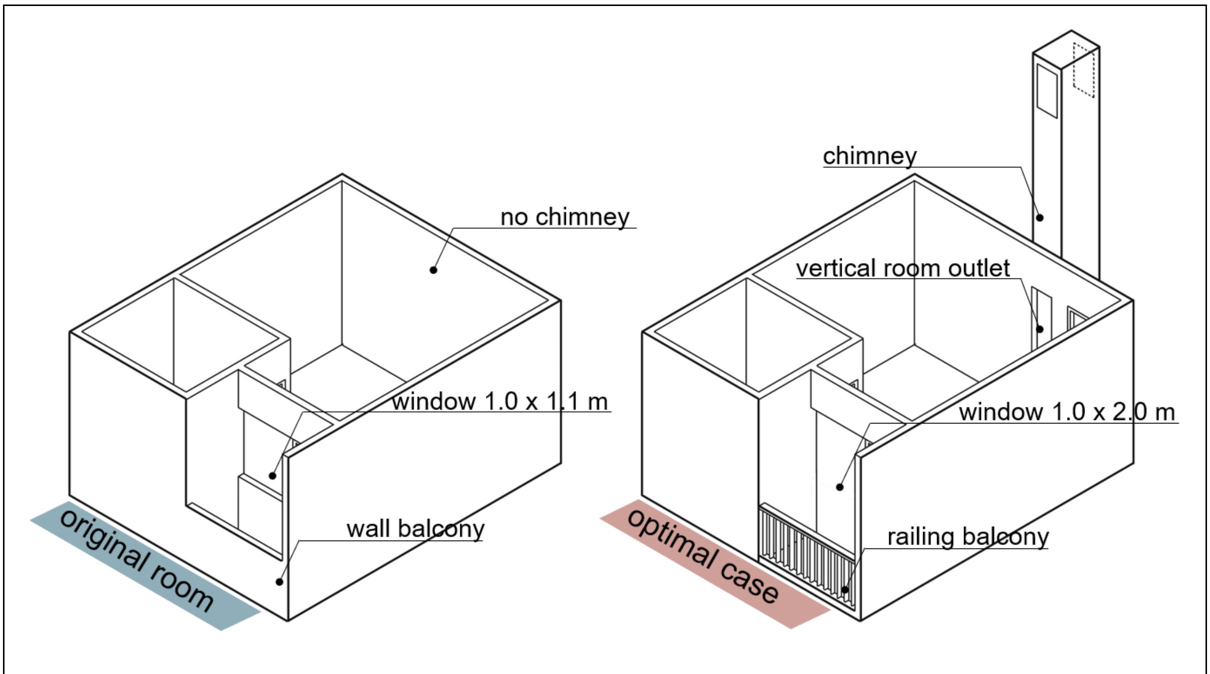


Figure 9- 1 the features of original room and the optimal case
(Source: Author)

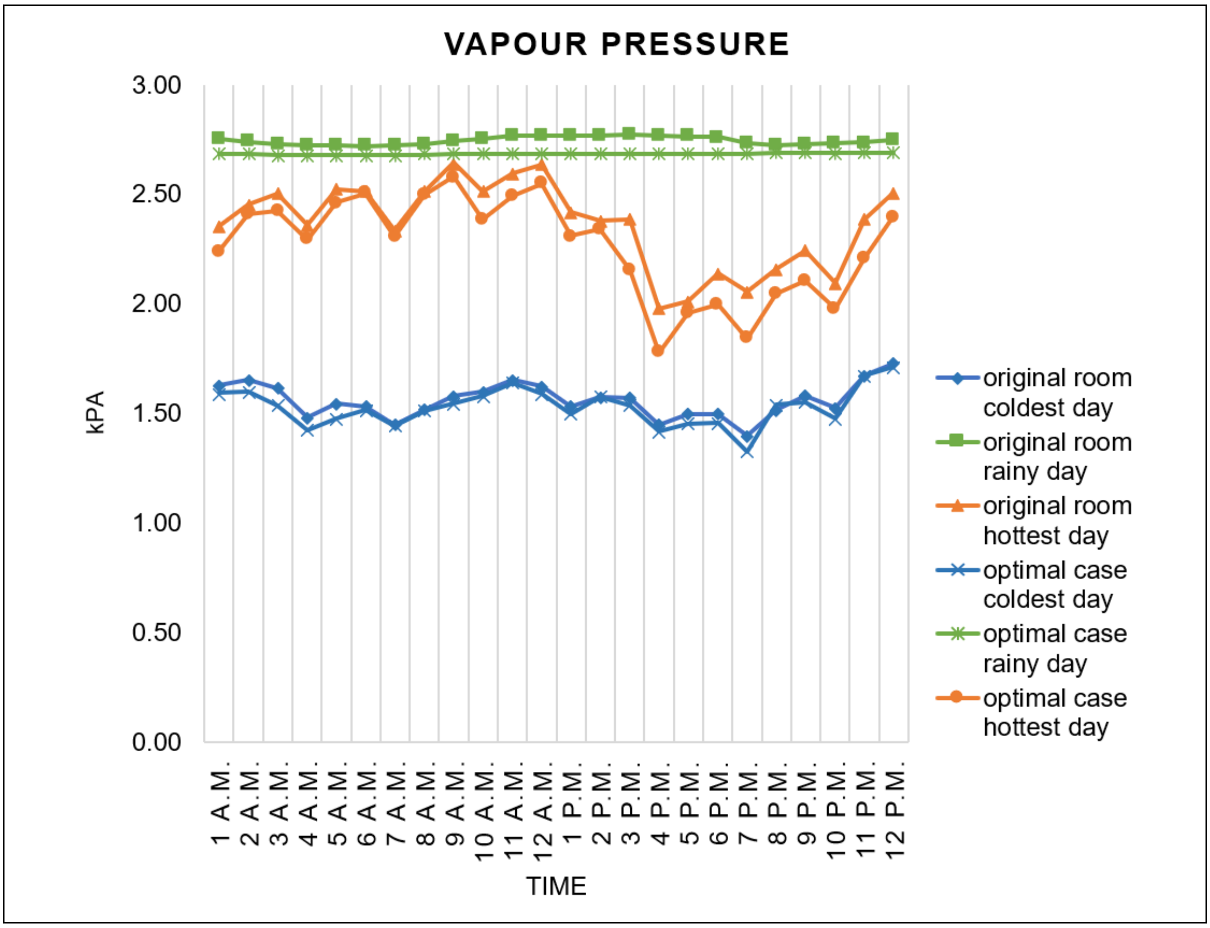


Figure 9- 2 comparison of air temperature and relative humidity between original room and the optimal case

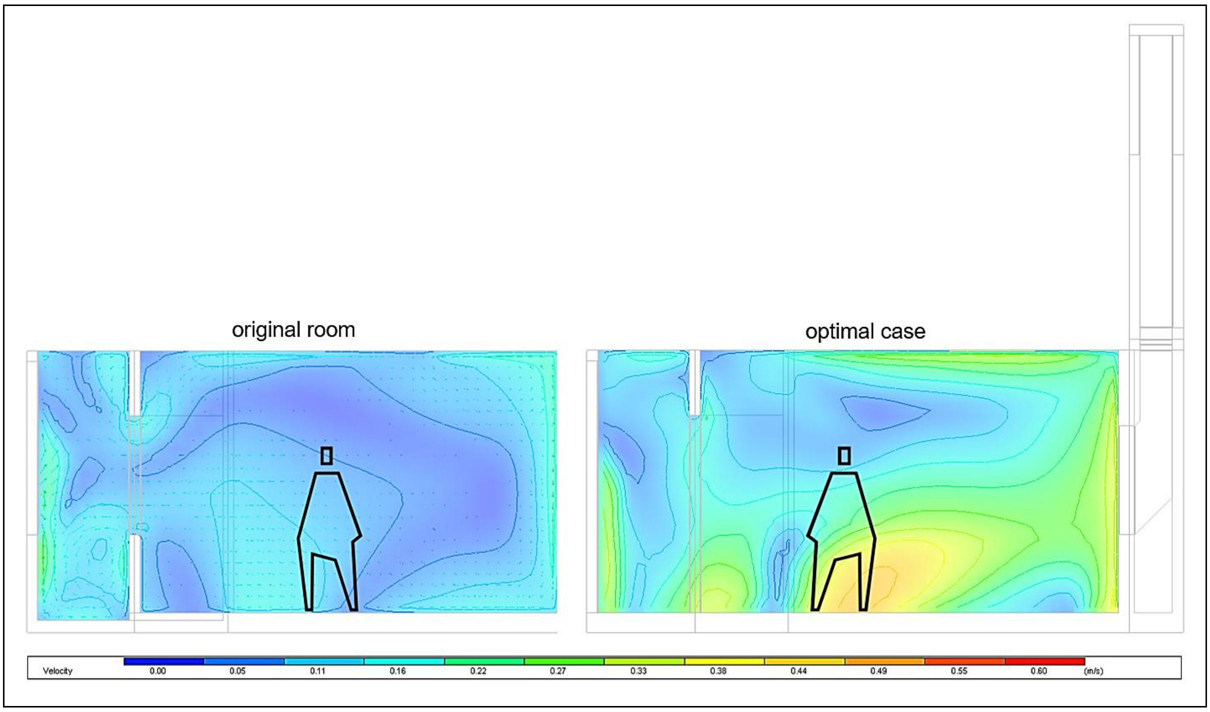


Figure 9- 3 comparison of CFD results between original room and the optimal case

The integration of solar chimneys in multi-storey buildings presents a satisfying option for tropical climates like Thailand. Previous studies have explored the incorporation of solar chimneys in multi-residential buildings within this region. For example, Punyasompun et.al 2009 indicated that integrating a solar chimney into a multi-storey building can enhance natural ventilation and decrease indoor temperatures by approximately 5°C. Additionally, Prajongsan et.al 2012 investigated into ventilation shafts in high-rise multi-residential buildings in Thailand showed that thermal comfort hours could extend by up to 33% and 64% per day for south- and north-facing buildings, respectively. Some studies have also explored the integration of solar chimneys on roof (Chungloo and Limmeechokchai 2007; Chungloo and Limmeechokchai 2009). However, these previous studies often do not consider buildings in close proximity, where external wind speed and direction differ significantly from those in urban area (Caciolo et al. 2011) (detailed in Section 9.2). This is why there was a need for further exploration in multi-residential buildings in urban areas for Thailand. Therefore, this study not only corroborates their findings of previous research but also contributes to knowledge by the research findings (see more details in Section 10.3).

One of the challenges which face natural ventilation is pollution (Cheng et al. 2013). however, previous research suggests that an air filtration unit can be added to limit airborne particle entering the space (Fennelly et al. 2023). Other studies confirmed that operating air filtration unit could increase fresh air entrainment from outside (Sloof et al. 2022; Butler et al. 2023).

It is also acknowledged that passive stacks may not always sufficiently provide ventilation. If necessary, this can be supplemented with a fan to create an active stack. Previous research has proved that active stack can achieved an air speed of 0.67 m. s^{-1} (Priyadarsini et al. 2004).

The integration of solar chimneys with active systems or renewable energy devices can enhance ventilation efficiency, which requires to explore more detail in future research.

10 Conclusion

10.1 Introduction

Multi-residential buildings in Thailand urban areas have significant issues in terms of indoor environmental quality (IEQ). These buildings are typically built with single-sided ventilation. The limited opening, particularly in thermally free-running buildings, causes poor ventilation, leading to elevated moisture load and, consequently, mould. These issues significantly impact living comfort and increase health risks, particularly for low-socioeconomic groups who are more vulnerable to inadequate IEQ. As a passive cooling strategy, natural ventilation is advantageous because it can improve thermal comfort for the indoor environment while promoting sustainability and cost-effectiveness. Passive design strategies to improve natural ventilation can be effectively selected based on climate conditions and building characteristics.

The preceding chapters have presented the findings of this study and provided design options for multi-residential buildings in Chiang Mai, Thailand, as a case study. Optimised design options entail the integration of building contexts and passive design strategies to provide natural ventilation and improve IEQ including temperature, relative humidity and air speed. This chapter relates the conclusions to the aim and objectives (section 10.2), states the key contribution to knowledge (section 10.3), limitations (section 10.4) and makes recommendations for further research (section 10.5).

10.2 Conclusions in relation to Aim and Objectives

The six objectives were formulated to facilitate the achievement of the research aim as follows:

Objective 1 is to evaluate current situation on indoor environmental quality in apartment blocks in Thailand– particularly air temperature, relative humidity, and air speed.

This research was accomplished through physical measurement and the results were reported in Chapter 4. The physical measurement was conducted in multi-residential buildings, with other buildings in proximity, in Chiang Mai city centre. Two spaces types were monitored, these were apartment’ rooms and stack ventilation area in stairway.

The physical measurements were conducted in four residential units within two multi-residential buildings, gathering temperature, relative humidity and airspeed data. Three primary factors were identified as influencing the water vapour pressure within the residential units, including building environment, room layout and occupant activity.

Building environment: Although the amount of water vapour pressure in the room varies depending on the outdoor water vapour pressure, building location was also found to be an influence. Both multi-residential buildings in this study were located in Chiang Mai city centre, but they had different urban environments. One was surrounded by more than 90% hardscape, whereas the other building had a larger area of softscape. This is because softscapes naturally enhance evapotranspiration processes in the urban area. This leads to an increase in outdoor humidity levels. Therefore, this different outdoor environment was found to have a significant impact on indoor water vapour pressure, which directly affect the relative humidity inside buildings (Section 4.3.3.1.2).

Room layout: The room layout also significantly influenced the water vapour pressure within the room. The physical measurements data revealed that the residential unit where the WC was situated further inside had notably higher vapour pressure. This is due to the more challenge in ventilating and releasing water vapour in comparison to the other room layout.

Occupant activity: Occupant activity had a substantial impact on the water vapour pressure inside the room. For example, when a window was opened, the room experienced more noticeable fluctuation in vapour pressure in relation to the outdoor water vapour pressure compared to a room with a closed window. In addition, a room with opened window but closed curtain exhibited higher water vapour levels. Activities that generate vapour, such as bathing, cooking, and hanging clothes for drying, can significantly elevated water vapour pressure within a room. Following the completion of these activities, it usually took approximately 10 to 35 minutes for the room to return to its normal water vapour levels.

The results provide data regarding the actual occupants' rooms in relation to the occupants' activities. This data can reveal insight to cause -and -effect relationships within the building, aiding in the investigation of internal parameters affecting occupants' room. The finding from the physical measurement indicate that the residential units have insufficient air ventilation, with an average air speed of 0.002 $m.s^{-1}$ for middle room and 0.005 $m.s^{-1}$ for corner room, which is inadequate for ventilating the room or achieving thermal comfort.

In the stack area, the findings indicate that higher elevations exhibit higher indoor temperatures. In contrast, indoor relative humidity is higher when located at a lower height. This is because the lower elevation of the building in city centre is typically overshaded by nearby buildings. In addition, relative humidity is inversely proportional to temperature. Indoor temperature and relative humidity in the stack area with only a single opening exhibited low fluctuation compared to the outdoor temperature and relative humidity, respectively. In this scenario, no air movement was detected in the stack area. However, when two openings, one positioned at the lower elevation and the other at the top elevation, are utilised in the stack area, indoor temperature and relative humidity are more significantly correlated to outdoor temperature and relative humidity than the previous scenario. In this scenario, air movement is between 0.02-0.05 $m.s^{-1}$. The result demonstrates that stack ventilation improves ventilation within the building. This result serves to validate the finding from literature review in Section 2.4.3 indicating that stack ventilation has potential benefit to improve IEQ where it can be challenging to achieve effective cross ventilation. This is useful because the presence of buildings in close proximity in city centre can limit cross ventilation. It is acknowledged that the improvement in air flow is slight, but the thermal stack area monitored was primarily a stairwell and not designed to be an effective thermal stack area.

Objective 2 is to characterise typology and key features of typical apartments in Thailand.

In order to achieve this objective, the study investigates the typology and key features of typical apartments in Thailand using a combination of secondary and primary sources. Secondary sources include Thailand building Regulation and census data, while primary sources involve occupant perception survey (Chapter 5).

In the secondary source, several available datasets support the investigation. These datasets encompass building regulations related to multi-storey residential building, which include Building Control Act and Town Planning Act. (See Section 3.2.1). These regulations define various building characteristics, including building height, building setback etc. Another valuable dataset is the census data, which provides information on the building types and population.

However, there are a limitation in obtaining typical multi-storey residential building information in Thailand from secondary data, particularly the information regarding the building's environment. In order to fill this gap, the study conducted a resident questionnaire to gather detailed information on the typology and key characteristics of the multi-residential building in Thailand.

The typology and key characteristics of multi-residential buildings in Thailand were investigated in the primary source through online questionnaires comprising multiple-choice and open-ended questions. The questionnaires were carried out in Chiang Mai as a case study. There were 482 respondents which is representative of the population.

The results are reported in Chapter 3.2.1 and Chapter 5.

Table 10- 1 Building regulations in relation to multi-storey residential building design

Building Regulation	Description
Building Control Act	Minimum space between site boundary is determined by the road width and the height of the building Building height: low-rise buildings in Thailand are defined as buildings lower than 23 meters in height according to Thailand's building regulations Minimum size and dimension of room: minimum 20 square metre and minimum 2.5 metre width of the narrowest side of bedroom, a minimum 2.6 metre ceiling high, minimum 1.5 metre width of corridor
Town Planning Act	Colour coded for permissible usage and also regulates the Open Space Ratio and Floor Area Ratio

The results of demographic analysis show that 95% of respondents are tenants. The participants commonly spent time in their room between 8 to 12 hours during weekdays and 12 to 16 hours during weekends.

In terms of the physical environment, the participants tend to live in the low-rise buildings (no more than 8 floors, incompliance with Thai Building regulations). Most of the participants live in seven-floor buildings. Across the building heights, occupants tended to live on the 1st, 2nd and 3rd floors. Approximately two-third of participants lived in buildings located within 0 to 6 metres from the nearest building. Almost half of the participants' room openings faced north. For building plan and room location, over 90% of the respondents lived in double-load corridor buildings and over 70% of their rooms' locations were at the middle of the building. The majority of rooms comprised of one bedroom, one toilet and one balcony, with room sizes ranging from 21 to 30 sq.m.

Typical room materials include wood for room doors and furniture, concrete for walls and ceilings, tile for flooring, and plastic for toilet door material. These most common materials were used as a material base case for simulation of a multi-storey building in Thailand and also for the design options.

In addition, the activity in the room such as clothes washing, cleaning, cooking and hanging clothes for drying may affect to the accumulation of moisture in the rooms. Cooking in the bedroom was the most popular choice, preferred by almost 45% of people due to the layout of one-bedroom flat in Thailand. However, the bedroom is not design for cooking activity, which will increase heat and water vapour accumulating in the room. The common material in the bedroom is fabric (in the bed area and wardrobe), which easily absorbs moisture and then germinates mould in the room.

Objective 3 is to establish the relationship between key features of typical buildings in Thailand and current occupants' perceptions with regard to their indoor environmental quality.

This objective is also achieved through conducting occupant perception survey and the result is reported in Chapter 5.

In the questionnaire, the participants were tasked with providing information not only related to their physical environment but also their perception of the indoor environmental quality (IEQ), such as temperature, natural lighting, air humidity, air freshness, ventilation, and mould. Additionally, the participants were asked to rate the comfort levels in their rooms. The study then conducted an analysis to determine correlations between the key features of typical buildings in Thailand and current occupants' perceptions. The analysis employed statistical methods, including correlation coefficients and multiple regression, to assess the level of relationship between key features of typical buildings in Thailand and occupants' perceptions about their IEQ.

The study reveals significant correlations between **physical environment**, such as distance between occupants' building and nearby buildings and building height, and IEQ. The proximity between buildings demonstrates a strong positive relationship to the perception of natural lighting, ventilation and air freshness. Conversely, it has a negative relationship with the perception of air humidity and mould level. Occupants perceive the air as rather humid when the distance between their building and nearby buildings is smaller. Additionally, occupants living in a building with a short distance from nearby buildings tend to keep privacy by keeping the curtains down, which can obstruct natural ventilation from entering the room. Larger room sizes are associated with higher occupants' room satisfaction levels. Building height impacts the perception of natural lighting within the room. Such tall buildings cause large "air shadows" which affect natural ventilation significantly.

Furthermore, **human behaviour characteristics** demonstrate a notably significant correlation with IEQ. For example, cooking activity exhibits a strong negative relationship with the perception of air freshness within a room. Similarly, washing within room has a solidly positive correlation with the increased humidity and higher mould rating scale.

The study establishes the relationship between **IEQ and occupant's satisfaction**. Notably, the overall comfort satisfaction has significant relationship ($p<0.01$) with various indoor environment perception scale, including temperature, ventilation, humidity, and mould levels. Increased humidity satisfaction is associated with enhanced natural lighting, increased air freshness, reduced humidity, improved ventilation, and decreased mould levels. Increased ventilation satisfaction level positively correlates with heightened fresh air, minimised humidity, improved ventilation, and minimised mould level. The overall comfort satisfaction has significant association, with p-value lower than 0.01, to various satisfaction categories, involving temperature satisfaction, humidity satisfaction, ventilation satisfaction etc.

The strong significant correlations observed were subsequently analysed through stepwise multiple regression analysis to identify the primary factors influencing occupant satisfaction. The results reveal that overall comfort satisfaction is primarily contingent upon IEQ satisfaction. The major influencers of overall comfort satisfaction are temperature satisfaction, natural lighting satisfaction and ventilation satisfaction, respectively. Humidity satisfaction is primarily influenced by natural lighting, air freshness and mould level. In addition, room privacy satisfaction is mainly influenced by ventilation rate, while air humidity and air freshness perception level have minor impact on the satisfaction. The correlation between ventilation perception and privacy satisfaction can be explained by the notion that rooms with greater privacy level can open their room apertures, which results in enhanced room ventilation. Furthermore, the three main factors influencing ventilation satisfaction are ventilation, air freshness and air humidity level within a room.

Objective 4 is to investigate the influence of external factors on natural ventilation in apartment blocks in Thailand. External factors include wind speed, apartment position within building, building height, proximity/ direction and density of nearby buildings.

In order to fulfill the objective, outdoor CFD sensitivity analysis was conducted to explore air movement at the building envelope under various scenarios. The findings of the analysis are detailed in Chapter 6.

As natural ventilation is contingent upon outdoor climatic conditions, the investigation of the external factors on the building is an important role in the passive building design process. Outdoor climatic conditions, such as air movement and wind direction, exhibit variability within microclimates depending on site contexts. For example, topography and surrounding parameters are considered as significant impact on thermal conditions in building level. Additionally, the presence of nearby buildings significantly impacts thermal comfort. The exploration of air movement at the building envelope is undertaken not only to determine the feasibility of ventilation but also to establish boundary condition for internal CFD model.

The study employs EnergyPlus calculated natural ventilation to calculate pressure coefficient and DesignBuilder programme to simulate and provide the distribution of air velocity and pressure around building. At macroclimate level, the meteorological data of Chiang Mai, a case study, is set and analysed to the model. Subsequently, city terrain and microclimate factors are respectively investigated including apartment position within building, building height, proximity to nearby buildings, and density of nearby buildings. In summary, five independent factors and such factors' combinations are explored. The five independent factors are wind speed, position on building (vertical and horizontal), road width between buildings, building height, and nearby building.

The findings reveal that several variables influence the air movement on a building surface, including as follow

Wind direction and wind speed: wind direction has a considerable impact on air movement and pattern around building surface. The building surface on windward side has the highest wind speed as a result of direct wind impingement. The leeward side, on the other hand, has reduced the air velocity due to shelter effect. Eddies and vortices tend to occur at each corner of building. The turbulence flow occurring affects wind direction to be changed from the original wind direction. Varying the initial wind speed produced a consistent pattern of changes in air movement, each corresponding to a different wind speed.

Road width and building height: Buildings located alongside road act as obstructions of wind flow, causing the air to change direction. The initial wind flows over the buildings, creating skimming flow region in the narrow space between the buildings. In addition, the presence of building in proximity obstructs the wind, resulting funnelling effect causing the increasing of velocity in the space between building. The potential existence of skimming flow within the space between such building configurations need to be taken into account during designing and simulation building. This is essential because external wind significantly impacts on natural ventilation in passive building design.

Nearby buildings: Air movement can experience a reduction of up to approximately 60% from the initial wind due to the increasing of nearby buildings layers from one layer to three layers of nearby building. Furthermore, varying heights of neighbouring buildings also influence wind speed and direction on a building's surface.

Air movement can be reduced up to 60% of the initial wind due to the increasing of nearby buildings layers. In addition, different heights of nearby buildings also affect wind speed and wind direction on building surface. Air movement of a 7-storey building surrounded by 3-storey buildings flows more uniformly than for the building surrounded by 7-storey buildings. Turbulence flow patterns are observed in the space between the buildings due to the obstruction, whereas the air movement near the building surface exhibits the flow complying the contour of building façade. This observation emphasises the impact of building in viscosity on wind flow pattern, particularly in high-density urban area. The building alignment and orientation cause deviations in wind direction from the initial wind direction provided by methodological weather data.

Objective 5 is to investigate the influence of internal factors on natural ventilation in apartment blocks in Thailand. Internal factors include room planning, room orientation, room inlet and outlet size, room outlet location, etc.

This objective is achieved through CFD sensitivity analysis and BES analysis, which aim to investigate each parameter of the apartment rooms that influence ventilation. The findings of the explorations are reported in Chapter 7.

The investigation of the influence of internal factors on natural ventilation is divided into three phases: preliminary study, exploring of room and exploring of chimney.

Preliminary study phase: the criteria of the study, derived from literature review (Section 2.2), encompass temperature range between 22.3°C and 29.3 °C and relative humidity range from 20 %RH to 80%RH. It is noted that natural ventilation from 0.2 m.s^{-1} to 1.0 m.s^{-1} can extend the thermal comfort range to be 22.3°C to 34.3 °C and 20%RH to 100%RH, respectively. The optimal relative humidity for health benefits is identified from 40%RH to 60%RH. Furthermore, the ventilation air requirement for acceptable indoor air quality for residential buildings is 10 L. s^{-1} or 0.001 m^3. s^{-1}. The air movement in building in range of 0.2 to 0.8 m. s^{-1} can provide cooling effect and occupant satisfaction. The key characteristics of multi-residential buildings in Thailand, as identified in the residential questionnaire reported in Chapter 5, as well as the air movement at building façades from CFD sensitivity analysis (outdoor) in Chapter 6, are incorporated as boundary condition of the base case. The study also explores variations in room types (full balcony and half balcony), building orientation, floor level, season, and room location. Results indicate that rooms with a half balcony, located in the middle of the building and facing north, exhibit the poorest thermal comfort and ventilation, in comparison to other configurations. Consequently, this specific room scenario is selected as the base case for exploring of room phase and exploring of chimney phase.

Exploring of room phase: In this phase, the study conducts a thorough investigation of various parameters utilising CFD sensitivity analysis and BES simulation. The focus of this exploration encompasses room with and without chimney and room inlet size. The summary of the findings is in Table 10- 2.

Table 10- 2 A summary: Exploration of Room

exploring of room parameters	summary
Room with and without chimney	Room with chimney has lower temperature compared to the room without chimney. The presence of chimney helps to maintain temperature levels within thermal comfort zone. Additionally, average ventilation in a room with chimney can increase by up to 0.2 $m.s^{-1}$.
Room inlet size	• Air temperature and airflow are directly proportional to the inlet and outlet size, while relative humidity is an inverse correlation with the inlet and outlet size. • A room with equal area for both inlet and outlet, despite varying in dimensions, consistently maintains temperature, relative humidity and airflow. • The room with a narrower outlet provides more flexibility in designing chimney for a multi-storey building as each room can be designed to have one chimney per room. • A room with an inlet of 1.0m x 2.0m and outlet of 0.3m x 1.0m can achieve the minimum acceptable ventilation, Therefore, this inlet and outlet dimension is established as the base case for further exploring chimney depth and width.

Exploring of chimney phase: This phase examines how various chimney parameters affect the thermal environment (temperature, relative humidity and natural ventilation) within a room using CFD sensitivity analysis and BES simulation. The investigation focuses on chimney width and depth, location of chimney inlet (room outlet), and chimney material. The summary of the findings is in Table 10- 3.

Table 10- 3 A summary: Exploration of Chimney

exploring of chimney parameters	summary
Chimney width and depth	The size of the chimney outlet influences airflow within the chimney more than the chimney depth and width. Temperature has a positive correlation to the dimension of the chimney outlet size. Conversely, relative humidity is inversely related to the outlet size. Larger chimney outlet area results in reduced relative humidity within bedroom. Airflow is directly proportioned to the chimney outlet size. The wider outlet size brings about the chimney having a higher airflow rate.

Table 10- 3 A summary: Exploration of Chimney (continued)

exploring of chimney parameters	summary
Chimney inlet location (room outlet location)	Temperature varies noticeably due to the location of the room outlet, whereas different room outlet locations within the room exhibit similar level relative humidity. The lower room outlet location results in the higher airflow in the room. However, airflow difference between the upper and lower location is lower than 0.005 $m^3.s^{-1}$.
Chimney outlet design and material	• chimney with and without solar chimney outlet • Integrating solar chimney into the design results in a threefold rise in airflow within the room. Additionally, vapour pressure is reduced approximately 3%. • trimmed chimney design • Room with a 45-degree trimmed chimney exhibited enhanced ventilation at occupant level - reaching 0.35 $m.s^{-1}$, which is considered acceptable ventilation for cooling effect. • chimney outlet aperture height • Optimal airflow is achieved when the chimney aperture height is set at 1.1m. The height also corresponds to the lowest vapour pressure in bedroom. • Room with and without grille and mosquito wire In order to align with practical applications, simulations were conducted with room outlet fitted with grilles and mosquito wire on its apertures. The finding indicates that airflow within room with these additions is approximately half of the amount in room without them.

Objective 6 is to create and validate design options to improve the indoor environmental conditions in residential apartment block in Thailand. The effectiveness of the designs will be evaluated using CFD and validated with built environment professionals in Thailand.

The integration of the key features of typical building in Thailand in Chapter 5, combined with CFD sensitivity analysis of outdoor in Chapter 6, the exploration of indoor parameter in Chapter 7, has facilitated the development of design options. These proposed design options were subsequently validated through built environment professional (BEP) interviews, which was reported in Chapter 8.

Semi-structured interviews were employed to explore BEP opinions regarding indoor environmental quality (IEQ) in multi-residential buildings. The exploration established 1) context of the expert’s experience and knowledge in relation to current multi-storey residential building and passive design, and 2) design options to improve natural ventilation in thermally free-running multi-residential buildings in Thailand.

The findings regarding the exploration of the expertise and knowledge of BEPs in the context of current multi-residential buildings revealed the existence of various IEQ issues, such as poor ventilation, high humidity and mould growth occurrence in the buildings. Most of the BEPs have suggested that improving building design can enhance IEQ, mainly by increasing natural ventilation and integrating climate and site consideration into the building design process. Furthermore, they unanimously emphasize the importance of natural ventilation in thermally free-running building in Thailand. The BEPs suggested that the building and room features should be redesigned to enhance natural ventilation, such as double-sided ventilation design and ventilated chimney. Additionally, the majority of BEPs strongly support the possibility of integrating solar chimney with the design.

In terms of design options, the BEPs provide their opinions encompassing three topics, which were design and construction, IEQ and occupant wellbeing. The study explored 20 design options, each comprising different components of the room design that included balcony type, room inlet size, room with and without solar chimney, chimney design and room outlet design. Three topics (design and construction, IEQ and occupant wellbeing) were compared for each design option. For example, the design of options with a room with railing balcony, window size 1.0 x 2.0 m, one chimney connected to only one room and vertical room outlet received the highest overall support percentage indicating a great potential for implementation (81%), (100% for IEQ, 82% for occupant wellbeing, and 67% for design and constructions). In contrast, the design option involving a room with wall balcony, window size 1.0 x 1.1 m, and without chimney demonstrates the lowest overall support percentage (23%), (0% for IEQ, 45% for occupant wellbeing, and 29% for design and constructions). Notably, all room cases without chimney exhibit an overall support percentage lower than 50%, even though some design options have larger inlet size. All participants (100%) addressed preference for a room with a chimney and most of the BEPs selected one chimney connected to only one room.

Overall, the majority of BEPs recognise the potential of integrating railing balcony, room inlet size of 1.0 m wide and 2.0 m high, room with chimney, one chimney connected to only one room and vertical room outlet into the future multi-residential design.

This research aim has therefore been achieved:

> Investigating the potential of passive design options (focussing on natural ventilation) to improve indoor environment quality – specifically relative humidity, thermal comfort and natural ventilation in thermally free-running apartment dwellings in Thailand climate condition.

10.3 Contribution to knowledge

This research contributes to knowledge in several key areas relevant to multi-residential buildings in Thailand, particularly in the context of passive cooling and IEQ.

10.3.1 **Evaluation of internal parameters affecting on indoor environmental quality**: The study provides detailed analysis of how building environment, room layout and occupant activity in actual multi-residential buildings in Thailand impact on IEQ, such as thermal comfort, temperature, relative humidity, and airspeed. (see further details in Chapter 4)

10.3.2 **Dataset of typical apartment features in Thailand**: The study establishes a comprehensive dataset detailing typical features of multi-residential buildings in Thailand, such as building and room planning, material utilised, building height etc. (further more details in Chapter 5)

10.3.3 **Establishing the relationship between key features of typical multi-residential building and current occupants' perceptions on IEQ**: The research explains the connection between the building features and the occupants' perceptions, satisfaction and thermal comfort. By establishing these correlations, the study contributes to more data-driven approach in the field of architecture and building design, particularly in Thailand context. The findings provide valuable guidance for architects, urban design planners, and developers in designing structures that are more aligned with the needs, IEQ, and preferences of their occupants. (further details in Section 5.5)

10.3.4 **Database of key factors influencing external air movement in Thai city and context**: A database has been established that focuses on the impact of local surroundings and building density on airflow, which is crucial for natural ventilation in building design (further details in Chapter 6).

10.3.5 **Database of key factors influencing internal natural ventilation in multi-residential buildings in Thailand**: The development of a detailed database provides information regarding key factors influencing natural ventilation in multi-residential buildings. These insights help in identifying and understanding the key factors that can be used to enhance the design and efficiency of multi-residential buildings. This information offers guidance for sustainable architecture practices. (further details in Chapter 7)

10.3.6 **Engaging with built environment professionals**: The research establishes in-depth insights into practical aspects of designing and constructing multi-residential building in Thailand. This engagement with the BEPs, academics, architects and engineers, bridges the gap between theoretical research and real-world application. In addition, this involvement of the BEPS in validating the proposed design options ensures that the designs are practically feasible and relevant to the current practices. (further details in Chapter 8)

10.3.7 **Design options for new multi-residential buildings in Thailand**: The research proposes design options, especially focusing on the design frameworks for multi-residential buildings in urban areas with passive cooling by natural ventilation. The design options demonstrate significant potential for future implementation in Thailand. (further details in Chapter 9)

10.4 Limitations

Despite numerous attempts to mitigate their impact, this research encountered several limitations as follow:

10.4.1 Limitation of other issues

The Covid outbreak significantly impacted the research. Due to the travel restrictions within Thailand, the case study location was changed from Bangkok to Chiang Mai, causing challenges in acquiring local data such as meteorological and demographic statistics. This resulted in significant changes to the research plan and time. In addition, the Work from Home (WFH) policy further extended the time required to access data.

10.4.2 Limitation of Current Context Investigation

- The research faced the limited availability of measurement devices, especially during the Covid pandemic.
- Local context sources provided by the local government are primarily focused on Bangkok, resulting in limited information for the Chiang Mai area.

10.4.3 Limitation of CFD Exploration

- Due to the time-consuming and computational-demanding process, the CFD models had to be built using simplified designs.

10.5 Recommendations for future research

Further work could include:

- Detailed investigation of design options: While this study focused on investigating parameters affecting indoor environmental quality, further investigation into construction details is recommended. Specifically, an in-depth analysis of the construction and structural design of the solar chimney integrated into multi-residential buildings in Thailand is needed. This entails developing comprehensive construction procedures and assessing the associated construction costs to evaluate the feasibility of implementing the proposed design options. This approach would provide a more comprehensive knowledge of the practical and economic viability feasibility of implementing different design options proposed in this research.
- Application in similar climates and context: While the study used Chiang Mai as a case study, there's potential to extend its findings to other urban areas in Thailand. It is recommended to explore further integrating the proposed design options into multi-residential buildings in regions with climates and contexts similar to Chiang Mai. This expansion could enhance adaptability and effectiveness, particularly in dense urban areas with tropical climates. To accomplish this, further investigation into the specific details and contexts of each region is necessary. Understanding the particular challenges and requirements of each location allows design options to be implemented more effectively, contributing to improved indoor environmental quality in a wide range of urban contexts. This holistic approach ensures that the research

findings are applicable and beneficial beyond the scope of the initial case study in Chiang Mai.

- Practical investigation of Cp data: Most available Cp data provided are suitable for simple buildings with minimal architectural ornamentation. A practical investigation into the pressure coefficient (Cp) for buildings of various forms and architectural elements is required. This would involve conducting physical measurement or simulation for real-world building scenarios in order to investigate Cp data. Encompassing a wider range of architectural complexities conducts a more practical investigation into the pressure coefficient (Cp) of buildings to increase the relevance and applicability of the findings.

11 References

Abdulaali, H. S. et al. 2020. Impact of poor indoor environmental quality (IEQ) to inhabitants' health, wellbeing and satisfaction. International Journal of Advanced Science Technology 29(3), pp. 1-14.

Abraham, S. and Ming, T. eds. 2018. Numerical analysis on the thermal performance of a building with solar chimney and double skin façade in tropical country. IOP Conference Series: Materials Science and Engineering. IOP Publishing.

Adam, Z. et al. eds. 2002. Mathematical model and experimental study of airflow in solar chimneys. Proc. 8th International Conference on Air Distribution in Rooms (ROOMVENT 2002).

Addis, B. 2012. Building with reclaimed components and materials: a design handbook for reuse and recycling. Routledge.

AdministrativeStrategyDivision. 2018. Population and Density in Bangkok 2010-2019. Department of Local Administration, Ministry of Interior. Available at: http://www.bangkok.go.th/pipd/page/sub/16730/%E0%B8%AA%E0%B8%96%E0%B8%B4%E0%B8%95%E0%B8%B4%E0%B8%94%E0%B9%89%E0%B8%B2%E0%B8%99%E0%B8%AA%E0%B8%B1%E0%B8%87%E0%B8%84%E0%B8%A1 [Accessed: 10th June 2020].

Aflaki, A. et al. 2015. A review on natural ventilation applications through building façade components and ventilation openings in tropical climates. Energy Buildings 101, pp. 153-162.

Aflaki, A. et al. 2016. The influence of single-sided ventilation towards the indoor thermal performance of high-rise residential building: A field study. Energy Buildings 126, pp. 146-158.

Afonso, C. and Oliveira, A. 2000. Solar chimneys: simulation and experiment. Energy Buildings 32(1), pp. 71-79.

Ai, Z. and Mak, C. M. 2015. From street canyon microclimate to indoor environmental quality in naturally ventilated urban buildings: Issues and possibilities for improvement. Building Environment 94, pp. 489-503.

Ai, Z. et al. 2015. On-site measurements of ventilation performance and indoor air quality in naturally ventilated high-rise residential buildings in Hong Kong. Indoor and built environment 24(2), pp. 214-224.

Al-Kayiem, H. H. et al. 2014. Mathematical analysis of the influence of the chimney height and collector area on the performance of a roof top solar chimney. Energy Buildings 68, pp. 305-311.

Allard, F. et al. 2009. Natural Ventilation in High-Density Cities. Designing High-Density Cities: For Social Environmental Sustainabilit, pp. 137-162.

Allocca, C. et al. 2003. Design analysis of single-sided natural ventilation. Energy and buildings 35(8), pp. 785-795.

Alvarez, G. et al. 2004. Thermal performance of an air solar collector with an absorber plate made of recyclable aluminum cans. Solar Energy 77(1), pp. 107-113.

Amori, K. E. and Mohammed, S. W. 2012. Experimental and numerical studies of solar chimney for natural ventilation in Iraq. Energy Buildings 47, pp. 450-457.

Anđelković, A. S. et al. 2016. Experimental validation of a EnergyPlus model: Application of a multi-storey naturally ventilated double skin façade. Energy Buildings 118, pp. 27-36.

Anderson, A. E. et al. 2007. Verification, validation and sensitivity studies in computational biomechanics. Computer methods in biomechanics and biomedical engineering 10(3), pp. 171-184.

Anderson, D. B. 1936. Relative humidity or vapor pressure deficit. Ecology 17(2), pp. 277-282.

Andrew Corney, P. et al. 2018. HOW TO IMPROVE ASHRAE 55 AND MAKE IT MORE RELEVANT. 2018 Building Performance Analysis Conference and SimBuild. Chicago, Illinois, 26-28 September 2018. ASHRAE and IBPSA-USA.

An-Naggar, A. S. et al. 2017. Energy performance simulation in residential buildings. Procedia Engineering 205, pp. 4187-4194.

Arce, J. et al. 2009. Experimental study for natural ventilation on a solar chimney. Renewable Energy 34(12), pp. 2928-2934.

Arnfield, A. J. 2003. Two decades of urban climate research: a review of turbulence, exchanges of energy and water, and the urban heat island. International journal of climatology 23(1), pp. 1-26.

Arumugam, P. et al. 2022. Effective PCM, insulation, natural and/or night ventilation techniques to enhance the thermal performance of buildings located in various climates–A review. Energy Buildings 258, p. 111840.

Arundel, A. V. et al. 1986. Indirect health effects of relative humidity in indoor environments. Environmental Health Perspectives 65, pp. 351-361.

Asdrubali, F. et al. 2015. A review of unconventional sustainable building insulation materials. Sustainable Materials Technologies 4, pp. 1-17.

Asfour, O. S. and Gadi, M. B. 2008. Using CFD to investigate ventilation characteristics of vaults as wind-inducing devices in buildings. Applied Energy 85(12), pp. 1126-1140.

ASHRAE, I. 2009. 2009 ASHRAE handbook: fundamentals. American Society of Heating, Refrigeration and Air-Conditioning Engineers.

ASHRAE. 2009. Air Contaminants. ASHRAE Handbook. Fundamentals.

ASHRAE. 2009. Duct Design. Atlanta: ASHRAE.

ASHRAE. 2010. Thermal Environmental Conditions for Human Occupancy, ASHRAE Standard 55.

ASHRAE. 2017. Thermal Environmental Conditions for Human Occupancy. Atlanta: ASHRAE.

Awbi, H. and Gan, G. 1992. Simulation of solar-induced ventilation. Renewable Energy Technol 4(Environ), pp. 2016-2030.

Ayegbusi, O. G. et al. 2018. Overall Thermal Transfer Value of Naturally Ventilated Double Skin Façade in Malaysia. Progress in Energy Environment, pp. 16-26.

Azam, M. et al. 2018. Effect of tourism on environmental pollution: Further evidence from Malaysia, Singapore and Thailand. Journal of cleaner production 190, pp. 330-338.

Azarbayjani, M. 2013. Climatic based consideration of double skin facade system: Natural ventilation performance of a case study with double skin facade in mediterranean climate. 13th Conference of International Building Performance Simulation Association. Chambéry, France.

Azizi, M. M. and Javanmardi, K. 2017. The effects of urban block forms on the patterns of wind and natural ventilation. Procedia Engineering 180, pp. 541-549.

Bady, M. et al. 2011. Experimental investigations of the indoor natural ventilation for different building configurations and incidences. Building and Environment 46(1), pp. 65-74.

Baharvand, M. et al. 2013. DesignBuilder verification and validation for indoor natural ventilation. Journal of Basic and Applied Scientific Research (JBASR) 3(4), p. 8.

Ballal, H. 2022. What Are The 3 Methods Of Data Collection? AnalyticsLearn. Available at: https://analyticslearn.com/what-are-the-3-methods-of-data-collection [Accessed: 27th April 2022].

Balocco, C. 2002. A simple model to study ventilated facades energy performance. Energy Buildings 34(5), pp. 469-475.

Bansal, N. et al. 1993. Solar chimney for enhanced stack ventilation. Building and Environment 28(3), pp. 373-377.

Bansal, N. et al. 2005. Modeling of window-sized solar chimneys for ventilation. Building Environment 40(10), pp. 1302-1308.

Barbason, M. and Reiter, S. 2014. Coupling building energy simulation and computational fluid dynamics: Application to a two-storey house in a temperate climate. Building and Environment 75, pp. 30-39.

Barbosa, S. and Alberto, K. C. 2019. Effect of the double skin façade material on the thermal performance of the educational building in tropical climate. Architectural science review 62(3), pp. 206-215.

Barbosa, S. and Ip, K. 2014. Perspectives of double skin façades for naturally ventilated buildings: A review. Renewable sustainable energy reviews 40, pp. 1019-1029.

Barnette, J. J. 2000. Effects of stem and Likert response option reversals on survey internal consistency: If you feel the need, there is a better alternative to using those negatively worded stems. Educational and psychological measurement 60(3), pp. 361-370.

Barozzi, G. S. et al. 1992. Physical and numerical modelling of a solar chimney-based ventilation system for buildings. Building and Environment 27(4), pp. 433-445.

Bassiouny, R. and Korah, N. S. 2009. Effect of solar chimney inclination angle on space flow pattern and ventilation rate. Energy Buildings 41(2), pp. 190-196.

Bassiouny, R. and Koura, N. S. 2008. An analytical and numerical study of solar chimney use for room natural ventilation. Energy Buildings 40(5), pp. 865-873.

Beck, H. E. et al. 2018. Present and future Köppen-Geiger climate classification maps at 1-km resolution. Scientific data 5, p. 180214.

Berman, J. J. 2016. Data simplification: taming information with open-source tools. Morgan Kaufmann.

Bhamare, D. K. et al. 2019. Passive cooling techniques for building and their applicability in different climatic zones-The State of Art. Energy Buildings,

Bortolini, R. and Forcada, N. 2021. Association between building characteristics and indoor environmental quality through post-occupancy evaluation. Energies 14(6), p. 1659.

Bouchair, A. 1989. Solar induced ventilation in the Algerian and similar climates. University of Leeds.

Boyes, W. 2009. Instrumentation reference book. Butterworth-Heinemann.

Braun, V. and Clarke, V. 2006. Using thematic analysis in psychology. Qualitative research in psychology 3(2), pp. 77-101.

Briga-Sa, A. et al. 2013. Textile waste as an alternative thermal insulation building material solution. Construction Building Materials 38, pp. 155-160.

Brown, C. 2016. The power of qualitative data in post-occupancy evaluations of residential high-rise buildings. Journal of Housing and the Built Environment 31, pp. 605-620.

Bu, Z. et al. 2010. Wind tunnel experiments on wind-induced natural ventilation rate in residential basements with areaway space. Building and Environment 45(10), pp. 2263-2272.

BuildingScienceCorporation. 2013. Vapor Permeance of Some Building Materials. Available at: https://buildingscience.com/documents/information-sheets/info-312-vapor-permeance-some-materials [Accessed: 21st Septermber 2023].

Buonocore, C. et al. 2018. Influence of relative air humidity and movement on human thermal perception in classrooms in a hot and humid climate. Building Environment International 146, pp. 98-106.

Burek, S. and Habeb, A. 2007. Air flow and thermal efficiency characteristics in solar chimneys and Trombe Walls. Energy Buildings 39(2), pp. 128-135.

Busch Jr, J. F. 1990. From comfort to kilowatts: an integrated assessment of electricity conservation in Thailand's commercial sector.

Butler, M. et al. 2023. Impact of supplementary air filtration on aerosols and particulate matter in a UK hospital ward: a case study. Journal of Hospital Infection 135, pp. 81-89.

Caciolo, M. et al. 2011. Full scale experimental study of single-sided ventilation: Analysis of stack and wind effects. Energy and buildings 43(7), pp. 1765-1773. doi: https://doi.org/10.1016/j.enbuild.2011.03.019.

Calautit, J. K. and Hughes, B. R. 2014. Wind tunnel and CFD study of the natural ventilation performance of a commercial multi-directional wind tower. Building and Environment 80, pp. 71-83.

CambridgeUniversityPress. 2020. Recycled. Available at: https://dictionary.cambridge.org/dictionary/english/recycled [Accessed: 2nd April 2020].

Cândido, C. et al. 2011. Combined thermal acceptability and air movement assessments in a hot humid climate. Building Environment International 46(2), pp. 379-385.

Castillo, J. A. et al. eds. 2019. Natural ventilation of an isolated generic building with a windward window and different windexchangers: CFD validation, sensitivity study and performance analysis. Building Simulation. Springer.

Castleberry, A. and Nolen, A. 2018. Thematic analysis of qualitative research data: Is it as easy as it sounds? Currents in Pharmacy Teaching Learning 10(6), pp. 807-815.

Cengel, A. 2007. Heat Transfer. Boston, Mass.: McGraw-Hill.

Cengel, Y. A. 2014. Heat and mass transfer a practical approach. Boston, Mass.: McGraw-Hill.

Cengel, Y. and Ghajar, A. 2015. Heat and mass transfer: fundamentals and applications. McGraw-Hill Higher Education.

Center, R. E. I. 2020. The Number of Multi-Storey Buildings in Thailand in 2015-2019. Government Housing Bank. Available at: https://www.reic.or.th/Product/Transfer [Accessed: 10th June 2020].

Chan, E. H. et al. 2008. Evaluation on indoor environment quality of dense urban residential buildings. Journal of Facilities Management 6(4), pp. 245-265.

Chantawong, P. et al. 2006. Investigation on thermal performance of glazed solar chimney walls. Solar Energy 80(3), pp. 288-297.

Chatzipoulka, C. 2011. The Potential Use of Solar Chimneys for a Natural Ventilation in Residential Buildings in Thessaloniki. Cardiff University.

Chen, Q. 1995. Comparison of different k-ε models for indoor air flow computations. Numerical Heat Transfer, Part B Fundamentals 28(3), pp. 353-369.

Chen, Y. L. and Wen, J. 2010. Comparison of sensor systems designed using multizone, zonal, and CFD data for protection of indoor environments. Building and Environment 45(4), pp. 1061-1071.

Chen, Z. D. et al. 2003. An experimental investigation of a solar chimney model with uniform wall heat flux. Building and Environment 38(7), pp. 893-906.

Cheng, Z. et al. 2013. Characteristics and health impacts of particulate matter pollution in China (2001–2011). Atmospheric Environment 65, pp. 186-194.

Chetty, P. 2015. Correlation of variables in SPSS. Available at: https://www.projectguru.in/correlation-variables-spss/ [Accessed: 10th November 2021].

ChiangMaiProvincialStatisticalOffice. 2020. Population from Registration Record, Percentage Change and Density by District: 2003 - 2020.

Chinazzo, G. et al. 2019. Daylight affects human thermal perception. Scientific reports 9(1), pp. 1-15.

ChooChuay, C. et al. 2020. Impacts of PM2. 5 sources on variations in particulate chemical compounds in ambient air of Bangkok, Thailand. Atmospheric Pollution Research 11(9), pp. 1657-1667.

Chowdhury, A. A. et al. 2009. An Analysis of the Indoor Air Quality and Mould Growth in a Multi-zone Building. Water, Air, & Soil Pollution: Focus 9(5-6), pp. 517-527.

Christopher Frey, H. and Patil, S. R. 2002. Identification and review of sensitivity analysis methods. Risk analysis 22(3), pp. 553-578.

Chungloo, S. and Limmeechokchai, B. 2007. Application of passive cooling systems in the hot and humid climate: The case study of solar chimney and wetted roof in Thailand. Building Environment International 42(9), pp. 3341-3351.

Chungloo, S. and Limmeechokchai, B. 2009. Utilization of cool ceiling with roof solar chimney in Thailand: The experimental and numerical analysis. Renewable Energy 34(3), pp. 623-633.

Cleave, P. 2021. What Is A Good Survey Response Rate?.

Committee, C. F. D. 1998. Guide: Guide for the Verification and Validation of Computational Fluid Dynamics Simulations (AIAA G-077-1998 (2002)). American Institute of Aeronautics and Astronautics, Inc.

Confederation, B. G. M. 2020. Recycling. Available at: https://www.britglass.org.uk/our-work/recycling [Accessed: 18th March 2020].

Cook, J. 1989. Passive cooling.

Cóstola, D. et al. 2009. Overview of pressure coefficient data in building energy simulation and airflow network programs. Building and Environment 44(10), pp. 2027-2036. doi: https://doi.org/10.1016/j.buildenv.2009.02.006.

Daemei, A. B. et al. 2016. Opening performance simulation in natural ventilation using design builder (case study: a residential home in Rasht). Energy Procedia 100, pp. 412-422.

Daghigh, R. et al. 2009. Thermal comfort of an air-conditioned office through different windows-door opening arrangements. Building services engineering research technology 30(1), pp. 49-63.

Dai, Y. et al. 2003. Enhancement of natural ventilation in a solar house with a solar chimney and a solid adsorption cooling cavity. Solar Energy 74(1), pp. 65-75.

Davies, M. G. 2004. Building heat transfer. John Wiley & Sons.

De Dear, R. and Leow, K. 1990. Indoor climate and thermal comfort in high-rise public housing in an equatorial climate: a field-study in Singapore. Atmospheric Environment. Part B. Urban Atmosphere 24(2), pp. 313-320.

De Dear, R. J. and Brager, G. S. 2002. Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55. Energy and buildings 34(6), pp. 549-561.

De Flander, K. and Rovers, R. 2009. One laminated bamboo-frame house per hectare per year. Construction Building Materials 23(1), pp. 210-218.

Dehghan, A. et al. 2013. Natural ventilation characteristics of one-sided wind catchers: experimental and analytical evaluation. Energy and buildings 61, pp. 366-377.

DeKay, M. and Brown, G. 2013. Sun, wind, and light: architectural design strategies. John Wiley & Sons.

Delzendeh, E. et al. 2017. The impact of occupants' behaviours on building energy analysis: A research review. Renewable and Sustainable Energy Reviews 80, pp. 1061-1071.

DesignBuilder. 2019. DesignBuilder v6 Simulation Documentation. Available at: https://designbuilder.co.uk/download/documents/407-designbuilder-printable-documentation-v6-a4-pages/file [Accessed:4th August 2021].

DesignBuilder. 2023. Natural Ventilation Modelling. Available at: https://designbuilder.co.uk/helpv7.0/Content/_Natural_ventilation_modelling.htm [Accessed: 6th April 2023].

DesignBuilder. 2023a. CFD Calculations And Convergence. Available at: http:// designbuilder-v2.co.uk/helpv2/Content/CFD%20Calculations%20and%20 Converg ence.htm [Accessed: 6th April 2023].

DesignBuilder. 2023b. Natural Ventilation Modelling. Available at: https://designbuilder.co.uk/helpv7.0/Content/_Natural_ventilation_modelling.htm [Accessed: 6th April 2023].

Dhahri, M. et al. 2021. Thermal performance modeling of modified absorber wall of solar chimney-shaped channels system for building ventilation. Journal of Thermal Analysis Calorimetry 145, pp. 1137-1149.

Dimoudi, A. 2009. Solar chimneys in buildings—The state of the art. Advances in Building Energy Research 3(1), pp. 21-44.

Ding, W. et al. 2005. Natural ventilation performance of a double-skin façade with a solar chimney. Energy Buildings 37(4), pp. 411-418.

Djongyang, N. et al. 2010. Thermal Comfort: A review paper. Renewable sustainable energy reviews 14(9), pp. 2626-2640.

Dong, Y. H. and Ng, S. T. 2015. A life cycle assessment model for evaluating the environmental impacts of building construction in Hong Kong. Building Environment 89, pp. 183-191.

Du, J. et al. 2020. In-situ monitoring of occupant behavior in residential buildings – a timely review. Energy and buildings 212, p. 109811. doi: https://doi.org/10.1016/j.enbuild.2020.109811.

Du, Y. et al. eds. 2018. Effects of building height and porosity on pedestrian level wind comfort in a high-density urban built environment. Building Simulation. Springer.

Duy, T. N. and Pham, H.-T. T. eds. 2021. CFD based investigation on the performance of solar chimney for room natural ventilation. AIP Conference Proceedings. AIP Publishing LLC.

Edussuriya, P. et al. 2011. Urban morphology and air quality in dense residential environments in Hong Kong. Part I: District-level analysis. Atmospheric Environment. Part B. Urban Atmosphere 45(27), pp. 4789-4803.

Elshafei, G. et al. 2017. Numerical and experimental investigations of the impacts of window parameters on indoor natural ventilation in a residential building. Energy and buildings 141, pp. 321-332.

EnergyPlus. 2016. Outside Surface Heat Balance. Available at: https://bigladdersoftware.com/epx/docs/8-5/engineering-reference/outside-surface-heat-balance.html [Accessed. 6th April 2023]

EnergyPlus. 2023. EnergyPlus. Available at: https://energyplus.net/ [Accessed: 6th April 2023].

ENVI-met. 2022. ENVI-met Microclimate Simulation Software. Available at: https://www.envi-met.com/software/ [Accessed: 22th August 2022].

Evans, G. W. and Kantrowitz, E. 2002. Socioeconomic status and health: the potential role of environmental risk exposure. Annual review of public health 23(1), pp. 303-331.

Fan, S. et al. 2021. A full-scale field study for evaluation of simple analytical models of cross ventilation and single-sided ventilation. Building Environment 187, p. 107386.

Fanger, P. O. 1970. Thermal comfort. Analysis and applications in environmental engineering.

Fanger, P. O. and Toftum, J. 2002. Extension of the PMV model to non-air-conditioned buildings in warm climates. Energy Buildings 34(6), pp. 533-536.

Farea, T. G. et al. 2012. Common configuration of light-well in high-rise residential buildings in Kuala Lumpur. 4th International Network for Tropical Architecture, National University of Singapore, pp. 1-8.

Farea, T. G. et al. 2012. Common configuration of light-well in high-rise residential buildings in Kuala Lumpur. 4th International Network for Tropical Architecture. Singapore, pp. 12-13.

Feng, X. et al. 2016. A preliminary research on the derivation of typical occupant behavior based on large-scale questionnaire surveys. Energy and buildings 117, pp. 332-340.

Fennelly, M. et al. 2023. Portable HEPA filtration successfully augments natural-ventilation-mediated airborne particle clearance in a legacy design hospital ward. Journal of Hospital Infection 131, pp. 54-57. doi: https://doi.org/10.1016/j.jhin.2022.09.017.

Fernando, H. J. et al. 2010. Flow, turbulence, and pollutant dispersion in urban atmospheres. Physics of Fluids 22(5).

Foster, M. and Oreszczyn, T. 2001. Occupant control of passive systems: the use of Venetian blinds. Building and Environment 36(2), pp. 149-155.

Francis, J. J. et al. 2010. What is an adequate sample size? Operationalising data saturation for theory-based interview studies. Psychology and health 25(10), pp. 1229-1245.

Franke, J. et al. 2011. The COST 732 Best Practice Guideline for CFD simulation of flows in the urban environment: a summary. International Journal of Environment and Pollution 44(1-4), pp. 419-427.

Freitas, S. et al. 2015. Modelling solar potential in the urban environment: State-of-the-art review. Renewable sustainable energy reviews 41, pp. 915-931.

Galvin, R. 2015. How many interviews are enough? Do qualitative interviews in building energy consumption research produce reliable knowledge? Journal of building engineering 1, pp. 2-12.

Gan, G. 1998. A parametric study of Trombe walls for passive cooling of buildings. Energy and buildings 27(1), pp. 37-44.

Gan, G. 2006. Simulation of buoyancy-induced flow in open cavities for natural ventilation. Energy Buildings 38(5), pp. 410-420.

Gan, Y. and Chen, H. 2016. Discussion on the applicability of urban morphology index system for block natural ventilation research. Procedia Engineering 169, pp. 240-247.

Garcia-Nevado, E. et al. 2016. Solar Access Assessment in Dense Urban Environments: The Effect of Intersections in an Urban Canyon. Energies 9(10), p. 796.

Ghiaus, C. et al. 2006. Urban environment influence on natural ventilation potential. Building and Environment 41(4), pp. 395-406. doi: https://doi.org/10.1016/j.buildenv.2005.02.003

Gilani, S. et al. 2016. CFD simulation of stratified indoor environment in displacement ventilation: Validation and sensitivity analysis. Building and Environment 95, pp. 299-313.

Giridharan, R. and Emmanuel, R. 2018. The impact of urban compactness, comfort strategies and energy consumption on tropical urban heat island intensity: A review. Sustainable Cities Society 40, pp. 677-687.

Givoni, B. 1992. Comfort, climate analysis and building design guidelines. Energy Buildings 18(1), pp. 11-23.

Gliem, J. A. and Gliem, R. R. eds. 2003. Calculating, interpreting, and reporting Cronbach's alpha reliability coefficient for Likert-type scales. Midwest research-to-practice conference in adult, continuing, and community education. Midwest Research-to-Practice Conference in Adult, Continuing, and Community.

GlobalEvaluationInitiative. 2023. Questionnaires. BetterEvaluation. Available at: https://www.betterevaluation.org/methods-approaches/methods/questionnaires [Accessed: 10th February 2023].

Gong, N. et al. 2006. The acceptable air velocity range for local air movement in the tropics. HVACR Research 12(4), pp. 1065-1076.

González-Alonso, J. et al. 1999. Influence of body temperature on the development of fatigue during prolonged exercise in the heat. Journal of applied physiology 86(3), pp. 1032-1039.

Good, J. et al. 2008. The role of wind in natural ventilation simulations using airflow network models. Proceedings of SimBuild. pp. 140-147.

Gou, S. et al. 2018. Passive design optimization of newly-built residential buildings in Shanghai for improving indoor thermal comfort while reducing building energy demand. Energy Buildings 169, pp. 484-506.

Gratia, E. and De Herde, A. 2004. Natural cooling strategies efficiency in an office building with a double-skin façade. Energy Buildings 36(11), pp. 1139-1152.

Haase, M. and Amato, A. 2009. An investigation of the potential for natural ventilation and building orientation to achieve thermal comfort in warm and humid climates. Solar Energy 83(3), pp. 389-399. doi: https://doi.org/10.1016/j.solener.2008.08.015

Hadded, A. et al. 2016. Thermo physical characterisation of recycled textile materials used for building insulating. Journal of building engineering 5, pp. 34-40.

Hammond, G. and Jones, C. 2019. Inventory of Carbon & Energy (ICE) version 3.0. University of Bath.

Han, G. et al. 2015. Different modeling strategies of infiltration rates for an office building to improve accuracy of building energy simulations. Energy and buildings 86, pp. 288-295. doi: https://doi.org/10.1016/j.enbuild.2014.10.028.

Hänninen, O. et al. 2017. Analysis of CO 2 monitoring data demonstrates poor ventilation rates in Albanian schools during the cold season. Air Quality, Atmosphere & Health 10, pp. 773-782.

Harris, D. and Helwig, N. 2007. Solar chimney and building ventilation. Applied Energy 84(2), pp. 135-146.

Heseltine, E. and Rosen, J. 2009. WHO guidelines for indoor air quality: dampness and mould. WHO Regional Office Europe.

Hidalgo, J. P. et al. 2015. Performance criteria for the fire safe use of thermal insulation in buildings. Construction Building Materials 100, pp. 285-297.

Hirunlabh, J. et al. 1999. Study of natural ventilation of houses by a metallic solar wall under tropical climate. Renewable Energy 18(1), pp. 109-119.

Holmer, B. and Eliasson, I. 1999. Urban–rural vapour pressure differences and their role in the development of urban heat islands. International Journal of Climatology: A Journal of the Royal Meteorological Society 19(9), pp. 989-1009.

Hong, S.-W. et al. 2017. Validation of an open source CFD code to simulate natural ventilation for agricultural buildings. Computers and Electronics in Agriculture 138, pp. 80-91.

Hu, S. et al. 2019. Investigation and analysis of Chinese residential building occupancy with large-scale questionnaire surveys. Energy and buildings 193, pp. 289-304.

Huck, S. W. et al. 1974. Reading Statistics and Research. New York: Harper & Row.

Humphreys, M. 1978. Outdoor temperatures and comfort indoors. Batiment International, Building Research Practice 6(2), pp. 92-92.

Hussain, S. and Oosthuizen, P. H. 2012. Numerical investigations of buoyancy-driven natural ventilation in a simple atrium building and its effect on the thermal comfort conditions. Applied Thermal Engineering 40, pp. 358-372.

IBM. 2023. IBM SPSS software. Available at: https://www.ibm.com/spss?mhsrc=ibmsearch_a&mhq=spss [Accessed: 5th May 2023].

IdealSimulations. 2023. Turbulence Models In CFD. London: IdealSimulations Ltd. Available at: https://www.idealsimulations.com/resources/turbulence-models-in-cfd/ [Accessed: 28th March 2023].

IES. 2018. Wind Pressure. Glasgow, UK: Integrated Environmental Solutions. Available at: https://help.iesve.com/ve2018/wind_pressure.htm?ms=cwAAEAAFAAAAAAAAAAQAAAAAAAAAAAAAAAAAAAAUAgIQAQDBBAg&q=cHJlc3N1cmUgY29lZmZpY2llbnQ%3D&st=Mg%3D%3D&sct=MA%3D%3D&mw=MjQw [Accessed. 8th November 2022].

Imran, A. A. et al. 2015. Induced flow for ventilation and cooling by a solar chimney. Renewable Energy 78, pp. 236-244.

Indraganti, M. et al. 2015. Thermal comfort in offices in India: Behavioral adaptation and the effect of age and gender. Energy and buildings 103, pp. 284-295.

Ingrao, C. et al. 2014. Recycled-PET fibre based panels for building thermal insulation: environmental impact and improvement potential assessment for a greener production. Science of the total environment 493, pp. 914-929.

Institution, B. S. 2011. Code of Practice for Control of Condensation in Buildings. British Standards Institution.

Interior, M. o. 2000. Relavant Laws. Available at: https://www.ieat.go.th/handbook/Program_IEAT/pages/en/Department/MOI.html [Accessed: 21st April 2020].

Israel, G. D. 1992. Determining Sample Size. Agricultural Education and Communication Department.

JapanInternationalCooperationAgency. 2003. The Study on Development of a Building Safety System Focusing on Fire Prevention in the Kingdom of Thailand The Building Center of Japan Nippon Koei co.,LTD.

Jauregui, R. and Silva, F. 2011. Numerical validation methods. Numerical analysis—theory and application, pp. 155-174.

Ji, L. et al. 2011. Wind tunnel investigation on influence of fluctuating wind direction on cross natural ventilation. Building and Environment 46(12), pp. 2490-2499.

Jiang, Y. et al. 2020. Impact of Residential Building Layouts on Microclimate in a High Temperature and High Humidity Region. 12(3), p. 1046.

Jing, H. et al. 2015. Experimental study of the prediction of the ventilation flow rate through solar chimney with large gap-to-height ratios. Building Environment 89, pp. 150-159.

Jiru, T. E. and Bitsuamlak, G. T. 2010. Application of CFD in modelling wind-induced natural ventilation of buildings-A review. International Journal of Ventilation 9(2), pp. 131-147.

Jitkhajornwanich, K. ed. 2006. Shifting comfort zone for hot-humid environments. The 23rd Conference on Passive and Low Energy Architecture.

Johnson, M.-H. et al. 2012. Performance evaluation of network airflow models for natural ventilation. Hvac&R Research 18(3), pp. 349-365.

Jones, C. Embodied Carbon Assessment. Citcular Ecology. Available at: https://circularecology.com/embodied-carbon.html [Accessed: 20 April 2020].

Juangjandee, W. ed. 2017. Analysis Thermal Comfort Condition in Complex Residential Building, Case Study: Chiangmai, Thailand. IOP Conference Series: Materials Science and Engineering. IOP Publishing.

Juangjandee, W. ed. 2017. Thermal Comfort Condition in Complex Residential Building, case study: Chiangmai, Thailand. World Multidisciplinary Civil Engineering-Architecture-Urban Planning Symposium (WMCAUS 2017). Prague, Czech Republic.

Juangjandee, W. et al. 2022. Key factors of occupants' behaviour characteristics and indoor air quality perception on occupancy comfort in multi-storey residential buildings in Thailand. Eco-Architecture IX: Harmonisation between Architecture and Nature 210, p. 63.

Jun, Y. et al. 2011. Income distribution, human capital and environmental quality: empirical study in China. Energy Procedia 5, pp. 1689-1696.

Kallio, H. et al. 2016. Systematic methodological review: developing a framework for a qualitative semi-structured interview guide. Journal of Advanced Nursing 72(12), pp. 2954-2965.

Karagiozis, A. and Salonvaara, M. 2001. Hygrothermal system-performance of a whole building. Building Environmental Health Perspectives 36(6), pp. 779-787.

Kato, S. 2018. Review of airflow and transport analysis in building using CFD and network model. Japan Architectural Review 1(3), pp. 299-309.

Khanal, R. and Lei, C. 2011. Solar chimney—A passive strategy for natural ventilation. Energy and buildings 43(8), pp. 1811-1819.

Khat, C. et al. 2015. The Effects of a Trombe Wall on the Ground Floor Ventilation of Row House. JOURNAL OF ENVIRONMENTAL DESIGN 2(2), pp. 11-28.

Khedari, J. et al. 2000a. Ventilation impact of a solar chimney on indoor temperature fluctuation and air change in a school building. Energy Buildings 32(1), pp. 89-93.

Khedari, J. et al. 2000b. Thailand ventilation comfort chart. Energy Buildings 32(3), pp. 245-249.

Khedari, J. et al. 2003. Field study of performance of solar chimney with air-conditioned building. Energy 28(11), pp. 1099-1114.

Kim, J. T. and Todorovic, M. S. 2013. Tuning control of buildings glazing's transmittance dependence on the solar radiation wavelength to optimize daylighting and building's energy efficiency. Energy and buildings 63, pp. 108-118.

Kishk, S. S. et al. 2019. Effectiveness of recyclable aluminum cans in fabricating an efficient solar collector for drying agricultural products. Renewable Energy 133, pp. 307-316.

Klepeis, N. E. et al. 2001. The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. Journal of Exposure Science Environmental Epidemiology 11(3), p. 231.

Koronaki, I. 2013. The impact of configuration and orientation of solar thermosyphonic systems on night ventilation and fan energy savings. Energy Buildings 57, pp. 119-131.

Kothari, C. R. 2004. Research methodology: Methods and techniques. New Age International.

Kozielska, B. et al. 2020. Investigation of indoor air quality in offices and residential homes in an urban area of Poland. Air Quality, Atmosphere Health 13, pp. 131-141.

Kozminska, U. ed. 2019. Circular design: reused materials and the future reuse of building elements in architecture. Process, challenges and case studies. IOP Conference Series: Earth and Environmental Science. IOP Publishing.

Krosnick, J. A. 2018. Questionnaire design. The Palgrave handbook of survey research, pp. 439-455.

Kubba, S. 2012. Handbook of green building design and construction: LEED, BREEAM, and Green Globes. Butterworth-Heinemann.

Kumar, R. 2018. Research methodology: A step-by-step guide for beginners. Sage.

Kuttler, W. et al. 2007. Urban/rural atmospheric water vapour pressure differences and urban moisture excess in Krefeld, Germany. International Journal of Climatology: A Journal of the Royal Meteorological Society 27(14), pp. 2005-2015.

Kwok, H. H. et al. 2020. Multi-zone indoor CFD under limited information: An approach coupling solar analysis and BIM for improved accuracy. Journal of cleaner production 244, p. 118912.

Lal, S. et al. 2013. A case study on solar chimney-assisted ventilation for residential building in India. International Journal of Energy Sector Management.

Lau, K. K.-L. et al. 2019. Outdoor thermal comfort in different urban settings of sub-tropical high-density cities: An approach of adopting local climate zone (LCZ) classification. Building and Environment 154, pp. 227-238.

LeBlanc, K. 2019. Moisture-Associated Skin Damage. WoundSource. Available at: https://www.woundsource.com/patientcondition/moisture-associated-skin-damage-masd [Accessed: 13th June 2020].

Lee, D. S.-H. 2017. Impacts of surrounding building layers in CFD wind simulations. Energy Procedia 122, pp. 50-55. doi: https://doi.org/10.1016/j.egypro.2017.07.313.

Lee, D.-S. et al. 2015. Experimental investigations on solar chimney for optimal heat collection to be utilized in organic Rankine cycle. Applied Energy 154, pp. 651-662.

Lee, J.-H. et al. 2013. Analyses on human responses to illuminance variations for resident-friendly lighting environment in a small office. Indoor and built environment 22(3), pp. 535-550.

Lee, K. H. and Strand, R. K. 2009. Enhancement of natural ventilation in buildings using a thermal chimney. Energy and buildings 41(6), pp. 615-621.

Leng, P. C. et al. 2019. The Impact of Air Well Geometry in a Malaysian Single Storey Terraced House. Sustainability 11(20), p. 5730.

Level, B. 2017. Passive Design. Available at: http://www.level.org.nz/passive-design/controlling-indoor-air-quality/humidity-and-condensation/ [Accessed: 5th December 2019].

Levermore, G. 2002. The exponential limit to the cooling of buildings by natural ventilation. Building Services Engineering Research and Technology 23(2), pp. 119-125.

Li, A. et al. 2004. Heat transfer and natural ventilation airflow rates from single-sided heated solar chimney for buildings. Journal of Asian Architecture Building Engineering 3(2), pp. 233-238.

Li, D. et al. 2011. Performance of light redirection systems in model buildings under typical sky and building obstruction conditions encountered in Hong Kong. Indoor Built Environment 20(6), pp 638-648.

Li, P. et al. 2018. Post-occupancy evaluation: State-of-the-art analysis and state-of-the-practice review. Building and Environment 133, pp. 187-202.

Li, Y. and Ren, S. 2011. Building decorative materials. Elsevier.

Liddament, M. W. 1986. Air infiltration calculation techniques: An applications guide. Air infiltration and ventilation centre Berkshire, UK.

Limited, I. E. S. 2013. MacroFlo Calculation Methods. Glasgow, UK.

Liu, B. et al. 2015. Experimental study of the chimney effect in a solar hybrid double wall. Solar Energy 115, pp. 1-9.

Liu, C.-H. et al. 2015. A theory of ventilation estimate over hypothetical urban areas. Journal of Hazardous Materials 296, pp. 9-16. doi: https://doi.org/10.1016/j.jhazmat.2015.04.018.

Liu, J. et al. 2015. Numerical evaluation of the local weather data impacts on cooling energy use of buildings in an urban area. Procedia Engineering 121, pp. 381-388.

Liu, S. et al. 2017. CFD simulations of wind distribution in an urban community with a full-scale geometrical model. Building and Environment 117, pp. 11-23.

Liu, X. et al. 2020. Experimental study of airflow and pollutant dispersion in cross-ventilated multi-room buildings: Effects of source location and ventilation path. Sustainable cities and society 52, p. 101822. doi: https://doi.org/10.1016/j.scs.2019.101822.

Lo Brano, V. et al. 2011. Quality of wind speed fitting distributions for the urban area of Palermo, Italy. Renewable Energy 36(3), pp. 1026-1039. doi: https://doi.org/10.1016/ j. renene.2010.09.009.

López-Pérez, L. et al. 2019. Adaptive thermal comfort model for educational buildings in a hot-humid climate. Building Environment International 150, pp. 181-194.

Lou, H. and Ou, D. 2019. A comparative field study of indoor environmental quality in two types of open-plan offices: Open-plan administrative offices and open-plan research offices. Building and Environment 148, pp. 394-404. doi: https://doi.org/10.1016/j.buildenv.2018.11.022.

Ma, X.-Y. et al. 2017. Full numerical investigations on the wind driven natural ventilation: cross ventilation and single-sided ventilation. Procedia Engineering 205, pp. 3797-3803.

Madhlopa, A. 2022. Chapter 10 - Modeling and optimization of solar receivers. In: Madhlopa, A. ed. Solar Receivers for Thermal Power Generation. Academic Press, pp. 297-369.

Maghrabie, H. M. et al. 2022. A review of solar chimney for natural ventilation of residential and non-residential buildings. Sustainable Energy Technologies and Assessments 52, p. 102082. doi: https://doi.org/10.1016/j.seta.2022.102082.

Manca, O. et al. 2014. Numerical investigation of thermal and fluid dynamic behavior of solar chimney building systems. Journal of Chemical Technology and Metallurgy 49(1), pp. 106-116.

Mansikkasalo, A. et al. 2014. Market behavior and policy in the recycled paper industry: A critical survey of price elasticity research. Forest Policy Economics 38, pp. 17-29.

Marshall, B. et al. 2013. Does sample size matter in qualitative research?: A review of qualitative interviews in IS research. Journal of computer information systems 54(1), pp. 11-22.

Martins, N. R. and da Graça, G. C. eds. 2016. Validation of numerical simulation tools for wind-driven natural ventilation design. Building Simulation. Springer.

Mathur, J. et al. 2006. Experimental investigations on solar chimney for room ventilation. Solar Energy 80(8), pp. 927-935.

Mesa, A. et al. 2010. Solar obstruction assessment model for densely forested urban environments. Architectural science review 53(2), pp. 224-237.

Milton, D. K., P. Mark Glencross, and Michael D. Walters. 2000. Risk of sick leave associated without door ventilation level, humidification, and building related complaints. Indoor air 10.4 10(4), pp. 212-221.

MinistryofInterior. 1994. Ministerial Regulation No. 33. Thailand: Department of Public Works and Town & Country Planning.

MinistryofInterior. 2012. Ministerial Regulation of Chiang Mai Comprehensive Plan B.E. 2555. Thailand: Department of Public Works and Town & Country Planning.

MinistryofInterior. 2015. Ministerial Regulation No. 55. Thailand: Department of Public Works and Town & Country Planning.

MinistryofInterior. 2017. Ministerial Regulation No. 55 (B.E. 2543) issued by virtue of the Building Control Act,B.E. 2522. Department of Public Works and Town & Country Planning. Available at: http://office.dpt.go.th/legal/index.php/2-uncategorised/24-2017-06-15-06-23-57 [Accessed: 15th November 2019].

Mishra, A. K. and Ramgopal, M. 2013. Field studies on human thermal comfort — An overview. Building and Environment 64, pp. 94-106. doi: https://doi.org/10.1016/j.buildenv.2013.02.015

Miyazaki, T. et al. 2006. The effects of solar chimneys on thermal load mitigation of office buildings under the Japanese climate. Renewable Energy 31(7), pp. 987-1010.

Mochida, A. et al. 2005. Methods for controlling airflow in and around a building under cross-ventilation to improve indoor thermal comfort. Journal of Wind Engineering Industrial Aerodynamics 93(6), pp. 437-449.

Mohamed, A. M. et al. 2015. Towards exporting renewable energy from MENA region to Europe: An investigation into domestic energy use and householders' energy behaviour in Libya. Applied Energy 146, pp. 247-262.

Montazeri, H. and Blocken, B. 2013. CFD simulation of wind-induced pressure coefficients on buildings with and without balconies: validation and sensitivity analysis. Building and Environment 60, pp. 137-149.

Mora, L. et al. 2003. Comparing zonal and CFD model predictions of isothermal indoor airflows to experimental data. Indoor air 13(2), pp. 77-85.

Moriasi, D. N. et al. 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Transactions of the ASABE 50(3), pp. 885-900.

Mumovic, D. and Santamouris, M. 2013. A Handbook of Sustainable Building Design and Engineering:" An Integrated Approach to Energy, Health and Operational Performance". Routledge.

Mundo-Hernández, J. et al. 2015. Post-occupancy evaluation of a restored industrial building: A contemporary art and design gallery in Mexico. Frontiers of Architectural Research 4(4), pp. 330-340.

Munn, S. and Soebarto, V. eds. 2004. The issues of using recycled materials in architecture. The 38th international conference of architectural science association “Contexts of architecture”. Launceston, Tasmania, The Architectural Science Association (ANZAScA).

Murali, G. et al. 2020. Experimental study of thermal performance of solar aluminium cane air heater with and without fins. Materials Today: Proceedings 21, pp. 223-230.

Mustafa, F. A. 2017. Performance assessment of buildings via post-occupancy evaluation: A case study of the building of the architecture and software engineering departments in Salahaddin University-Erbil, Iraq. Frontiers of Architectural Research 6(3), pp. 412-429.

Naing, Y. M. et al. 2017. Green roof retrofitting: Potential assessment in an academic campus. Engineering Journal 21(7), pp. 57-74.

NationalStatisticalOffice. 2021. Demography Population and Housing Branch. Department of the Interior.

Nettleton, D. 2014. Selection of Variables and Factor Derivation. Commercial Data Mining, pp. 79-104.

Ng, E. 2016. Urban air ventilation in high-density cities in the tropics. Urban climate challenges in the tropics: Rethinking planning design opportunities, pp. 79-110.

Ng, E. and Cheng, V. 2012. Urban human thermal comfort in hot and humid Hong Kong. Energy Buildings 55, pp. 51-65.

Nguyen, A.-T. and Reiter, S. 2014. A climate analysis tool for passive heating and cooling strategies in hot humid climate based on Typical Meteorological Year data sets. Energy and buildings 68, pp. 756-763. doi: https://doi.org/10.1016/j.enbuild.2012.08.050.

Nguyen, J. L. and Dockery, D. W. 2016. Daily indoor-to-outdoor temperature and humidity relationships: a sample across seasons and diverse climatic regions. International Journal of Biometeorology 60, pp. 221-229.

Nielsen, P. V. 1998. The selection of turbulence models for prediction of room airflow. ASHRAE transactions 104 (B), pp. 1119-1127.

Nitmetawong, T. et al. 2019. Effect of indoor environmental quality on building-related symptoms among the residents of apartment-type buildings in Bangkok area. Human Ecological Risk Assessment: An International Journal, pp. 1-15.

Nugroho, A. 2010. The impact of solar chimney geometry for stack ventilation in Malaysia's single storey terraced house. Malaysia's Geography 2010, pp. 163-177.

Nugroho, A. M. 2009. Solar chimney geometry for stack ventilation in a warm humid climate. International Journal of Ventilation 8(2), pp. 161-173.

Oberkampf, W. L. and Roy, C. J. 2010. Verification and validation in scientific computing. Cambridge University Press.

Oke, T. R. 2002. Boundary layer climates. Routledge.

Olgyay, V. 2015. Design with climate: Bioclimatic approach to architectural regionalism-new and expanded edition. Princeton university press.

Olive, D. J. 2017. Multiple linear regression. Springer.

Omrani, S. et al. 2017. Natural ventilation in multi-storey buildings: Design process and review of evaluation tools. Building and Environment 116, pp. 182-194.

Omrany, H. et al. 2023. Applications of Building information modelling in the early design stage of high-rise buildings. Automation in Construction 152, p. 104934.

Ong, K. 2003. A mathematical model of a solar chimney. Renewable Energy 28(7), pp. 1047-1060.

Ong, K. and Chow, C. 2003. Performance of a solar chimney. Solar Energy 74(1), pp. 1-17.

Othman, N. L. et al. 2015. A case study on moisture problems and building defects. Procedia-Social Behavioral Sciences 170, pp. 27-36.

Oyedele, L. O. et al. 2014. Use of recycled products in UK construction industry: An empirical investigation into critical impediments and strategies for improvement. Resources, Conservation Recycling 93, pp. 23-31.

Pan, J. et al. 2021. Correlating indoor and outdoor temperature and humidity in a sample of buildings in tropical climates. Indoor air 31(6), pp. 2281-2295.

Papadopoulos, A. M. 2005. State of the art in thermal insulation materials and aims for future developments. Energy Buildings 37(1), pp. 77-86.

Park, J. and Kim, H. 2012. A field study of occupant behavior and energy consumption in apartments with mechanical ventilation. Energy and buildings 50, pp. 19-25.

Pasquay, T. 2004. Natural ventilation in high-rise buildings with double facades, saving or waste of energy. Energy Buildings 36(4), pp. 381-389.

Patnaik, A. et al. 2015. Thermal and sound insulation materials from waste wool and recycled polyester fibers and their biodegradation studies. Energy Buildings 92, pp. 161-169.

Pavlou, K. et al. 2009. The impact of several construction elements on the thermal performance of solar chimneys. International Journal of Ventilation 8(3), pp. 277-285.

Pearson, E. S. 1931. The test of significance for the correlation coefficient. Journal of the American Statistical Association 26(174), pp. 128-134.

Peden, D. and Reed, C. E. 2010. Environmental and occupational allergies. Journal of Allergy and Clinical Immunology 125(2), pp. S150-S160.

Peng, L. et al. 2018. Wind weakening in a dense high-rise city due to over nearly five decades of urbanization. Building Environment 138, pp. 207-220.

Pfundstein, M. et al. 2012. Insulating materials: principles, materials, applications. Walter de Gruyter.

Plummer-D'Amato, P. 2008. Focus group methodology Part 1: Considerations for design. International Journal of Therapy 15(2), pp. 69-73.

Prajongsan, P. and Sharples, S. 2012. Enhancing natural ventilation, thermal comfort and energy savings in high-rise residential buildings in Bangkok through the use of ventilation shafts. Building Environment 50, pp. 104-113.

Prajongsan, P. and Sharples, S. 2012. Enhancing natural ventilation, thermal comfort and energy savings in high-rise residential buildings in Bangkok through the use of ventilation shafts. Building and Environment 50, pp. 104-113. doi: https://doi.org/10.1016/j.buildenv.2011.10.020.

Priyadarsini, R. et al. 2004. Enhancement of natural ventilation in high-rise residential buildings using stack system. Energy Buildings 36(1), pp. 61-71.

Punyasompun, S. et al. 2009. Investigation on the application of solar chimney for multi-storey buildings. Renewable Energy 34(12), pp. 2545-2561.

Rahanjam, A. and Ilbeigi, M. 2021. Post-Occupancy evaluation of office buildings' indoor environmental quality from the perspectives of architects and non-architects (case study: Iran). Journal of building engineering 42, p. 102782.

Rajagopalan, P. et al. 2014. Urban heat island and wind flow characteristics of a tropical city. Solar Energy 107, pp. 159-170.

Rajesh, S. and Choudary, R. 2017. A Cost Effective Solar Air-Heater (SAH) with Recycled Aluminium Can (RAC) Collector. Journal Material Science Mechanical Engineering 4.

Rajesh, S. and Choudary, R. B. 2016. A Cost Effective Desalination Plant Using a Solar Chimney with Recycled Aluminum Can Collector. Journal of Solar Energy 1-10.

Richardson, D. 2020. Duct Dynasty: Understanding the Coanda Effect. Continental Industries. Available at: https://www.continentalindustries.com/DD-Coanda [Accessed: 18th May 2020].

Rodriguez, C. M. and D'Alessandro, M. 2019. Indoor thermal comfort review: The tropics as the next frontier. Urban Climate 29, p. 100488.

Rong, L. et al. 2016. Summary of best guidelines and validation of CFD modeling in livestock buildings to ensure prediction quality. Computers and Electronics in Agriculture 121, pp. 180-190.

Ryan, D. and Burek, S. 2010. Experimental study of the influence of collector height on the steady state performance of a passive solar air heater. Solar Energy 84(9), pp. 1676-1684.

Sadafi, N. et al. 2011. Evaluating thermal effects of internal courtyard in a tropical terrace house by computational simulation. Energy Buildings 43(4), pp. 887-893.

Saffie, N. A. M. and Rasmani, K. A. eds. 2016. Fuzzy delphi method: Issues and challenges. 2016 International Conference on Logistics, Informatics and Service Sciences (LISS). IEEE.

Saifi, N. et al. 2012. Experimental study and simulation of airflow in solar chimneys. Energy Procedia 18, pp. 1289-1298.

Sakonidou, E. et al. 2008. Modeling of the optimum tilt of a solar chimney for maximum air flow. Solar Energy 82(1), pp. 80-94.

Santamouris, M. and Asimakopoulos, D. 1996. Passive cooling of buildings. Earthscan.

Santamouris, M. et al. 2014. Freezing the poor—Indoor environmental quality in low and very low income households during the winter period in Athens. Energy Buildings 70, pp. 61-70.

Schiavoni, S. et al. 2016. Insulation materials for the building sector: A review and comparative analysis. Renewable sustainable energy reviews 62, pp. 988-1011.

Sedgwick, P. 2014. Spearman’s rank correlation coefficient. Bmj 349.

Sedlbauer, K. 2001. Prediction of mould fungus formation on the surface of and inside building components. Fraunhofer Institute for Building Physics.

Sekhar, S. C. 2016. Thermal comfort in air-conditioned buildings in hot and humid climates–why are we not getting it right? Indoor air 26(1), pp. 138-152.

Sharifi, A. and Khavarian-Garmsir, A. R. 2020. The COVID-19 pandemic: Impacts on cities and major lessons for urban planning, design, and management. Science of the total environment 749, p. 142391. doi: https://doi.org/10.1016/j.scitotenv .2020.142391.

Shi, L. et al. 2018. Determining the influencing factors on the performance of solar chimney in buildings. Renewable and Sustainable Energy Reviews 88, pp. 223-238.

Silveira, V. D. C. et al. 2019. Influence of environmental factors favorable to the development and proliferation of mold in residential buildings in tropical climates. Building Environment International 166, p. 106421.

Sjodin, B. 2016. What’s The Difference Between FEM, FDM, and FVM? Available at: https://www.machinedesign.com/3d-printing-cad/fea-and-simulation/article/21832072/whats-the-difference-between-fem-fdm-and-fvm [Accessed: 28th March 2023].

Sloof, D. et al. 2022. Impact of supplementary air filtration on airborne particulate matter in a UK hospital ward. medRxiv, p. 2022.2003. 2025.22272953.

Spencer, S. et al. 2000. Experimental investigation of a solar chimney natural ventilation system. Air Distribution in Rooms, pp. 813-818.

Spentzou, E. et al. eds. 2018. Natural ventilation strategies for indoor thermal comfort in Mediterranean apartments. Building Simulation. Springer.

Sreshthaputra, A. 2003. Building design and operation for improving thermal comfort in naturally ventilated buildings in a hot-humid climate. Texas A & M University.

Stathopoulos, T. ed. 2009. Wind and comfort. European & African Conferences on Wind Engineering (EACWE) 5th. Citeseer.

Sterling, E. et al. 1985. Criteria for human exposure to humidity in occupied buildings. ASHRAE transactions 91(1), pp. 611-622.

Stern, F. et al. 2001. Comprehensive approach to verification and validation of CFD simulations—part 1: methodology and procedures. J. Fluids Eng. 123(4), pp. 793-802.

Sternstein, M. 1996. Statistics: Barron's Educational Series. Barron's, Hauppauge, NY.

Sunarya, W. 2020. The importance of site on house heating energy modelling in Wellington-Integrating EnergyPlus with ENVI-met for site modelling. Open Access Te Herenga Waka-Victoria University of Wellington.

Sung, U. J. et al. 2013. Analysis of Reduced Cooling Load for a Multistorey-Building Incorporating a Ventilated Double Skin Façade with a Solar Chimney Channel. International Journal of Ventilation 11(4), pp. 381-391.

Szokolay, S. 2012. Introduction to architectural science. Routledge.

Tablada, A. et al. 2009. Airflow conditions and thermal comfort in naturally-ventilated courtyard buildings in a tropical-humid climate. Building and Environment 44, pp. 1943-1958.

Tagade, P. M. et al. 2013. A Gaussian process emulator approach for rapid contaminant characterization with an integrated multizone-CFD model. Building and Environment 70, pp. 232-244.

Taherdoost, H. 2016. Validity and reliability of the research instrument; how to test the validation of a questionnaire/survey in a research. How to test the validation of a questionnaire/survey in a research (August 10, 2016).

Tan, A. Y. K. and Wong, N. H. 2013. Parameterization studies of solar chimneys in the tropics. Energies 6(1), pp. 145-163.

Tan, A. Y. K. and Wong, N. H. 2014. Influences of ambient air speed and internal heat load on the performance of solar chimney in the tropics. Solar Energy 102, pp. 116-125.

Tan, G. and Glicksman, L. R. 2005. Application of integrating multi-zone model with CFD simulation to natural ventilation prediction. Energy and buildings 37(10), pp. 1049-1057.

Tantasavasdi, C. et al. 2001. Natural ventilation design for houses in Thailand. Energy Buildings 33(8), pp. 815-824.

Tao, Y. et al. 2020. The challenge of creating age-friendly indoor environments in a high-density city: Case study of Hong Kong’s care and attention homes. Journal of building engineering 30, p. 101280. doi: https://doi.org/10.1016/j.jobe.2020.101280.

Tezuka, A. 2006. Finite Element and Finite Difference Methods. In: Czichos, H. et al. eds. Springer Handbook of Materials Measurement Methods. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 973-1000.

ThaiMeteorologicalDepartment. 2014. Wind Energy. Rajamangala University of Technology Thanyaburi. Available at: https://www.tmd.go.th/info/info.php?FileID=54 [Accessed: 3rd November 2019].

ThaiMeteorologicalDepartment. 2021. Chiang Mai Weather Data 2010-2021.

ThaiMeteorologicalDepartment. 2021. Seasons in Thailand. Available at: https://www.tmd.go.th/info/info.php?FileID=53 [Accessed: 12 June 2021].

ThaiMeteorologicalDepartment. Annual ground temperature. Thai Meteorological Department. Available at: http://www.arcims.tmd.go.th/Research.html [Accessed: 2nd May 2020].

ThaiMeteorologicalDepartment. Intertropical Convergence Zone. Thai Meteorological Department. Available at: https://www.tmd.go.th/info/info.php?FileID=54 [Accessed: 2nd November 2019].

ThaiMeteorologicalDepartment. Relative Humidity. Thai Meteorological Department. Available at: https://www.tmd.go.th/info/info.php?FileID=56 [Accessed: 2nd November 2019].

Tian, W. 2013. A review of sensitivity analysis methods in building energy analysis. Renewable and Sustainable Energy Reviews 20, pp. 411-419.

Toe, D. H. C. and Kubota, T. 2013. Development of an adaptive thermal comfort equation for naturally ventilated buildings in hot–humid climates using ASHRAE RP-884 database. Frontiers of Architectural Research 2(3), pp. 278-291.

Tong, Z. et al. 2016. Defining the Influence Region in neighborhood-scale CFD simulations for natural ventilation design. Applied Energy 182, pp. 625-633.

Toparlar, Y. et al. 2017. A review on the CFD analysis of urban microclimate. Renewable and Sustainable Energy Reviews 80, pp. 1613-1640.

Tuniki, H. P. et al. 2021. A review on the approaches in analysing energy-related occupant behaviour research. Journal of building engineering 40, p. 102630.

Udawattha, C. et al. 2018. Mold growth and moss growth on tropical walls. Building Environment International 137, pp. 268-279.

UnitedNations. 2022. Thailand Population 2023.

Valchanov, I. 2023. Measuring Explanatory Power with the R-squared. Available at: https://365datascience.com/tutorials/statistics-tutorials/r-squared/ [Accessed: 26th April 2023].

Valtonen, V. 2017. Clinical diagnosis of the Dampness and Mold Hypersensitivity Syndrome: Review of the literature and suggested diagnostic criteria. Frontiers in immunology 8, p. 951.

Valverde, I. et al. 2013. Development of new insulation panels based on textile recycled fibers. Waste Biomass Valorization 4(1), pp. 139-146.

Van Druenen, T. et al. 2019. CFD evaluation of building geometry modifications to reduce pedestrian-level wind speed. Building and Environment 163, p. 106293. doi: https://doi.org/10.1016/j.buildenv.2019.106293

Van Hooff, T. and Blocken, B. 2012. Full-scale measurements of indoor environmental conditions and natural ventilation in a large semi-enclosed stadium: possibilities and limitations for CFD validation. Journal of Wind Engineering and Industrial Aerodynamics 104, pp. 330-341.

Vrána, T. 2007. Impact of moisture on long term performance of insulating products based on stone wool. KTH.

Wagner, A. et al. 2007. Thermal comfort and workplace occupant satisfaction—Results of field studies in German low energy office buildings. Energy Buildings 39(7), pp. 758-769.

Wahab, I. A. and Ismail, L. H. eds. 2012. Natural ventilation approach in designing urban tropical houses. Proceeding of International Conference of Civil & Environmental Engineering for Sustainability, Johor Bahru.

Wang, B. and Malkawi, A. 2019. Design-based natural ventilation evaluation in early stage for high performance buildings. Sustainable cities and society 45, pp. 25-37.

Wang, B. et al. 2012. Simulating naturally ventilated buildings with detailed CFD-based wind pressure database. Proceedings of SimBuild. pp. 353-360.

Wang, L. and Chen, Q. 2007. Theoretical and numerical studies of coupling multizone and CFD models for building air distribution simulations. Indoor air 17(5), pp. 348-361.

Wang, L. L. and Chen, Q. 2008. Evaluation of some assumptions used in multizone airflow network models. Building and Environment 43(10), pp. 1671-1677.

Wang, S. et al. 2021. Applicability of passive design strategies in China promoted under global warming in past half century. Building and Environment 195, p. 107777.

Wang, Y. et al. 2021. Ventilation Characteristics and Performance Evaluation of Different Window-Opening Forms in a Typical Office Room. 11(19), p. 8966.

Ward, I. and Derradji, M. eds. 1987. Air Movement within Buildings Cooled by Passive Solar Means. 1987 European Conference on Architecture: proceedings of an international conference held at Munich, FR Germany, 6-10 April 1987. Munich, 6-10 April 1987. Stephens.

Wei, D. et al. 2011. A study of the ventilation performance of a series of connected solar chimneys integrated with building. Renewable Energy 36(1), pp. 265-271.

Williams, M. and Moser, T. 2019. The art of coding and thematic exploration in qualitative research. International Management Review 15(1), pp. 45-55.

Wolkoff, P. 2018. Indoor air humidity, air quality, and health–An overview. International Journal of Hygiene Environmental Health 221(3), pp. 376-390.

Wong, P. et al. 2008. A new type of double-skin façade configuration for the hot and humid climate. Energy Buildings 40(10), pp. 1941-1945.

Wong, S.-K. et al. 2009. Sick building syndrome and perceived indoor environmental quality: A survey of apartment buildings in Hong Kong. Habitat International 33(4), pp. 463-471.

WorldBank. 2021. Thailand: Urbanization from 2011 to 2021.

Xie, X. et al. 2023. Use of wind pressure coefficients to simulate natural ventilation and building energy for isolated and surrounded buildings. Building and Environment 230, p. 109951. doi: https://doi.org/10.1016/j.buildenv.2022.109951.

Xue, P. et al. 2014. The effects of daylighting and human behavior on luminous comfort in residential buildings: A questionnaire survey. Building and Environment 81, pp. 51-59.

Xue, P. et al. 2016. Post-occupancy evaluation of sunshades and balconies' effects on luminous comfort through a questionnaire survey. Building services engineering research technology 37(1), pp. 51-65.

Yan, D. et al. 2015. Occupant behavior modeling for building performance simulation: Current state and future challenges. Energy and buildings 107, pp. 264-278.

Yan, D. et al. 2017. IEA EBC Annex 66: Definition and simulation of occupant behavior in buildings. Energy and buildings 156, pp. 258-270. doi: https://doi.org/10.1016/j.enbuild.2017.09.084.

Yik, F. et al. 2004. Moisture generation through Chinese household activities. Indoor and built environment 13(2), pp. 115-131.

Yik, F. et al. 2004. Moisture generation through Chinese household activities. Indoor Built Environment 13(2), pp. 115-131.

You, S. et al. 2017. Study on moisture condensation on the interior surface of buildings in high humidity climate. Building Environment 125, pp. 39-48.

Yu, Y. et al. eds. 2019. A review of the development of airflow models used in building load calculation and energy simulation. Building Simulation. Springer.

Yunus, A. C. 2010. Fluid Mechanics: Fundamentals And Applications (Si Units). Tata McGraw Hill Education Private Limited.

Yusoff, W. F. M. et al. 2010. Enhancement of stack ventilation in hot and humid climate using a combination of roof solar collector and vertical stack. Building Environment International 45(10), pp. 2296-2308.

.

Zain-Ahmed, A. et al. 1998. The bioclimatic design approach to low-energy buildings in the Klang Valley, Malaysia. Renewable Energy 15(1-4), pp. 437-440.

Zamora, B. and Kaiser, A. S. 2009. Thermal and dynamic optimization of the convective flow in Trombe Wall shaped channels by numerical investigation. Heat Mass Transfer 45(11), pp. 1393-1407.

Zemitis, J. et al. 2016. Measurements of moisture production caused by various sources. Energy and buildings 127, pp. 884-891.

Zemitis, J. et al. 2016. Measurements of moisture production caused by various sources. Energy Buildings 127, pp. 884-891.

Zhai, X. et al. 2005. Experimental investigation on air heating and natural ventilation of a solar air collector. Energy Buildings 37(4), pp. 373-381.

Zhai, X. et al. 2011. A review for the applications of solar chimneys in buildings. Renewable and Sustainable Energy Reviews 15(8), pp. 3757-3767.

Zhai, Y. et al. 2013. Comfort under personally controlled air movement in warm and humid environments. Building Environment International 65, pp. 109-117.

Zhai, Z. J. and Chen, Q. Y. 2006. Sensitivity analysis and application guides for integrated building energy and CFD simulation. Energy and buildings 38(9), pp. 1060-1068.

Zhai, Z. J. et al. 2007. Evaluation of various turbulence models in predicting airflow and turbulence in enclosed environments by CFD: Part 1—Summary of prevalent turbulence models. Hvac&R Research 13(6), pp. 853-870.

Zhang, H. and Yoshino, H. 2010a. Analysis of indoor humidity environment in Chinese residential buildings. Building and Environment 45(10), pp. 2132-2140. doi: https://doi.org/10.1016/j.buildenv.2010.03.011.

Zhang, H. and Yoshino, H. 2010b. Analysis of indoor humidity environment in Chinese residential buildings. Building Environment 45(10), pp. 2132-2140.

Zhang, H. et al. 2022. Ventilation performance of solar chimney integrated into a multi-storey building. Sustainable Energy Technologies and Assessments 54, p. 102868. doi: https://doi.org/10.1016/j.seta.2022.102868

Zhang, R. et al. 2013a. Coupled EnergyPlus and computational fluid dynamics simulation for natural ventilation. Building and Environment 68, pp. 100-113.

Zhang, T. et al. 2016. The application of air layers in building envelopes: A review. Applied Energy 165, pp. 707-734.

Zhang, W. et al. 2013b. Building energy simulation considering spatial temperature distribution for nonuniform indoor environment. Building and Environment 63, pp. 89-96.

Zhang, X. et al. eds. 2019. Experimental Analysis of Residential Ventilation and Dehumidification Strategies in Chongqing. E3S Web of Conferences. EDP Sciences.

Zhang, Y. et al. 2010. Thermal comfort in naturally ventilated buildings in hot-humid area of China. Building Environment International 45(11), pp. 2562-2570.

Zhang, Z. et al. 2018. Thermal comfort in interior and semi-open spaces of rural folk houses in hot-humid areas. Building Environment International 128, pp. 336-347.

Zhao, B. et al. 2004. Comparison of indoor aerosol particle concentration and deposition in different ventilated rooms by numerical method. Building Environment 39(1), pp. 1-8.

ZHIVOV, A. et al. 2001. Principles of air and contaminant movement inside and around buildings.Industrial ventilation design guidebook. Elsevier, pp. 415-599.

Zhiyi, Z. et al. 2021. Potential of cross-ventilation channels in an ideal typical apartment building predicted by CFD and multi-zone airflow model. Journal of building engineering 44, p. 103408.

Zhong, H.-Y. et al. 2022. Single-sided natural ventilation in buildings: a critical literature review. Building and Environment, p. 108797.

Zhou, L. 2018. Chapter 5 - Modeling of Single-Phase Turbulence. In: Zhou, L. ed. Theory and Modeling of Dispersed Multiphase Turbulent Reacting Flows. Butterworth-Heinemann, pp. 89-120.

Zia, K. M. et al. 2007. Methods for polyurethane and polyurethane composites, recycling and recovery: A review. Reactive functional polymers 67(8), pp. 675-692.

Ziskind, G. et al. 2002. Ventilation by natural convection of a one-story building. Energy and buildings 34(1), pp. 91-101.

Zriken, Z. and Bilgen, E. 1985. Thermal performance of solar chimney in North eastern African climate. Alternative Energy Sources VII 2, pp. 225-232.

Appendix A:

Wind pressure coefficients

The interaction of wind on building façade involves with various factors, including, wind speed, wind direction, building geometry, surrounding terrain and nearby obstructions. Wind pressure can be estimated via wind pressure coefficient. The coefficient establishes a relationship between wind pressure on the building façade to the wind speed as following equation [1]:

$$P_w = 0.5 \cdot \rho \cdot Cp \cdot v^2$$

where Pw is the surface pressure due to wind (Pa), ρ is air density ($kg.m^{-3}$),·Cp is wind pressure coefficient, and· v^2 represent the wind speed at height Z ($m.s^{-1}$). The variable v is calculated based on the meteorological wind speed.

$$v = uKh^a$$

where u is meteorological wind speed at 10 m of height ($m.s^{-1}$), h is height above the ground (m), a and K are coefficient depended on the following information.

Terrain type	Description	Exponent (a)	K
Country	Open terrain	0.14	0.7244
Suburb	Urban and suburb area	0.22	0.4319
City	Lasrge city centre	0.33	0.2097

Wind pressure coefficient are as following table:

	Wind Pressure Coefficient (Cp)			
	semi-expose wall, up to 3 storeys building	sheltered wall, more than three storeys building		
Wind angle to the building surface (°)	default data in DB	h/H =0.2	h/H =0.6	h/H = 1.0
0	0.40	0.11	0.19	0.14
45	0.10	0.04	0.09	0.05
90	-0.30	-0.15	-0.21	-0.22
135	-0.35	-0.15	-0.14	-0.13
180	-0.20	-0.08	-0.10	-0.09
225	-0.35	-0.15	-0.14	-0.13
270	-0.30	-0.15	-0.21	-0.22
315	0.10	0.04	0.08	0.05

1. IES. *Wind Pressure*. 2018; Available from: https://help.iesve.com/ve2018/wind_pressure.htm?ms=cwAAEAAFAAAAAAAAAAQAAAAAAAAAAAAAAAAAAAAAUAgIQAQDBBAg&q=cHJlc3N1cmUgY29lZmZpY2llbnQ%3D&st=Mg%3D%3D&sct=MA%3D%3D&mw=MjQw.

Appendix B: Occupancy Questionnaire (Thai version in Appendix G)

Introduction: The main aim of this research is to reduce indoor relative humidity regarding to thermal comfort condition by enhancing natural ventilation in apartment dwellings in Chiang Mai, Thailand. This surveying part will visualise how satisfied and the environment of participants' apartment rooms

Focus of review:

- Thermal Comfort Perceptions
- Occupant practices which are relevant to thermal comfort
- Residential

Institution: Welsh School of Architecture, Cardiff University

Contact detail: Warangkana Juangjandee (juangjandeew@cardiff.ac.uk),

Dr. Vicki Stevenson (stevensonv@cardiff.ac.uk) (supervisor)

Consent:

I understand that my participation in this project will involve collecting data about my attitudes to buildings which will require approximately 20 minutes of my time.

I understand that participation in this study is entirely voluntary and that I can withdraw from the study at any time without giving a reason.

I understand that I am free to ask any questions at any time. I am free to withdraw or discuss my concerns with Dr Vicki Stevenson (stevensonv@cardiff.ac.uk).

I understand that the information provided by me will be held confidentially, such that only the Principal Investigator can trace this information back to me individually. The information will be retained for up to 3 years when it will be deleted/destroyed.

I understand that I can ask for the information I provide to be deleted/destroyed at any time and, in accordance with the UK Data Protection Act, I can have access to the information at any time.

☐ I agree to take part in this research project

General

1. Gender

☐ male ☐ female ☐ other_______________ ☐ prefer not to answer

2. Age

☐ 18-24 ☐ 25-34 ☐ 35-44 ☐ 45-54 ☐ 55 and over

3. Occupation

____

4. Time in building

4.1 Occupied period during weekday?

☐ < 8 hours ☐ 8-12 hours☐ 12-16 hours ☐ 16-20 hours ☐ 20-24 hours

4.2 Occupied period during weekend?

☐ < 8 hours ☐ 8-12 hours☐ 12-16 hours ☐ 16-20 hours ☐ 20-24 hours

5. How you occupy your room

☐ owner ☐ renter ☐ other ____________

Location and building

building

6. How tall (in floor) is your building?

☐ 1 floor ☐ 2 floors ☐ 3 floors ☐ 4 floors ☐ 5 floors ☐ 6 floors

☐ 7 floors ☐ 8 floors ☐ other _____

7. How far away from your building is the nearest building which is higher than 3 storeys?

☐ no nearby building ☐ 0-3 metre ☐ 4-6 metre ☐ 7-9 metre ☐ 9 metre and over

Room location

8. On which floor level do you live?

☐ ground floor ☐ 1st floor ☐ 2nd floor ☐ 3rd floor ☐ 4th floor ☐ 5th floor

☐ 6th floor ☐ 7th floor ☐ other _____

9. On which orientation is your room opening?

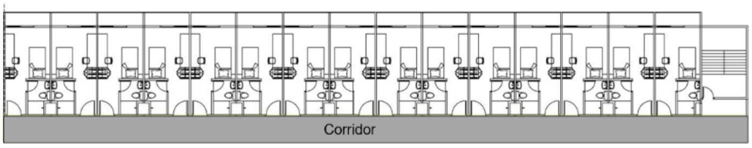
☐ north ☐ east ☐ west ☐ south

10. Which range is your room size?

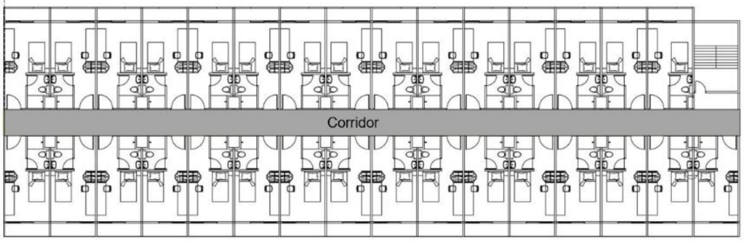
☐ 8-20m^2 ☐ 21-30m^2 ☐ 31-40m^2 ☐ 41-50m^2 ☐ 51m^2 and over

11. Which plan is similar to your building planning?

☐ single load corridor



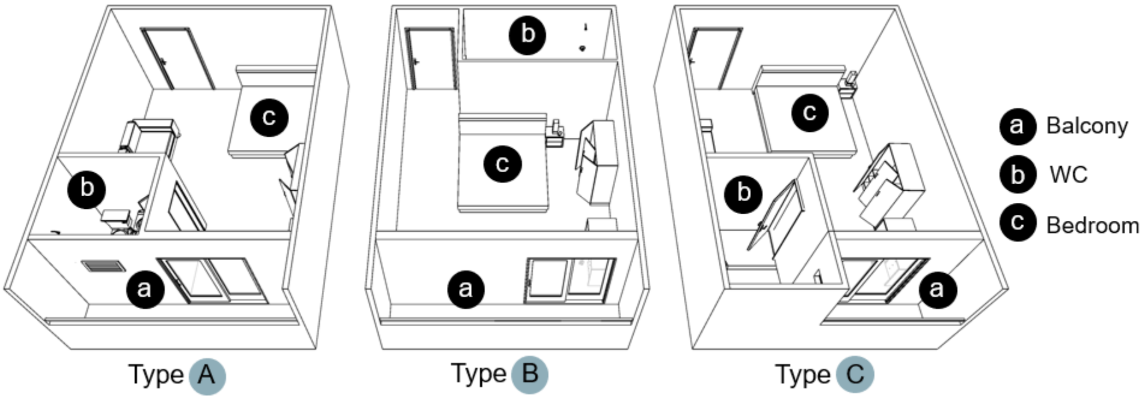
☐ double load corridor



12. Which is your room location?

☐ at the middle ☐ at the corner

13. Which plan is the most similar to your room plan?



☐ type A- balcony width is the same size with room width, WC locates next to the balcony

☐ type B- balcony width is the same size with room width, WC locates close to room's door

☐ type C- balcony width is half size of room width, WC locates close to the balcony

☐ other_________________

Behaviour

14. How often is you room cleaned?

☐ everyday☐ 3-4 times per week☐ 1-2 times per week ☐ Never

15. Does cooking take place in your room?

☐ yes ☐ no

16. Which is the character of cooking area in your room?

☐ cooking area separated from bedroom ☐ cooking area is in bedroom☐ other_______

17. Does clothes washing take place in your room?

☐ wash by hand in room ☐ wash by machine in room ☐ no washing in room

18. Are clothes hung to dry in your room or balcony?

☐ hanging in the room ☐ hanging at the balcony ☐ no hanging in room area

Building specific

Indoor environmental quality

19. Air temperature

Please rate the air temperature in winter on the scale between

Much too cold								Much too hot

Please rate the air temperature in summer on the scale between

Much too cold								Much too hot

20. Light

Is there too much or too little natural light

Not bright								Too bright

21. Air quality

Is the air fresh or stale?

Stale								Fresh

22. Is the air humid or dry?

Too dry								Too humid

23. Is there air movement?

Too little								Too much

24. Please rate the mould happening on the scale (% of the surface area)

No mould (0%)	(10%)	(20%)	(30%)	(40%)	(50%)	(60%)	(70%)	Very large amounts of mould (>80%)

Material

25. Which is the material used in your room? (Please tick)

Room door ☐ wood ☐ glass ☐ plastic ☐ steel ☐ other____

Toilet door ☐ wood ☐ tile ☐ glass ☐ plastic ☐ concrete ☐ steel ☐ other____

Floor ☐ wood ☐ tile ☐ brick ☐ glass ☐ plastic ☐ concrete ☐ steel ☐ other____

Wall ☐ wood ☐ tile ☐ brick ☐ glass ☐ plastic ☐ concrete ☐ steel ☐ other____

Ceiling ☐ wood ☐ tile ☐ brick ☐ glass ☐ plastic ☐ concrete ☐ steel ☐ other____

Furniture ☐ wood ☐ tile ☐ glass ☐ plastic ☐ concrete ☐ steel ☐ other____

Satisfaction

26. Please rate your comfort satisfaction with the following:

	Very satisfied	Somewhat satisfied	Neutral	Somewhat dissatisfied	Very dissatisfied
Room ventilation					
Natural lighting					
Humidity					
Air temperature					
Room location					
Room privacy					
Room size					
Room fee					
Overall					

27.If you have any further comments, please write them in the space below

____
____
____
____
____

Thank you very much for sparing the time to complete this question.

Appendix C: Ethics Approval form for conducting questionnaire and collecting physical measurement data

WELSH SCHOOL OF ARCHITECTURE
ETHICS APPROVAL FORM FOR STAFF AND PHD/MPHIL PROJECTS

Tick one box:	☐ STAFF ☒ PHD/MPHIL
Title of project:	Indoor Air Dehumidification of Residential Buildings with Passive Ventilation and Recycled Materials Installation: A Case Study of Thailand Urban Areas
Name of researcher(s):	Warangkana Juangjandee
Name of principal investigator	Dr Vicki Stevenson
Contact e-mail address:	Juangjandeew@cardiff.ac.uk
Date:	07/01/2021

Participants		YES	NO	N/A
Does the research involve participants from any of the following groups?	• Children (under 16 years of age)		x	
	• People with learning difficulties		x	
	• Patients (NHS approval is required)		x	
	• People in custody		x	
	• People engaged in illegal activities		x	
	• Vulnerable elderly people		x	
	• Any other vulnerable group not listed here		x	
• When working with children: I have read the University's Safeguarding Policy: https://intranet.cardiff.ac.uk/staff/policies				x

Consent Procedure	YES	NO	N/A
• Will you describe the research process to participants in advance, so that they are informed about what to expect?	x		
• Will you tell participants that their participation is voluntary?	x		
• Will you tell participants that they may withdraw from the research at any time and for any reason?	x		
• Will you obtain valid consent from participants? (specify how consent will be obtained in Box A)[1]	x		
• Will you give participants the option of omitting questions they do not want to answer?	x		
• If the research is observational, will you ask participants for their consent to being observed?			x
• If the research involves photography or other audio-visual recording, will you ask participants for their consent to being photographed / recorded and for its use/publication?			x

Possible Harm to Participants	YES	NO	N/A
• Is there any realistic risk of any participants experiencing either physical or psychological distress or discomfort?		x	
• Is there any realistic risk of any participants experience a detriment to their interests as a result of participation?		x	

Data Protection		YES	NO	N/A
• Will any non-anonymous and/or personalised data be generated or stored?		x		
• If the research involves non-anonymous and/or personalised data, will you:	• gain written consent from the participants	x		
	• allow the participants the option of anonymity for all or part of the information they provide	x		

Health and Safety	YES
Does the research meet the requirements of the University's Health & Safety policies? (https://intranet.cardiff.ac.uk/staff/supporting-your-work/manage-your-office-or-lab/health-safety-and-environment)	x

Research Governance	YES	NO	N/A
Does your study include the use of a drug? You need to contact Research Governance before submission (resgov@cf.ac.uk)		x	
Does the study involve the collection or use of human tissue? You need to contact the Human Tissue Act team before submission (hta@cf.ac.uk)		x	

[1] If any non-anonymous and/or personalised data be generated or stored, *written consent* is required.

Prevent Duty	YES	
Has due regard be given to the 'Prevent duty', in particular to prevent anyone being drawn into terrorism? Cardiff University Prevent Policy https://intranet.cardiff.ac.uk/staff/policies	x	

If any of the shaded boxes have been ticked, you must explain in Box A how the ethical issues are addressed. If none of the boxes have been ticked, you must still provide the following information.
The list of ethical issues on this form is not exhaustive; if you are aware of any other ethical issues you need to make the SREC aware of them.

Box A The Project (provide all the information listed below in a separate attachment)

1. Title of Project
2. Purpose of the project and its academic rationale
3. Brief description of methods and measurements
4. Participants: recruitment methods, number, age, gender, exclusion/inclusion criteria
5. Consent and participation information arrangements - please attached consent forms if they are to be used
6. A clear and concise statement of the ethical considerations raised by the project and how is dealt with them
7. Estimated start date and duration of project

All information must be submitted along with this form to the School Research Ethics Committee for consideration

Researcher's declaration (tick as appropriate)	
• I consider this project to have **negligible ethical implications** (*can only be used if none of the grey areas of the checklist have been ticked*).	x
• I consider this project research to have **some ethical implications**.	x
• I consider this project to have **significant ethical implications**	x

Signature **Name** Warangkana Juangjandee **Date** **12/01/2021**
Researcher or MPhil/PhD student

Signature **Name** Vicki Stevenson **Date** **13/1/21**
Lead investigator or supervisor

Advice from the School Research Ethics Committee

STATEMENT OF ETHICAL APPROVAL

This project had been considered using agreed Departmental procedures and is now approved

Signature **Name** Dr Chris Whitman **Date** 15/01/21
Chair, School Research Ethics Committee

Appendix D: Consent Form for collecting physical measurement data

Consent Form - Confidential data

I understand that my participation in this project will involve collecting diary about my practices and attitudes to buildings which will require approximately 5 minutes of my time each day.

I understand that my participation in this project will involve physical monitoring in my room for one month.

I understand the research involves photography or other audio-visual recording.

I understand that participation in this study is entirely voluntary and that I can withdraw from the study at any time without giving a reason.

I understand that I am free to ask any questions at any time. I am free to withdraw or discuss my concerns with Dr Vicki Stevenson (stevensonv@cardiff.ac.uk).

I understand that the information provided by me will be held confidentially, such that only the Principal Investigator can trace this information back to me individually. The information will be retained for up to 3 years when it will be deleted/destroyed.

I understand that I can ask for the information I provide to be deleted/destroyed at any time and, in accordance with the Data Protection Act, I can have access to the information at any time.

I, ______________________________________ consent to participate in the study conducted by Warangkana Juangjandee, Welsh School of Architecture, Cardiff University with the supervision of Dr Vicki Stevenson.

Signed:

Date:

Appendix E: Ethics Approval Letter for conducting interview

15.03.23

Dear Warangkana,

Research project title: Exploration of passive cooling potential to improve indoor environment quality (thermal comfort, relative humidity and air movement) in thermally free-running multi-residential dwellings in Thailand urban areas.

SREC reference: 23013

The Welsh School of Architecture's Research Ethics Committee ('Committee') reviewed the above application on 15.03.23 via its proportionate review process.

Ethical Opinion

The Committee gave

A a favourable ethical opinion of the above application on the basis described in the application form, protocol and supporting documentation.

Additional approvals

This letter provides an ethical opinion only. You must not start your research project until all appropriate approvals are in place.

Amendments

Any substantial amendments to documents previously reviewed by the Committee must be submitted to the Committee via ARCHI-ethics@cardiff.ac.uk for consideration and cannot be implemented until the Committee has confirmed it is satisfied with the proposed amendments.

You are permitted to implement non-substantial amendments to the documents previously reviewed by the Committee but you must provide a copy of any updated documents to the Committee via ARCHI-ethics@cardiff.ac.uk for its records.

Monitoring requirements

The Committee must be informed of any unexpected ethical issues or unexpected adverse events that arise during the research project.

The Committee must be informed when your research project has ended. This notification should be made to ARCHI-ethics@cardiff.ac.uk within three months of research project completion. For Student projects, submission of the associated dissertation will be considered to be notification.

Documents reviewed by Committee

The documents reviewed by the Committee were:

Document	Version	Date
WSA_Ethics-Review-Application_WJuangjandee	01	22.02.23
Appendix A_E_WJuangjandee	01	31.01.23
C_Evidence of completion Ethics training		22.02.23

Complaints/Appeals

If you are dissatisfied with the decision made by the Committee, please contact the Chair of the Committee via ARCHI-ethics@cardiff.ac.uk in the first instance to discuss your complaint. If this discussion does not resolve the issue, you are entitled to refer the matter to the Head of School for further consideration. The Head of School may refer the matter to the University Open Research Integrity and Ethics Committee (ORIEC), where this is appropriate. Please be advised that ORIEC will not normally interfere with a decision of the Committee and is concerned only with the general principles of natural justice, reasonableness and fairness of the decision.

Please use the Committee reference number on all future correspondence.

The Committee reminds you that it is your responsibility to conduct your research project to the highest ethical standards and to keep all ethical issues arising from your research project under regular review.

You are expected to comply with Cardiff University's policies, procedures and guidance at all times, including, but not limited to, its Policy on the Ethical Conduct of Research involving Human Participants, Human Material or Human Data and our Research Integrity and Governance Code of Practice.

Yours sincerely,

Dr Eshrar Latif

Senior Lecturer
School Ethics Officer and Research Integrity Lead
Welsh School of Architecture
Cardiff University
Bute Building
King Edward VII Avenue
Cardiff CF10 3NB
Wales U.K.
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Dr Eshrar Latif

Uwch Ddarlithydd
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Ysgol Pensaernïaeth Cymru
Prifysgol Caerdydd
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E-bost: latife@Cardiff.ac.uk

Appendix F: Interview questions (Thai version in Appendix H)

Introduction: The aim of this research is to investigate the perception of building professionals in Thailand on the potential of natural ventilation options in thermally free-running apartment dwellings in Thailand climate condition. The natural ventilation options are designed to improve indoor environmental quality – specifically relative humidity, thermal comfort and air quality.

The focus of interview: **I**nterviews will be sought with local built professionals, e.g., architects, engineers, and academics, who are involved in multi-storey building design and construction projects. The research will solicit the perception of the built professional judgements on concepts within a proposed design framework for improving indoor environmental quality. This includes passive design strategies and design options. Semi-structured interviews will be applied as a method to interpret the professionals' thoughts, ideas and perceptions of the options.

Institution: Welsh School of Architecture, Cardiff University

Contact detail: Warangkana Juangjandee (Juangjandeew@cardiff.ac.uk),

Dr. Vicki Stevenson (StevensonV@cardiff.ac.uk) (supervisor)

Interview Questions:

The interview is divided into two phases. The interview will take place for approximately 20 minutes.

<u>Phase One</u>

Establish context of the expert's experience and knowledge in relation to current multi-storey residential building and passive design

1.1 General question

What is your built profession? (architect, engineer, academics, others)

1.2 Issue of indoor environmental quality

What (if any) indoor environmental quality problems exist in free-running multi-storey residential buildings in Thailand?

What design solutions do you think could be implemented to solve these issues(s)?

1.3 Natural ventilation

Do you think natural ventilation is important in thermally free running building in Thailand?

If yes - what benefits do you think natural ventilation brings?

If no - are there specific issues that you associate with natural ventilation?

Phase Two

Focuses on specific questions about strategies and design options to improve natural ventilation in thermally free-running multi-residential buildings in Thailand.

2.1 improve natural ventilation in building

2.1.1: What feature in the picture below can be developed to improve ventilation in a thermally free running multi-residential building in Thailand

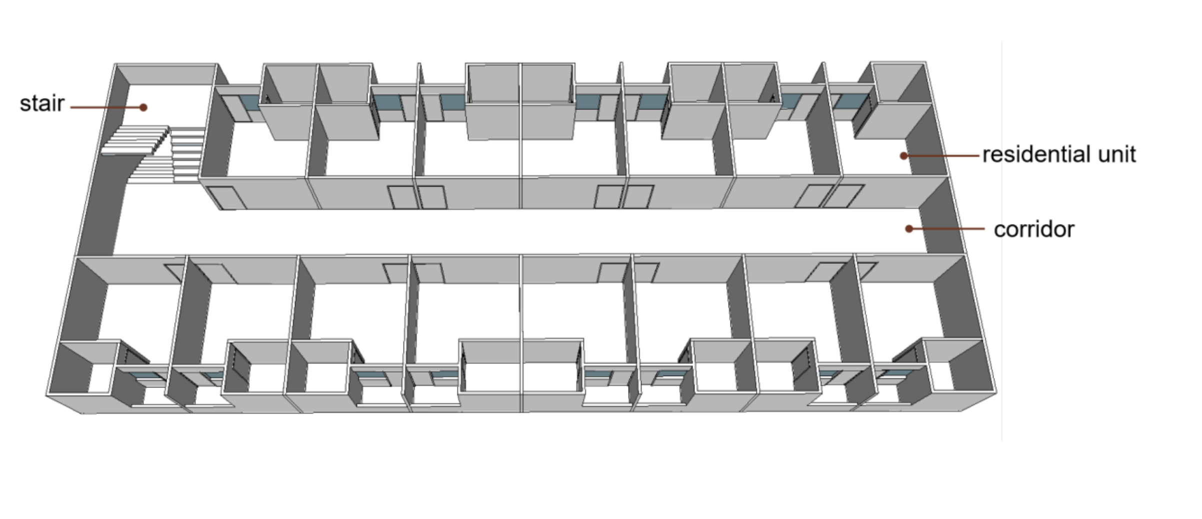


Figure: the whole floor plan of multi-residential building

2.1.2: What feature in the picture below can be developed to improve ventilation in a thermally-free running multi-residential building room in Thailand

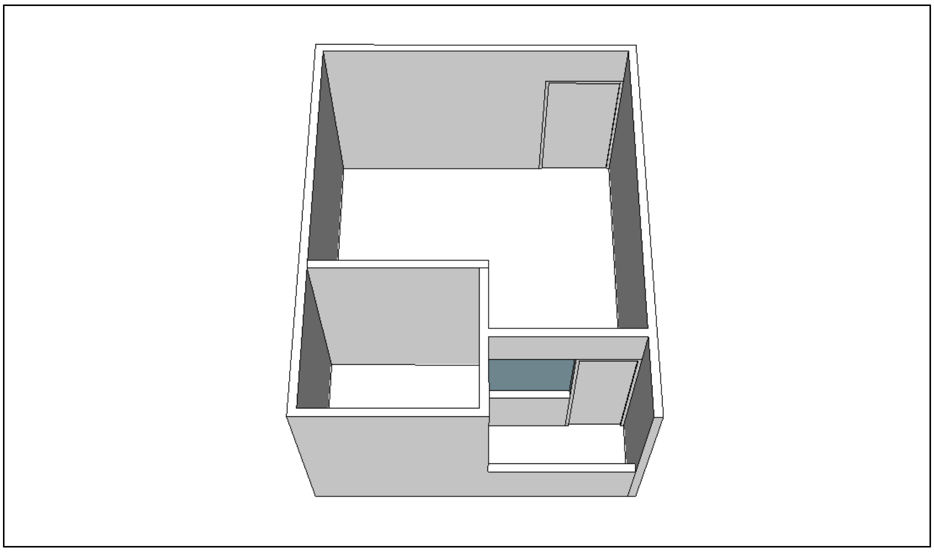


Figure: a plan of one room in multi-residential building

2.2 Solar chimney

2.2.1: What opportunities and obstructions do you see in integrating solar chimney with multi-residential building in relation to natural ventilation, building design, energy, and construction?

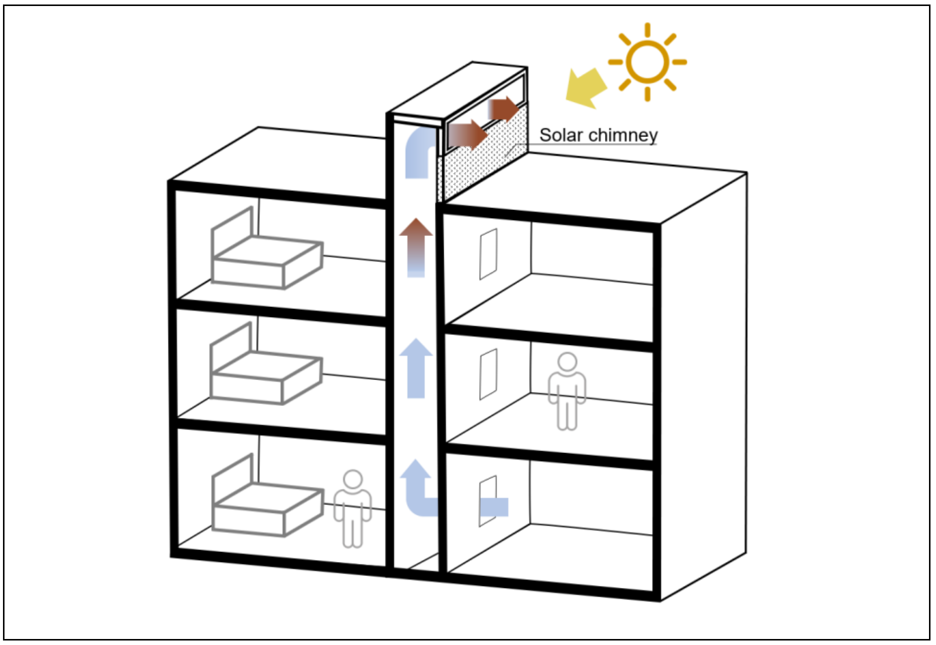


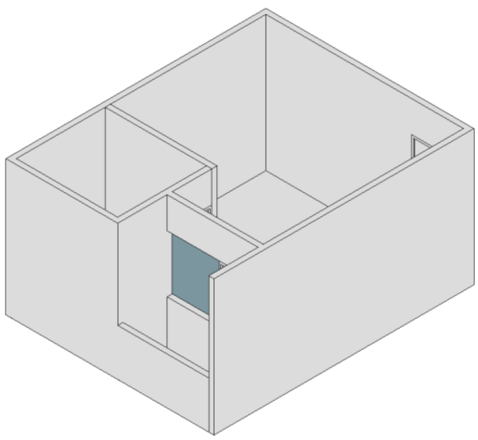
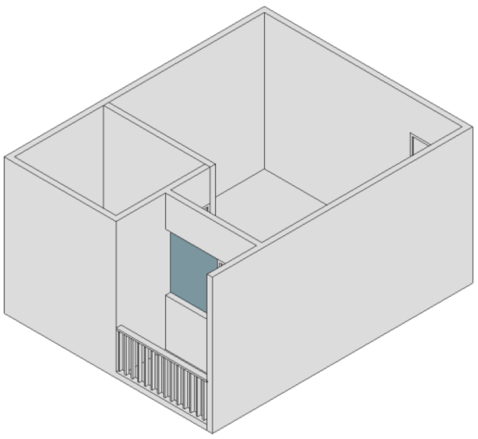
Figure: solar chimney integrating with multi-residential building

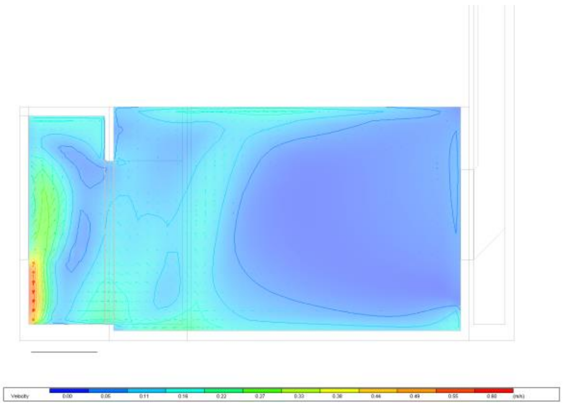
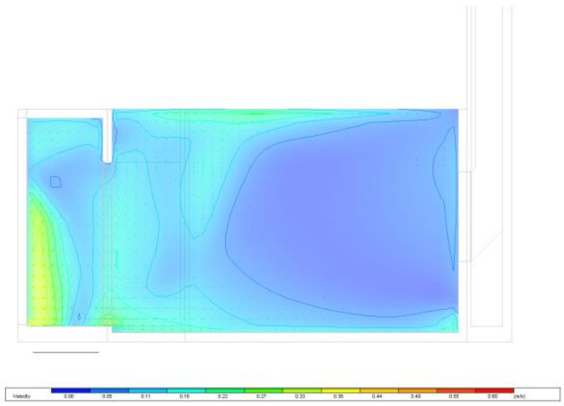
2.2.2: For obstruction, what additional system should be used to assist solar chimney in relation to natural ventilation, building design, energy, and construction?

2.3 Professionals' opinions on options

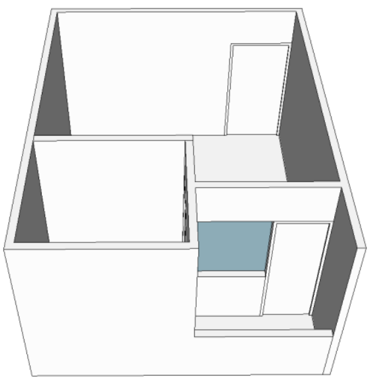
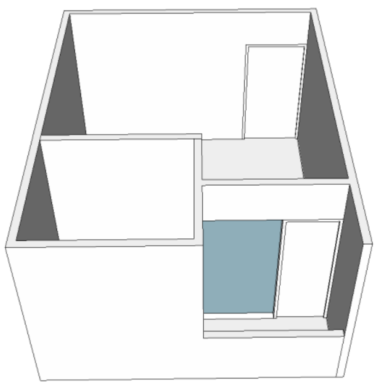
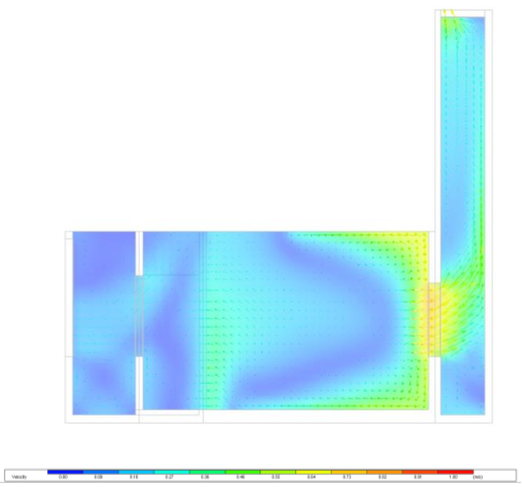
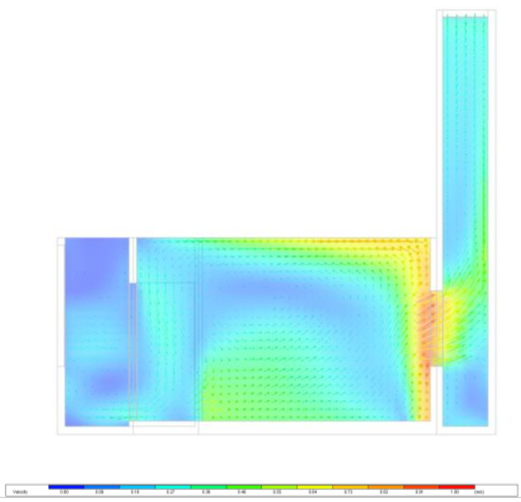
Please give your opinions on the options pictured below in relation to the potential of natural ventilation options in thermally free-running apartment dwellings in Thailand climate condition.

2.3.1: different balcony type

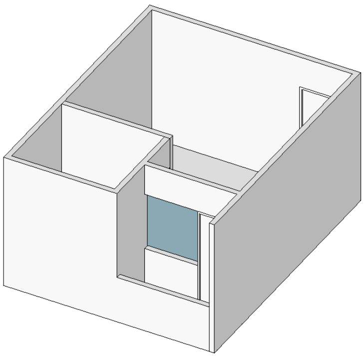
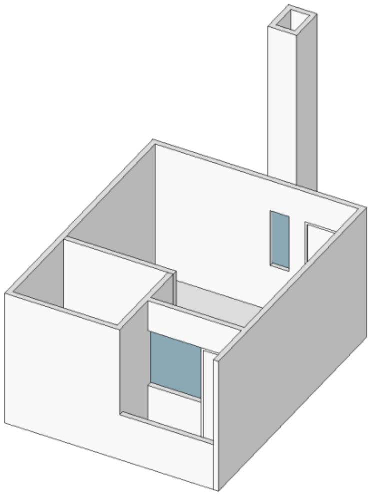
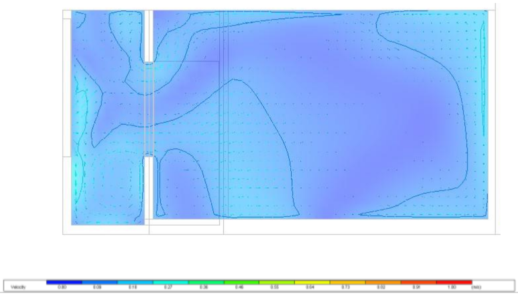
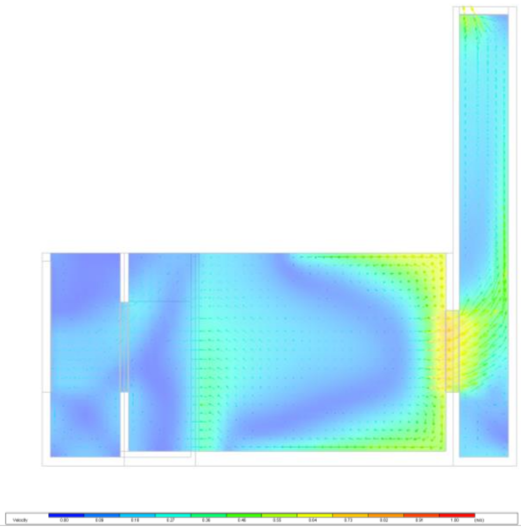
a) Room with solid wall balcony	b) Room with railing balcony
 Perspective	 Perspective

 CFD result	 CFD result

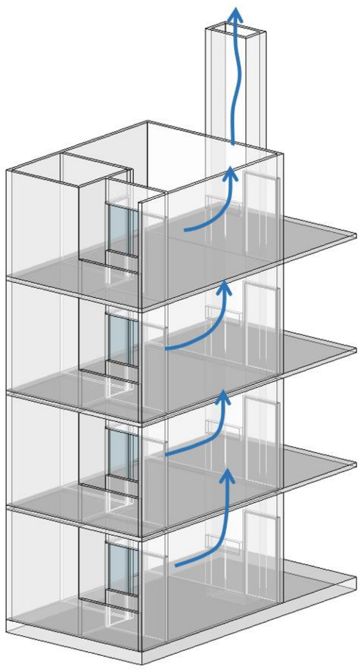
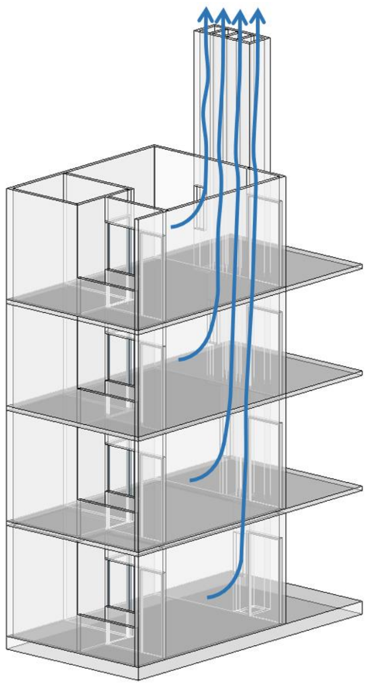
2.3.2: room inlet size

a) Room with window size 1.0 x1.1 m	b) Room with window size 1.0 x 2.0 m
 Perspective	 Perspective
 CFD result	 CFD result

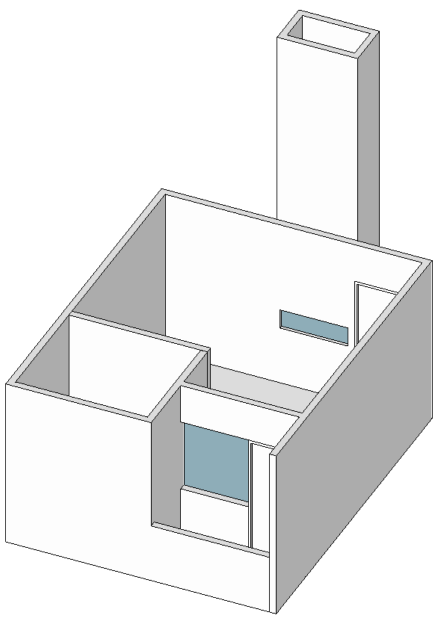
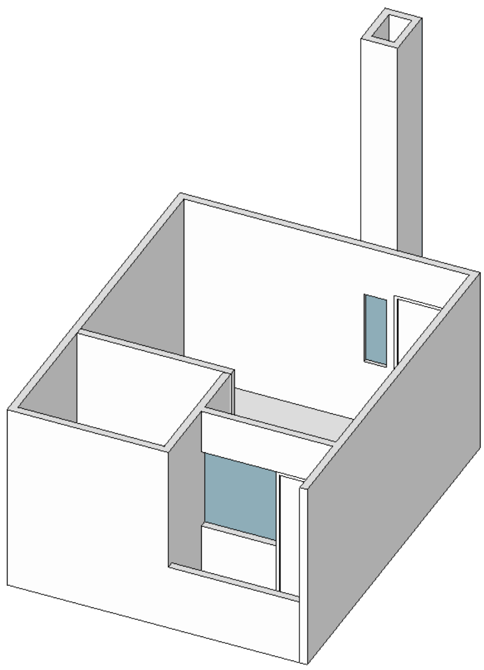
2.3.3: room with and without chimney

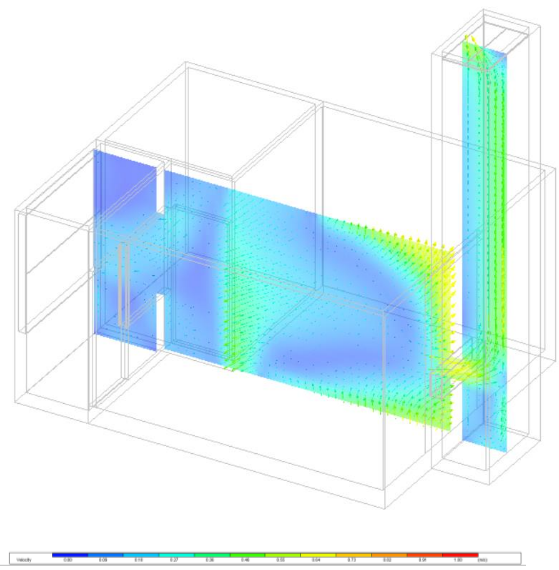
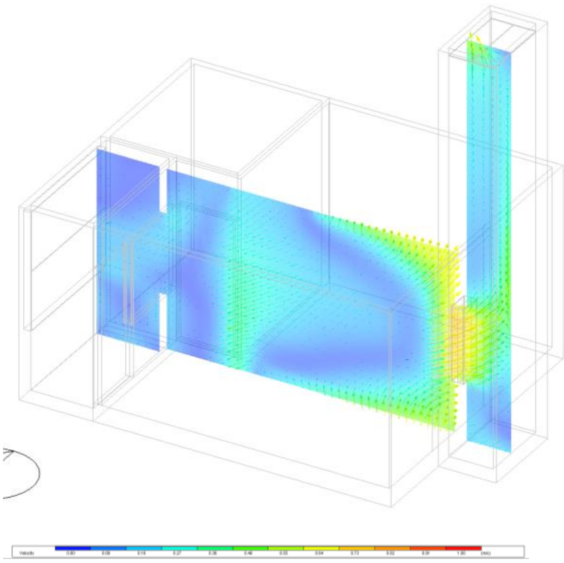
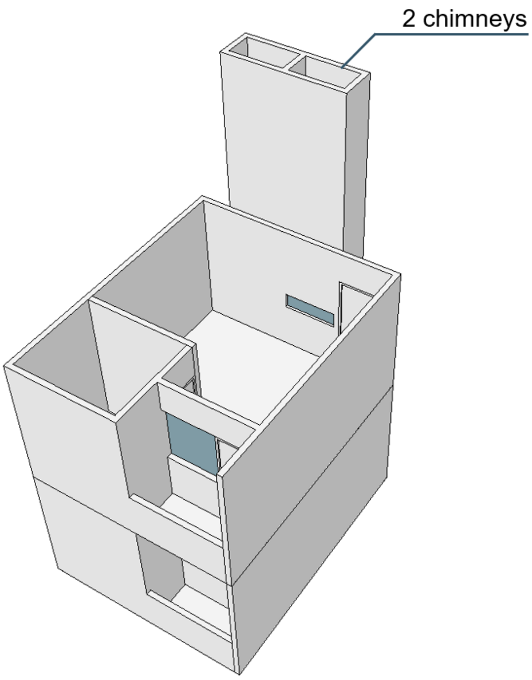
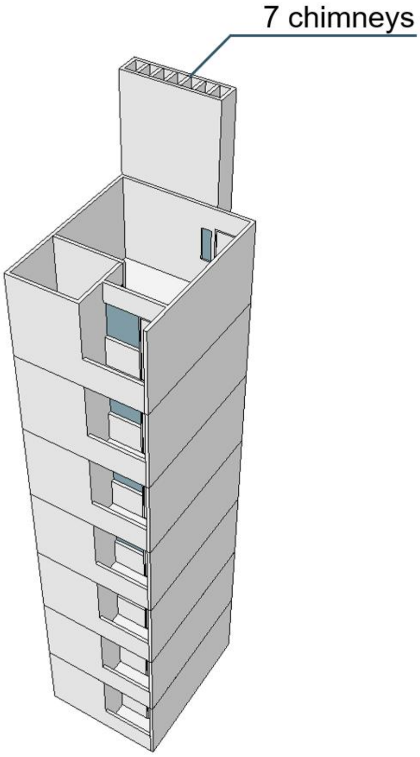
a) Room without chimney	b) Room with chimney
 Perspective	 Perspective
 CFD result	 CFD result

2.3.4: chimney design

a) One chimney connected to multi-rooms	b) One chimney connected to only one room
	
Perspective	Perspective

2.3.5: room outlet design

a) Room with horizon room outlet	b) Room with vertical room outlet
	
Perspective	Perspective

 CFD result	 CFD result
 Perspective: Room with horizontal room outlet with one chimney connected to only one room can designed for 2 storeys.	 Perspective: Room with horizontal room outlet with one chimney connected to only one room can designed for 7 storeys.

Appendix G: Occupancy Questionnaire (Thai language)

แบบสอบถามการอยู่อาศัย

บทนำ: วัตถุประสงค์หลักของงานวิจัยนี้ที่เป็นการวิจัยการลดความชื้นในอาคารชุดพักอาศัยในจังหวัดเชียงใหม่ ประเทศไทย ที่ส่งผลต่อภาวะน่าสบายโดยการเพิ่มการระบายอากาศโดยวิธีธรรมชาติ ซึ่งการสำรวจด้วยแบบสอบถามนี้จะสามารถแสดงความพึงพอใจและสภาพแวดล้อมของผู้ที่พักอาศัยในอาคารชุดได้

วัตถุประสงค์หลักของการศึกษา:

- การรับรู้ต่อสภาวะน่าสบายเชิงความร้อน (Thermal Comfort Perceptions)
- ลักษณะการอยู่อาศัยที่ส่งผลต่อสภาวะน่าสบายเชิงความร้อน
- ลักษณะอาคารชุดพักอาศัย

สถาบันการศึกษา: Welsh School of Architecture, Cardiff University

รายละเอียดการติดต่อ: Warangkana Juangjandee (juangjandeew@cardiff.ac.uk),
Dr. Vicki Stevenson (stevensonv@cardiff.ac.uk) (supervisor)

การยินยอมให้เก็บข้อมูล:

ข้าพเจ้าเข้าใจว่า การเข้าร่วมงานวิจัยนี้มีเป็นการเก็บข้อมูลเกี่ยวกับมุมมองของข้าพเจ้าที่มีต่ออาคารชุดที่ข้าพเจ้าพักอาศัยอยู่ โดยแบบสอบถามนี้ใช้เวลาประมาณ 20 นาทีในการทำแบบสอบถาม

ข้าพเจ้าเข้าร่วมโครงการวิจัยนี้ด้วยความสมัครใจ และมีสิทธิที่จะบอกเลิกการเข้าร่วมโครงการวิจัยนี้ได้โดยไม่ต้องแจ้งเหตุผล

ข้าพเจ้ามีสิทธิในการถามคำถาม และมีความอิสระในการบอกเลิกและถกถามข้อกังวลกับ Dr Vicki Stevenson (stevensonv@cardiff.ac.uk).

ข้าพเจ้าเข้าใจว่าข้อมูลที่ข้าพเจ้าให้ไว้จะถูกเก็บไว้เป็นความลับ มีเพียงผู้วิจัยหลักเท่านั้นที่สามารถติดตามข้อมูลนี้กลับมายังข้าพเจ้าได้ ข้อมูลจะถูกเก็บไว้นานถึง 3 ปีก่อนจะถูกลบหรือทำลาย

ข้าพเจ้าเข้าใจว่าข้าพเจ้าสามารถขอลบหรือทำลายข้อมูลที่ข้าพเจ้าให้ได้ตลอดเวลา ตามพระราชบัญญัติการปกป้องข้อมูลของสหราชอาณาจักร และข้าพเจ้าสามารถเข้าถึงข้อมูลได้ตลอดเวลา

☐ ข้าพเจ้ายินยอมในการเข้าร่วมทำแบบสอบถามนี้

ทั่วไป

1. เพศ

☐ ชาย ☐ หญิง ☐ อื่นๆ______________ ☐ ไม่ต้องการตอบ

2. อายุ

☐ 18-24 ☐ 25-34 ☐ 35-44 ☐ 45-54 ☐ 55 และมากกว่า

3. อาชีพ ____

4. ระยะเวลาในการใช้อาคาร

4.1 ระยะเวลาในการใช้อาคารช่วงวันธรรมดา?

☐ < 8 ชั่วโมง ☐ 8-12 ชั่วโมง ☐ 12-16 ชั่วโมง ☐ 16-20 ชั่วโมง ☐ 20-24 ชั่วโมง

4.2 ระยะเวลาในการใช้อาคารช่วงวันหยุด?

☐ < 8 ชั่วโมง ☐ 8-12 ชั่วโมง ☐ 12-16 ชั่วโมง ☐ 16-20 ชั่วโมง ☐ 20-24 ชั่วโมง

5. กรรมสิทธิ์ในการครอบครองห้องที่ท่านพักอาศัย

☐ เจ้าของห้อง ☐ ผู้เช่าอาศัย ☐ อื่น ___________

ตำแหน่งและอาคาร

<u>อาคาร</u>

6. อาคารที่ท่านพักอาศัยอยู่มีจำนวนกี่ชั้น?

☐ 1 ชั้น ☐ 2 ชั้น ☐ 3 ชั้น ☐ 4 ชั้น ☐ 5 ชั้น ☐ 6 ชั้น

☐ 7 ชั้น ☐ 8 ชั้น ☐ อื่นๆ ________

7. อาคารชุดที่ท่านพักอาศัยมีระยะห่างจากอาคารข้างเคียงที่ใกล้ที่สุดที่มีความสูงตั้งแต่ 3 ชั้นขึ้นไปกี่เมตร

☐ ไม่มีอาคารข้างเคียงที่สูงตั้งแต่ 3 ชั้นขึ้นไป ☐ 0-3 เมตร ☐ 4-6 เมตร ☐ 7-9 เมตร ☐ 9 เมตรขึ้นไป

<u>ตำแหน่งของห้อง</u>

8. คุณพักอาศัยอยู่ชั้นใด?

☐ ชั้น 1 ☐ ชั้น 2 ☐ ชั้น 3 ☐ ชั้น 4 ☐ ชั้น 5 ☐ ชั้น 6

☐ ชั้น 7 ☐ ชั้น 8 ☐ อื่นๆ ________

9. ห้องของท่านอยู่ทางทิศใด

☐ ทิศเหนือ ☐ ทิศตะวันออก ☐ ทิศตะวันตก ☐ ทิศใต้

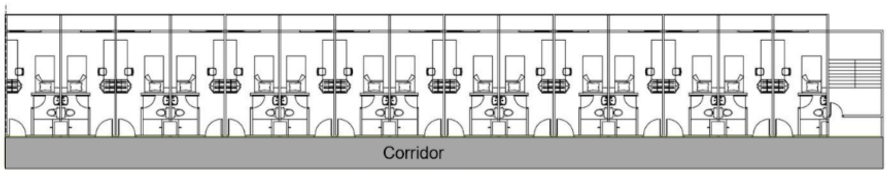
10. ห้องของท่านมีขนาดเท่าไร?

☐ 8-20m^2 ☐ 21-30m^2 ☐ 31-40m^2 ☐ 41-50m^2 ☐ 51m^2 and over

11. ผังพื้นใดมีลักษณะใกล้เคียงกับห้องพักอาศัยของท่านมากที่สุด?

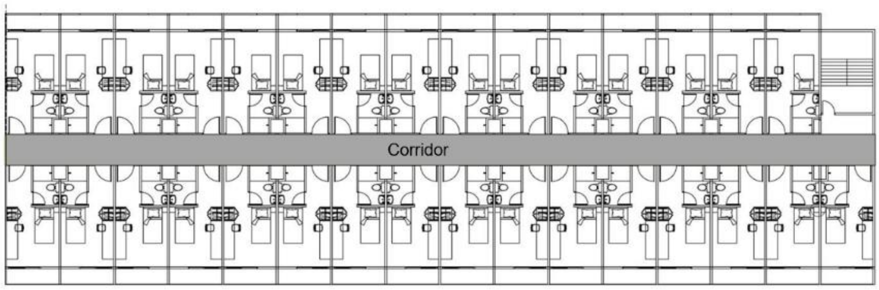
☐ single load corridor

มีห้องฝั่งเดียวของทางเดิน



☐ double load corridor

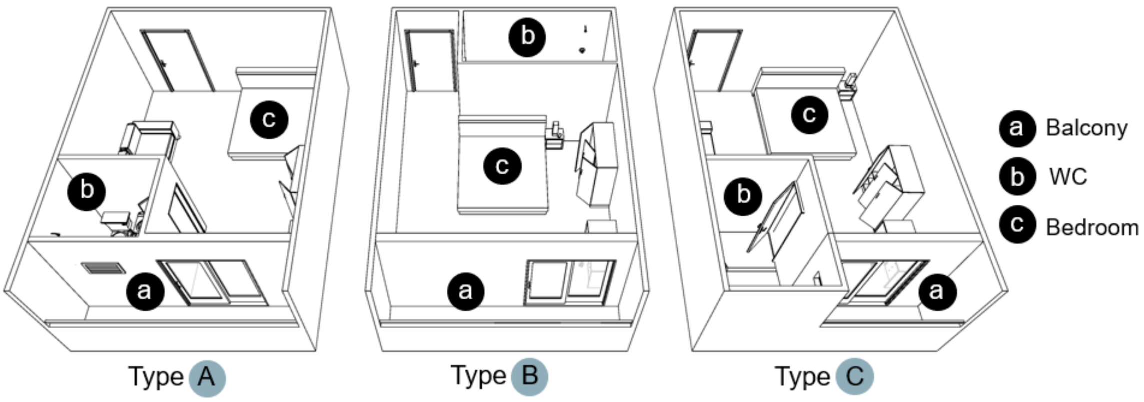
มีห้องสองฝั่งของทางเดิน



12. ห้องของท่านตั้งอยู่ในตำแหน่งใดของอาคาร?

☐ กลางอาคาร ☐ มุมอาคาร

13. รูปแบบห้องพักใดมีลักษณะใกล้เคียงกับห้องพักของท่านมากที่สุด?



☐ type A- ความกว้างของระเบียงเท่ากับความกว้างของห้อง,ห้องน้ำอยู่ติดกับระเบียง

☐ type B- ความกว้างของระเบียงเท่ากับความกว้างของห้อง, ห้องน้ำอยู่ติดกับทางเข้าห้องพัก

☐ type C- ความกว้างของระเบียงมีขนาดเป็นครึ่งหนึ่งของความกว้างของห้อง,ห้องน้ำอยู่ติดกับระเบียง

☐ other________________

พฤติกรรมในการอยู่อาศัย

14. ความถี่ในการทำความสะอาดห้องของท่าน

☐ ทุกวัน ☐ 3-4 ครั้งต่อสัปดาห์ ☐ 1-2 ครั้งต่อสัปดาห์ ☐ ไม่เคยทำความสะอาด

15. มีการทำอาหารในห้องของคุณหรือไม่?

☐ มี ☐ ไม่มี

16. ลักษณะพื้นที่ทำครัวในห้องคุณเป็นอย่างไร?

☐ พื้นที่ครัวแยกออกจากพื้นที่อื่นอย่างชัดเจน ☐ พื้นที่ครัวและพื้นที่นอนอยู่ในบริเวณเดียวกัน☐ อื่นๆ _______

17. ข้อใดเป็นลักษณะการซักผ้าในห้องของคุณ

☐ ซักผ้าด้วยมือในพื้นที่ห้อง ☐ ซักผ้าด้วยเครื่องซักผ้าในพื้นที่ห้อง ☐ ไม่มีการซักผ้าในห้อง

18. คุณตากผ้าในห้องหรือระเบียงหรือไม่

☐ ตากผ้าในพื้นที่ห้อง ☐ ตากผ้าที่ระเบียง ☐ ไม่มีการตากผ้าในพื้นที่ห้อง

ลักษณะเฉพาะBuilding specific

<u>คุณสิ่งแวดล้อมภายในอาคาร</u>

ส่วนนี้เป็นแบบมาตราส่วนประมาณค่า (Rating Scale) จงให้ค่าระดับตั้งแต่ 1 ถึง 9

19. อุณหภูมิอากาศ

ลักษณะอุณหภูมิอากาศในช่วงฤดูหนาวเป็นอย่างไร

หนาวเกินไป								ร้อนเกินไป

ลักษณะอุณหภูมิอากาศในช่วงฤดูร้อนเป็นอย่างไร

หนาวเกินไป								ร้อนเกินไป

20. แสงสว่างธรรมชาติ

ลักษณะแสงธรรมชาติภายในห้องพักมีลักษณะอย่างไร

ไม่สว่างเลย								สว่างเกินไป

21. คุณภาพอากาศ

ในห้องมีอากาศสดชื่นหรือเหม็นอับ

เหม็นอับ								สดชื่น

22. ในห้องอากาศชื้นหรือแห้ง

แห้งเกินไป								ชื้นเกินไป

23. ลักษณะการไหลเวียนอากาศเป็นอย่างไร

น้อยเกินไป								มากเกินไป

24. ลักษณะการเกิดขึ้นของเชื้อราเป็นอย่างไร (ปริมาณที่เกิดขึ้นบนพื้นผิววัสดุในห้อง)

ไม่มีเชื้อราเกินขึ้น (0%)	(10%)	(20%)	(30%)	(40%)	(50%)	(60%)	(70%)	มีพื้นที่ที่มีเชื้อรา ปริมาณมาก (>80%)

<u>วัสดุ</u>

25. วัสดุที่ใช้ในห้องพักของท่านมีลักษณะใด

ประตูห้อง ☐ ไม้ ☐ กระจก ☐ พลาสติก ☐ เหล็ก ☐ อื่นๆ____

ประตูห้องน้ำ ☐ ไม้ ☐ กระจก ☐ พลาสติก ☐ เหล็ก ☐ อื่นๆ____

พื้น ☐ ไม้ ☐ กระเบื้อง ☐ อิฐ ☐ กระจก ☐ พลาสติก ☐ คอนกรีต ☐ เหล็ก ☐ อื่นๆ____

ผนัง ☐ ไม้ ☐ กระเบื้อง ☐ อิฐ ☐ กระจก ☐ พลาสติก ☐ คอนกรีต ☐ เหล็ก ☐ อื่นๆ____

ฝ้าเพดาน ☐ ไม้ ☐ กระเบื้อง ☐ อิฐ ☐ กระจก ☐ พลาสติก ☐ คอนกรีต ☐ เหล็ก ☐ อื่นๆ____

เฟอร์นิเจอร์ ☐ ไม้ ☐ กระเบื้อง ☐ อิฐ ☐ กระจก ☐ พลาสติก ☐ คอนกรีต ☐ เหล็ก ☐ อื่นๆ____

ระดับความพึงพอใจต่อห้องที่ท่านพักอาศัย

26. ท่านมีความพึงพอใจต่อห้องพักของท่านในระดับใด

	พอใจมาก	พอใจ	ปานกลาง	ไม่พอใจ	ไม่พอใจมาก
การระบายอากาศ					
แสงสว่างธรรมชาติ					
ความชื้น					
อุณหภูมิอากาศ					
ตำแหน่งของห้องพัก					
ความเป็นส่วนตัวของห้องพัก					
ขนาดห้องพัก					
ราคาห้องพัก					
ภาพรวม					

27.แสดงความเห็นเพิ่มเติม

ขอบคุณสำหรับการช่วยเหลือในการทำแบบสอบถามนะคะ

Appendix H: Interview questions (Thai language)

บทนำ งานวิจัยนี้มีวัตถุประสงค์เพื่อศึกษามุมมองของผู้เชี่ยวชาญด้านอาคารและการก่อสร้างในประเทศไทย เกี่ยวกับศักยภาพของรูปแบบการระบายอากาศตามธรรมชาติในอาคารชุดพักอาศัยในสภาพอากาศของประเทศไทย ซึ่งรูปแบบการระบายอากาศตามธรรมชาติมีเป้าประสงค์เพื่อพัฒนาคุณภาพสิ่งแวดล้อมภายในอาคาร โดยเฉพาะความชื้นสัมพัทธ์ ภาวะน่าสบาย และคุณภาพอากาศ

จุดประสงค์ของของการสัมภาษณ์: การสัมภาษณ์จะเป็นสำรวจมุมมองของผู้เชี่ยวชาญด้านอาคารและการก่อสร้างในประเทศไทย เช่น สถาปนิก วิศวกร และนักวิชาการที่มีส่วนร่วมในโครงการออกแบบอาคาร งานวิจัยจะขอความอนุเคราะห์ในการขอข้อมูลและมุมมองจากผู้เชี่ยวชาญเกี่ยวกับทางเลือกของการออกแบบเพื่อการพัฒนาคุณภาพสิ่งแวดล้อมภายในอาคารโดยกลยุทธ์การออกแบบอาคารโดยพึ่งพาระบบธรรมชาติ (Passive Design) การสัมภาษณ์แบบกึ่งโครงสร้าง (Semi-structure interview) จะถูกใช้เป็นเครื่องมือเพื่อการตีความมุมมองความคิด และการรับรู้ของผู้เชี่ยวชาญเกี่ยวกับทางเลือกของการออกแบบแบบต่างๆ

สถาบันการศึกษา Welsh School of Architecture, Cardiff University

รายละเอียดการติดต่อ Warangkana Juangjandee (Juangjandeew@cardiff.ac.uk),
Dr. Vicki Stevenson (StevensonV@cardiff.ac.uk) (อาจารย์ที่ปรึกษา)

คำถามในการสัมภาษณ์

คำถามในการสัมภาษณ์แบ่งออกเป็นสองส่วน โดยการสัมภาษณ์จะใช้เวลาประมาณ 20- 30 นาที

<u>ส่วนที่ 1</u>

เกี่ยวกับบริบทขององค์ความรู้และประสบการณ์ของผู้เชี่ยวชาญในมุมมองเรื่องอาคารชุดพักอาศัยและการออกแบบอาคารโดยพึ่งพาระบบธรรมชาติ (Passive Design)

1.1 ทั่วไป

คุณเป็นผู้เชี่ยวชาญแขนงใด (สถาปนิก, วิศวกร, นักวิชาการ, อื่นๆ)

1.2 ประเด็นหรือปัญหาของคุณภาพสิ่งแวดล้อมภายในอาคาร

คุณคิดว่าอาคารชุดพักอาศัยมีปัญหาที่เกี่ยวกับสิ่งแวดล้อมภายในอาคารหรือไม่, ถ้ามีคืออะไร

คุณคิดว่าปัญหาดังกล่าวสามารถแก้ปัญหาได้ด้วยการออกแบบอาคารหรือไม่, ถ้าได้โปรดยกตัวอย่าง

1.3 การระบายอากาศแบบธรรมชาติ

คุณคิดว่าการระบายอากาศแบบธรรมชาติมีความสำคัญต่ออาคารที่ไม่พึ่งพาระบบเครื่องกลในการปรับอากาศหรือไม่

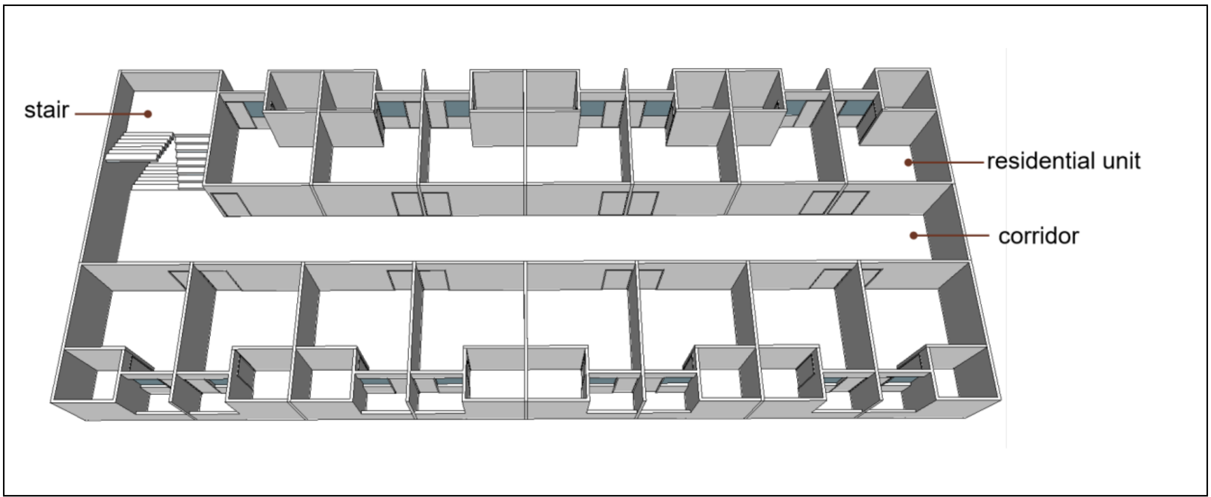
ถ้าตอบใช่- คุณคิดว่าการระบายอากาศแบบธรรมชาติให้ประโยชน์อย่างไร

ถ้าตอบไม่- คุณคิดว่าอะไรที่เป็นอุปสรรคต่อการใช้การระบายอากาศแบบธรรมชาติ

<u>ส่วนที่ 2</u> เกี่ยวกับกลยุทธ์และทางเลือกในการออกแบบเพื่อปรับปรุงการระบายอากาศตามธรรมชาติในอาคารชุดพักอาศัยโดยไม่พึ่งพาระบบเครื่องกลในการปรับอากาศ

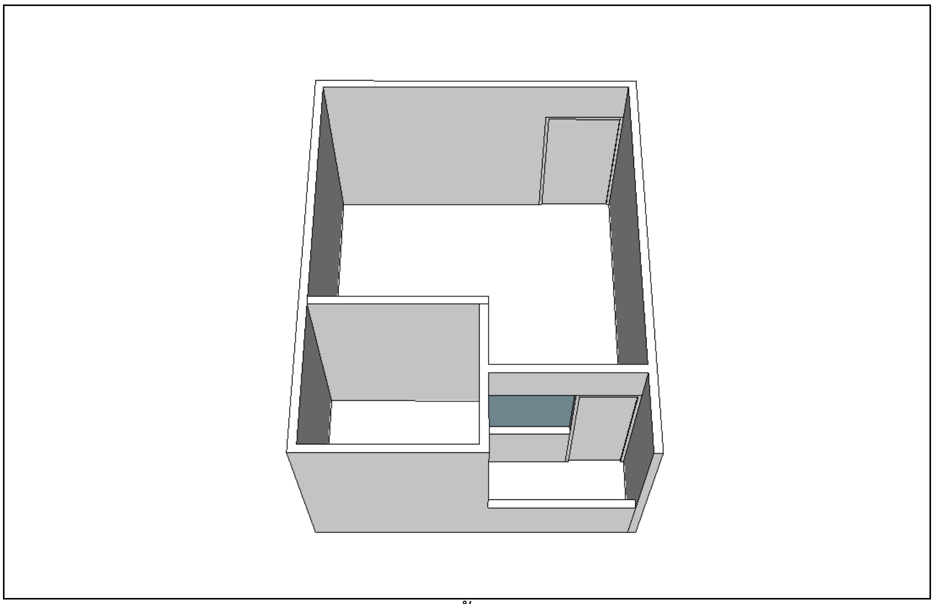
2.1 การเพิ่มการไหลเวียนของอากาศแบบธรรมชาติภายในอาคาร

2.1.1: คุณคิดว่าจากผังพื้นของอาคารชุดพักอาศัย(ภาพด้านล่าง) สามารถพัฒนาการไหลเวียนอากาศแบบธรรมชาติได้อย่างไรบ้าง โปรดวาด/อธิบาย



รูปภาพ: ผังพื้นรวมทั้งชั้นของอาคารพักอาศัยชุด

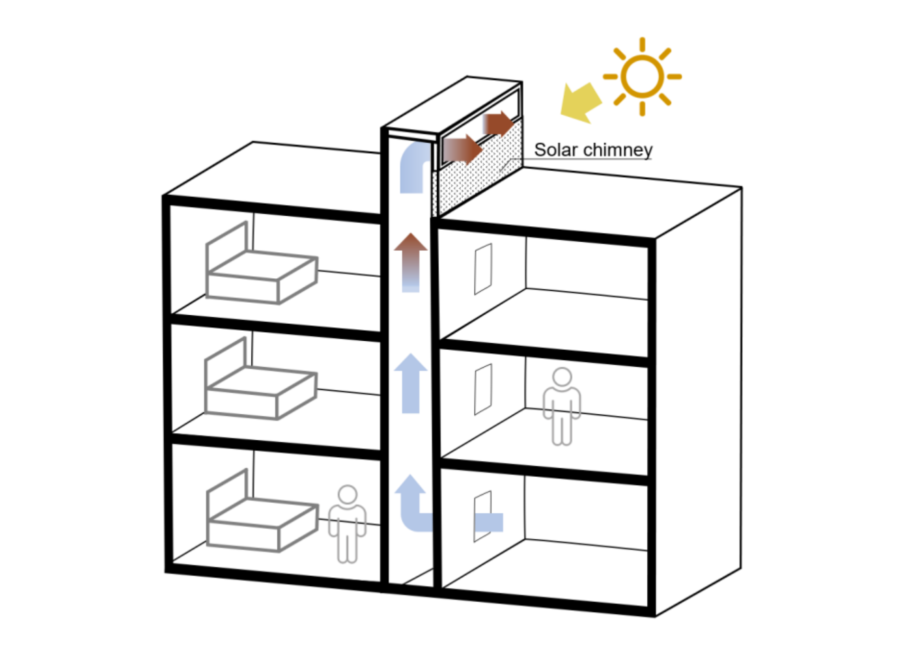
2.1.2: คุณคิดว่าจากผังพื้นของอาคารชุดพักอาศัย(ภาพด้านล่าง) สามารถพัฒนาการไหลเวียนอากาศแบบธรรมชาติได้อย่างไรบ้าง โปรดวาด/อธิบาย



รูปภาพ: ผังพื้นของห้องพักอาศัยชุด

2.2 ปล่องลมแสงอาทิตย์ (solar chimney)

2.2.1: คุณเห็นโอกาสและอุปสรรคใดบ้างในการผนวกปล่องลมแสงอาทิตย์เข้ากับอาคารชุดพักอาศัย ที่สืบเนื่องกับประเด็นเรื่องการระบายอากาศแบบธรรมชาติ, การออกแบบอาคาร, พลังงาน และการก่อสร้าง



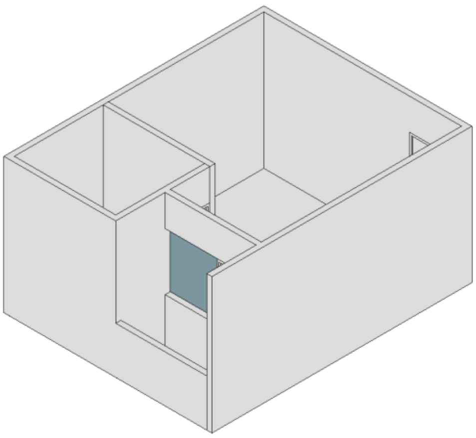
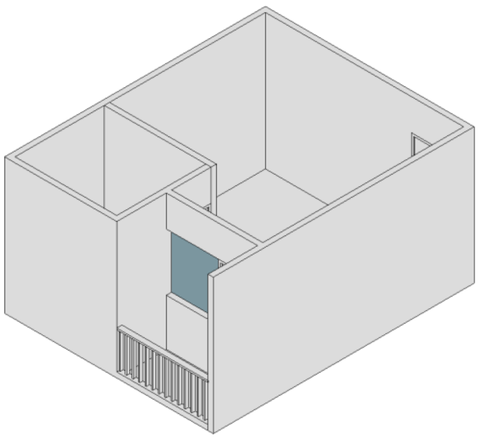
รูปภาพ: ปล่องลมแสงอาทิตย์ผนวกเข้ากับอาคารพักอาศัยชุด

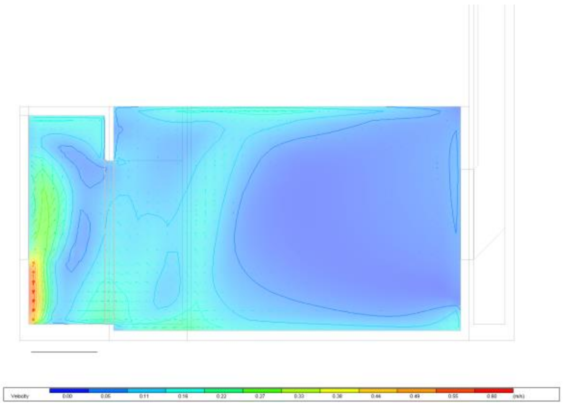
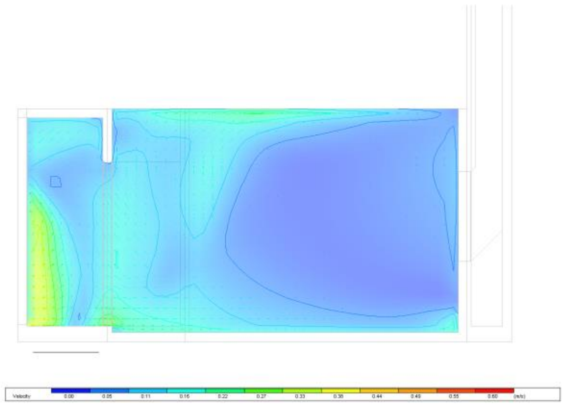
2.2.2: หากมีอุปสรรค คุณมีความเห็นว่ามีระบบอะไรเพิ่มเติมที่สามารถส่งเสริมศักยภาพของปล่องลมแสงอาทิตย์ในประเด็นที่เกี่ยวกับการระบายอากาศตามธรรมชาติ, การออกแบบอาคาร, พลังงาน และการก่อสร้าง

2.3 ความคิดเห็นของผู้เชี่ยวชาญเกี่ยวกับทางเลือกของการออกแบบเพื่อการพัฒนาคุณภาพสิ่งแวดล้อมภายในอาคารโดยกลยุทธ์การออกแบบอาคารโดยพึ่งพาระบบธรรมชาติ (Passive Design)

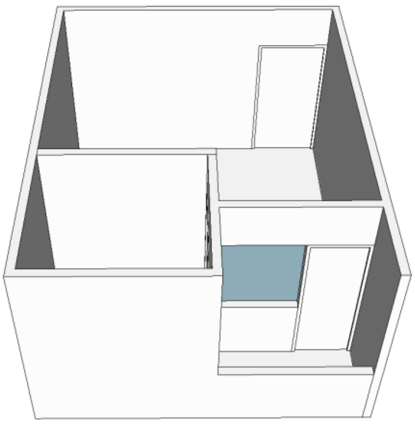
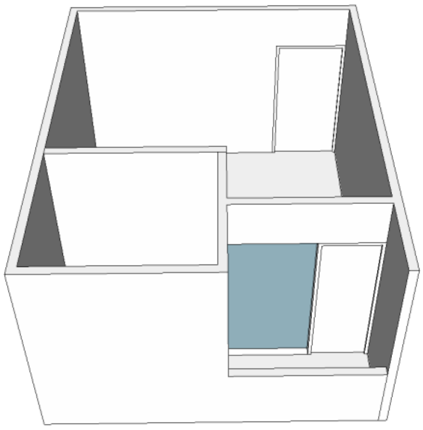
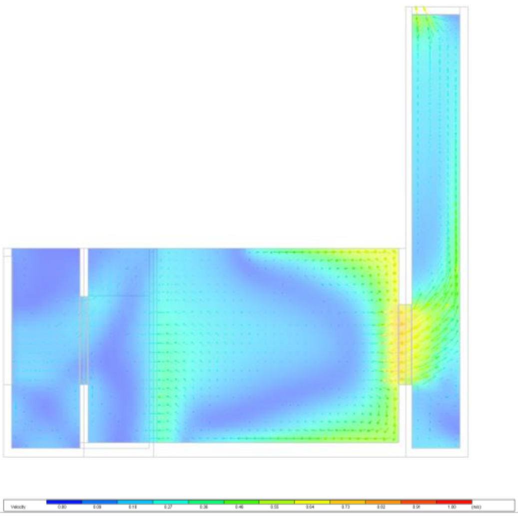
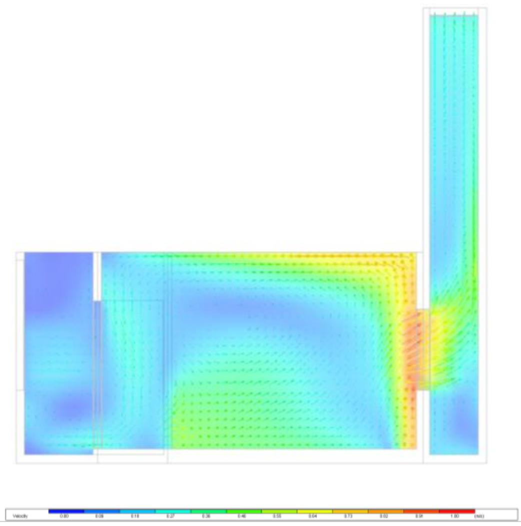
กรุณาแสดงความเห็นเกี่ยวกับรูปต่อไปนี้ในประเด็นเรื่องศักยภาพการระบายอากาศแบบธรรมชาติในอาคารที่ไม่พึ่งพาการระบบเครื่องกลในการปรับอากาศ

2.3.1: ระเบียงอาคาร

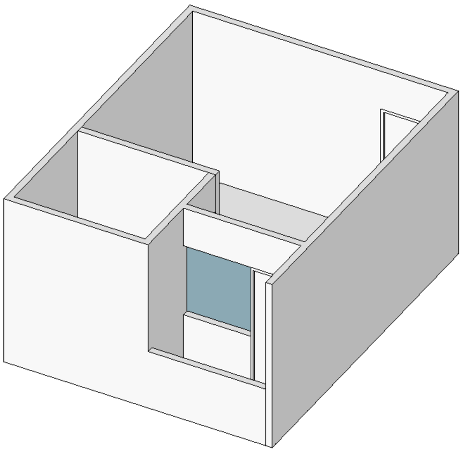
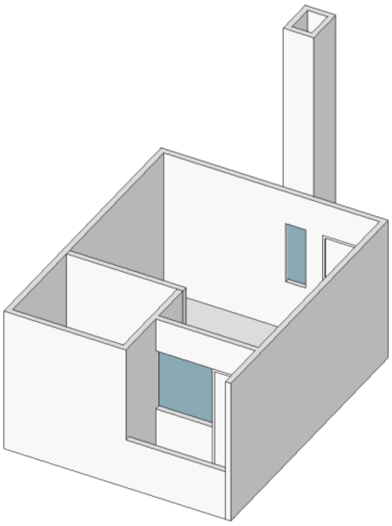
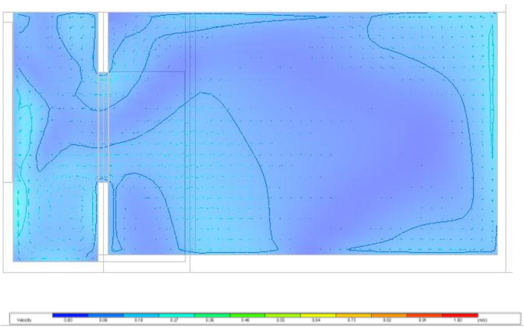
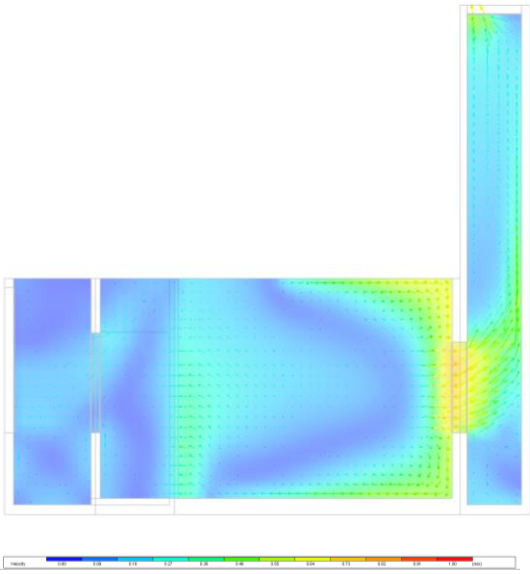
ก) ห้องอาคารชุดพักอาศัยซึ่งมีระเบียงแบบปิดทึบ	ข) ห้องอาคารชุดพักอาศัยซึ่งมีระเบียงแบบโปร่ง
	
ภาพจำลองสามมิติ	ภาพจำลองสามมิติ

 ภาพจำลองผล CFD	 ภาพจำลองผล CFD

2.3.2: ขนาดของช่องเปิด

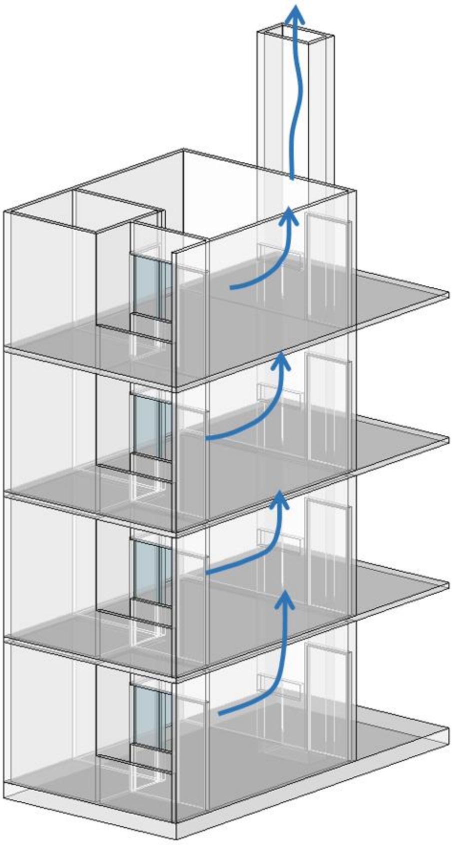
ก) ช่องเปิดขนาด 1.0 x1.1 ม.	ข) ช่องเปิดขนาด 1.0 x 2.0 ม.
 ภาพจำลองสามมิติ	 ภาพจำลองสามมิติ
 ภาพจำลองผล CFD	 ภาพจำลองผล CFD

2.3.3: ห้องที่ไม่มีปล่องลมแสงอาทิตย์เทียบกับห้องที่มีปล่องลมแสงอาทิตย์

ก) ห้องที่ไม่มีปล่องลมแสงอาทิตย์	ข) ห้องที่มีปล่องลมแสงอาทิตย์
 ภาพจำลองสามมิติ	 ภาพจำลองสามมิติ
 ภาพจำลองผล CFD	 ภาพจำลองผล CFD

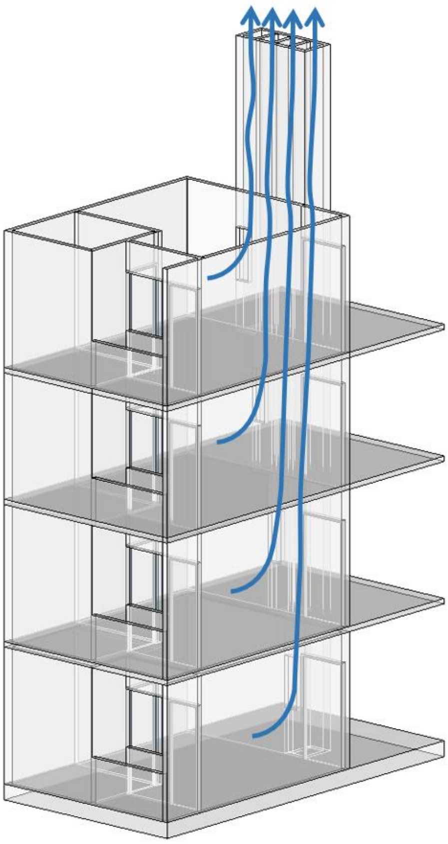
2.3.4: การออกแบบปล่องลมแสงอาทิตย์

ก) หนึ่งปล่องลมแสงอาทิตย์เชื่อมต่อกับหลายห้อง



ภาพจำลองสามมิติ

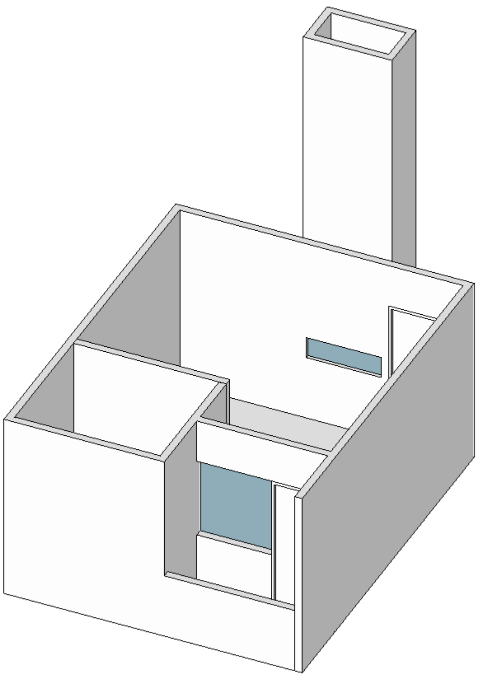
ข) หนึ่งปล่องลมแสงอาทิตย์เชื่อมต่อหนึ่งห้อง



ภาพจำลองสามมิติ

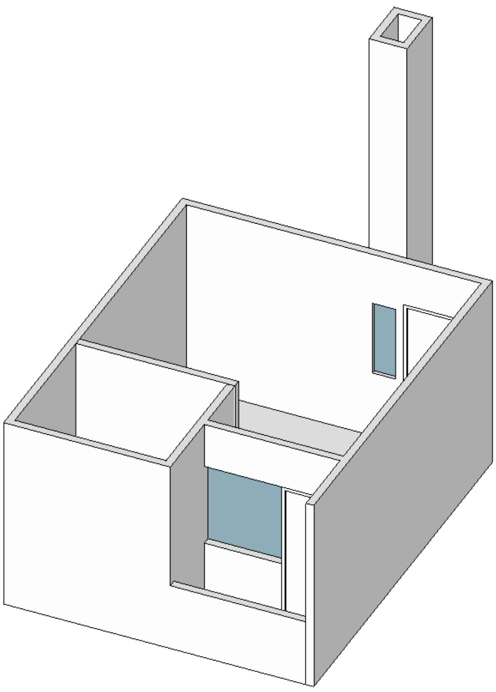
2.3.5: รูปแบบของช่องเปิดที่เชื่อมต่อกับปล่องลมแสงอาทิตย์

ก) ช่องเปิดแนวนอน

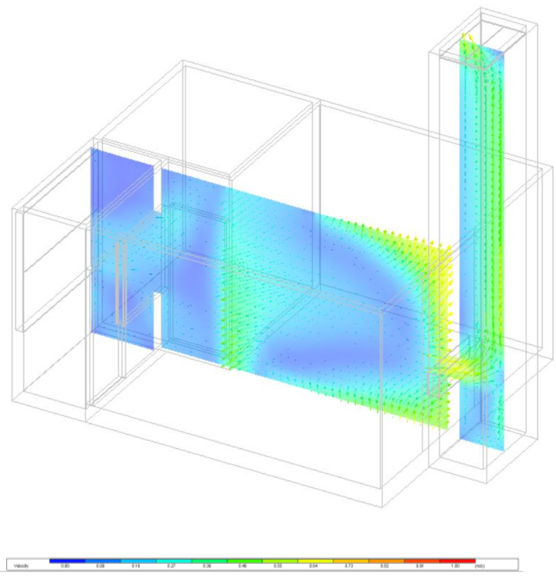
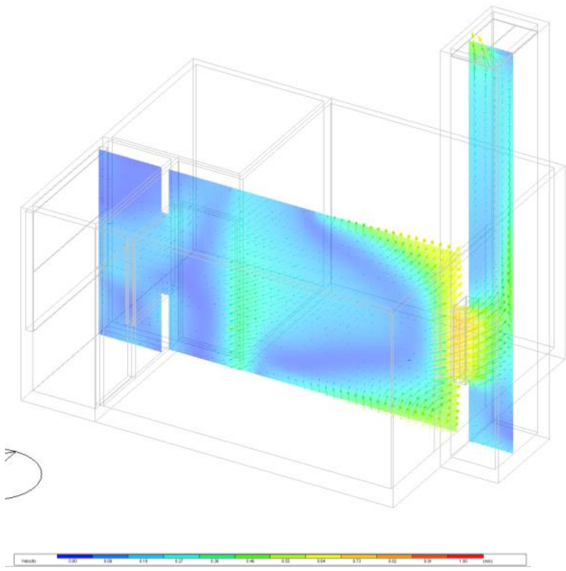
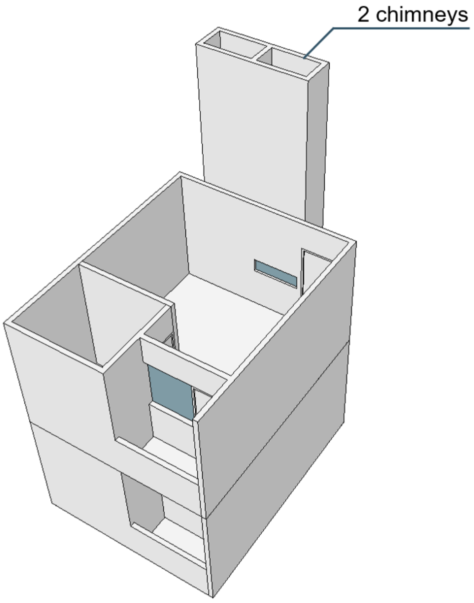
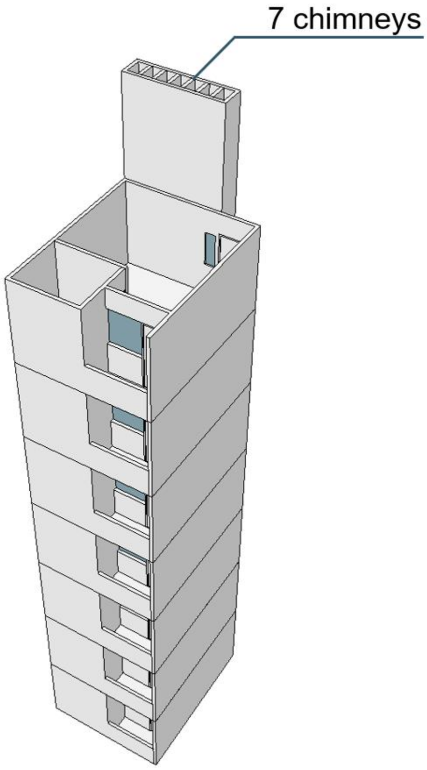


ภาพจำลองสามมิติ

ข) ช่องเปิดแนวตั้ง



ภาพจำลองสามมิติ

 ภาพจำลองผล CFD	 ภาพจำลองผล CFD
 ภาพแสดง: ตัวอย่างการออกแบบปล่องลมแสงอาทิตย์ที่เชื่อมต่อหนึ่งปล่องต่อหนึ่งห้องสำหรับห้องที่มีช่องเปิดแบบแนวนอนสามารถออกแบบได้ 2 ชั้น	 ภาพแสดง: ตัวอย่างการออกแบบปล่องลมแสงอาทิตย์ที่เชื่อมต่อหนึ่งปล่องต่อหนึ่งห้องสำหรับห้องที่มีช่องเปิดแบบแนวตั้งสามารถออกแบบได้ 7 ชั้น