Investigation of Thermal Comfort and Improvement Strategies for Multi-functional Transitional Spaces in Public Buildings

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ABSTRACT

Transitional spaces have been widely applied in building designs nowadays, which are present in the form of atria, lobbies, corridors and covered streets. As they have become common features of buildings, they may account for 10 to 40% of the total volume in different types of buildings.

However, thermal discomfort has been revealed in such spaces of several newly constructed buildings, where there are still no recommended acceptable comfort range and thermal comfort prediction methods for transitional spaces. This research aims to investigate environmental performance and adaptive comfort of transitional spaces in order to achieve acceptable thermal comfort level by identifying the thermal comfort ranges, people's adaptive behaviours and means to improve thermal comfort. Three public buildings in Cardiff were selected as case studies for the research. They were the National Assembly for Wales Senedd, the Hadyn Ellis Building and the Royal Welsh College of Music and Drama. The whole research consists of two major work stages – the field studies and computational analysis. The field studies included on-site questionnaire surveys and physical measurements; and the computational analysis was conducted by coupling software techniques of CFD modelling and HTB2.

The field studies were carried out in summer and winter period where the total responses from the questionnaire surveys were 736 and 580 for these buildings respectively. It is concluded from the research that people have adaptability to their thermal environment., based on the strong correlations between the clothing value and indoor operative temperature, and that the majority of people (nearly 80%) opted for self-adaptive actions to overcome uncomfortable situation. With the large thermal comfort dead bands identified, the research work also concluded that a fine control of the indoor temperature to maintain an acceptable comfort level within building transitional spaces is not necessary. Correlation analysis also suggested that PMV model is not accurate in thermal environmental prediction in building transitional spaces.

The computational analysis further evaluated the impacts of different system setups on the thermal comfort within the transitional spaces of the selected surveyed buildings under extended climatic scenarios. The study confirms that passive design such as natural ventilation is helpful in improving the thermal environment but under extreme weather conditions, active system shall be operated at the same time. By just operating the underfloor radiant system is good enough to maintain an acceptable thermal comfort within the building transitional spaces during warm season. However, in order to have effective control of thermal environment withing building transitional spaces, both the underfloor radiant system and underfloor air distribution system shall be designed and operated. The findings of this research could help the decision-makers and architects to improve thermal performance of both existing and future designs of indoor transitional spaces.

ACKNOWLEDGEMENTS

It is definitely not an easy process to get this thesis submitted. From the very beginning of the PhD where I did not have a solid idea of how to construct the analytic framework and how far I was from the end of "tunnel". Especially when I conducted the PhD as a part-time student while having a full-time work as an engineering consultant, it made the hard process even harder. Without the supports from my friends, parents, tutors and supervisors, I would not have made this happen.

Lord Jesus Christ, who has given me wisdom, opportunities of meeting all of my PhD supporters and power to help me through all the difficult times, is the very first one I would like to thank to.

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Chapter 1. INTRODUCTION

1.1 Background

Transitional spaces have been widely applied in building designs. They may account for 10 to 40% of total volume in different types of buildings. It is undoubted that there are a number of advantages of the incorporating transitional spaces into building developments, including introduction of natural daylight into interior spaces, creation of spaces for social activities and cultural connections and increase the market value of the building. However, maintaining an acceptable level of thermal comfort for transitional spaces poses challenges to building designers and engineers. In addition, there is not in general a recommended acceptable comfort range for transitional spaces, nor are there specific thermal comfort prediction methods. Drawbacks of such spaces in different dimensions, including thermal discomfort, increase in operational energy and operational costs have been revealed by a number of researchers. This chapter gives a general background of building transitional spaces, and review of the associated issues and challenges of the development of such spaces, which leads to the formation of the research basis with a list of research questions and research aims and objectives.

1.1.1 Background of Transitional Spaces

In many different kinds of buildings, transitional spaces are integrated with the architectural design. These spaces are claimed as “unavoidable spaces in non-domestic buildings”, which may typically occupy between 10% - 40% of the total volume in different types of buildings

(Pitts and Saleh 2006). Transitional spaces are defined as the spaces located in-between outdoor and indoor environments, which provide both a buffer space and physical link (Pitts and Saleh 2007). For transitional spaces, which serve as ‘environmental bridges’, connection between the interior and exterior environments and relaxation spaces are provided for the occupants to enjoy the surroundings and to experience the dynamic effects of the external climatic changes (Taleghani et al. 2014). People within the transitional spaces can also have the feeling of outdoor space and natural environment whilst they can enjoy the indoor air quality (Chu et al. 2017). Nevertheless, negative impacts due to extreme weather conditions may also be avoided as such spaces act as a buffer (Zhang et al. 2017).

From an architectural aspect, transitional spaces can be physically connected to a building development or can be separated from it (Monterio and Alucci 2007). Different functions can be provided by transitional spaces, including seating area, circulation passage, entrance lobby, cafeteria and meeting places (Ilham 2006). It provides a platform for occupants to have their social life through a variety of social activities such as resting, working and gardening within a sheltered environment (Danielski et al. 2016). This kind of social interactions can lead to different benefits to individuals within the spaces including psychological wellbeing (Kawachi and Berkman 2001), sense of community (Dempsey 2006), and emotional safety and security (McMillan and Chavis 1986).

Transitional spaces can also be considered as a means to provide natural air and daylight (Reynolds 2002; Sharples and Lash 2007; Aldawoud and Clark 2008; Yang et al. 2012), from which they have positive impacts on the indoor thermal and visual comfort (Baker and Steemers 2000; Khan et al. 2008). Typical forms of transitional spaces may be found fully or partially enclosed, and they may be top lit, side lit or a combination of both (Hussain and Oosthuizen 2012). For buildings in high latitude regions, transitional spaces can bring the benefits, particularly during cold seasons, by providing an environmentally controlled space with natural ventilation and useful heat gain from solar radiation (Ahmed 2013). They may also induce ventilating flow by providing a stack pressure difference between high level and low level in which buoyancy can accumulate (Acred and Hunt 2014). In hot climates, transitional spaces play an important role by providing buildings with cooling effect as they enhance natural ventilation (Al-Hemiddi and Megren Al-Saud 2001; Cantón et al. 2014; Kubota et al. 2017). Due to the capability to control solar radiation and ventilation, buildings with transitional spaces may be treated as a microclimate modifier (Hosseini et al. 2019).

1.1.2 Significance of Development of Transitional Spaces

Transitional spaces may be considered as the core of building developments as they are becoming increasingly popular (Chu et al. 2017). They are incorporated into large modern buildings more frequently than ever before as a feature of passive design (Moosavi et al. 2015), regardless of cultural and climatic conditions (Saxon 1983). Especially in the form of atrium, which have a long architectural tradition (James et al. 2009), has become a common feature for tall buildings (Wang et al. 2014). The driver for incorporating transitional spaces into building developments as a feature of technology is found to be more on an aesthetic consideration (Pino 2005). As presented in the Figure 1-1 below, it is found that the use of atrium has become popular in Asia (Wang et al. 2014).

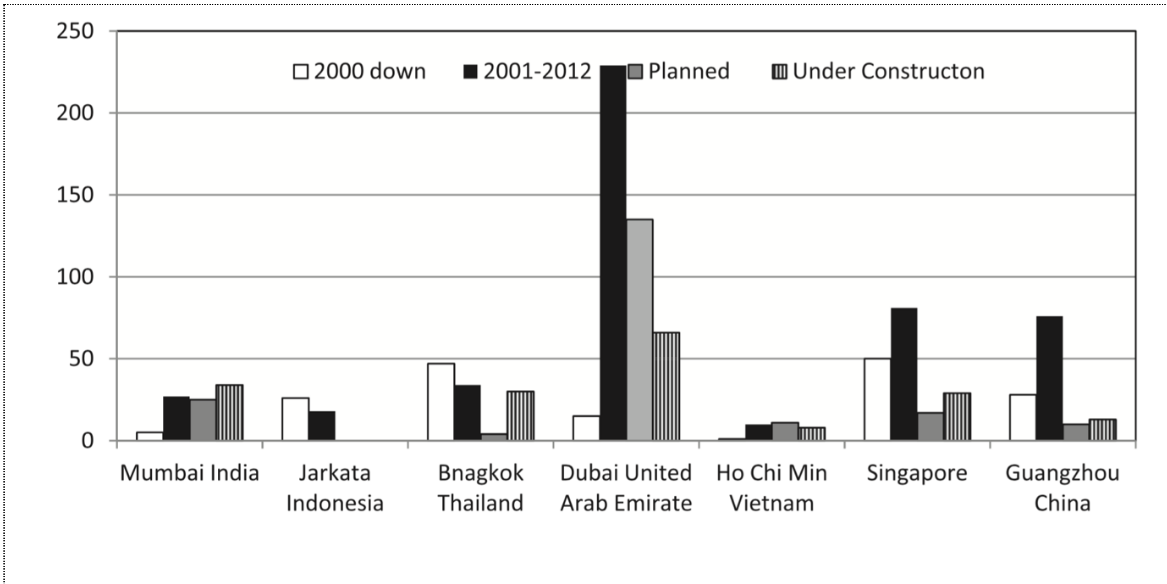
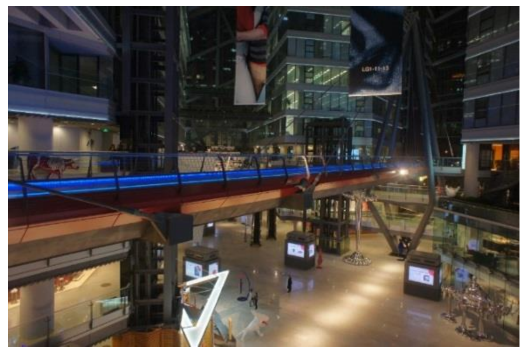
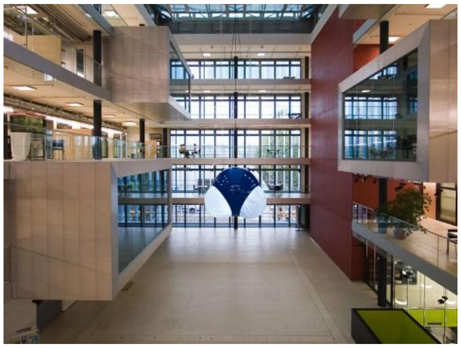


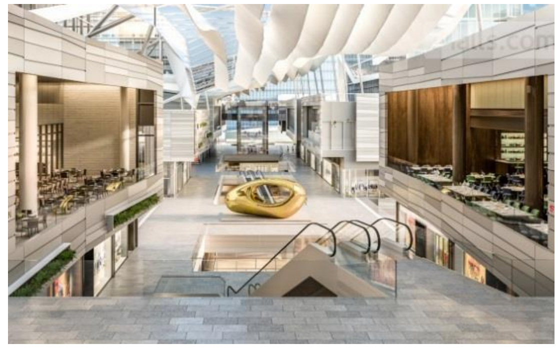
Figure 1-1 Statistics of Notable large commercial buildings with large atrium (Source: http://www.emporis.com/buildings, 2013)

Pan et al. suggested that more and more high-glazed atrium-type spaces are designed for modern high-rises (Pan et al. 2010a). Moosavi et al. supplemented that the glazed structure of atrium provides impressive aesthetic space, allowing daylight to penetrate through into the indoor spaces (Moosavi et al. 2014). Apart from increasing the socialisation and interactions of the building occupants, atrium can also enhance the psychological and physiological effects of its occupants and increase the market values of buildings (Laouadi et al. 2003). Figure 1-2 below illustrates some of the recently developed modern buildings with atrium spaces, from which it can be seen that the atrium space can beautifully connect to its adjacent indoor spaces, providing a social space and daylight penetration for the indoor zones.

 Hysan Place, Hong Kong, 2012	 Beijing Parkview Green, Beijing, 2012
 Shanghai Tower, Shanghai, 2014	 Starlight Place, Chongqing, 2011



Forum Chriesbach, Zurich, 2006



Brickell City Centre, Miami, 2016

Figure 1-2 Examples of Transitional Spaces in Modern Buildings

Transitional spaces have become common in commercial and service buildings such as shopping centres and institutional buildings all over the world (Danielski et al. 2016). As it is undeniable that transitional spaces are appealing to architects and building occupants because of its advantages brought to building developments and their occupants, the development of transitional spaces are expected to be continued in modern architecture, in particular, to large-scale buildings (Hung 2003). As building occupants are now more demanding on the building comfort and socialisation, such spaces will play a more important role in built environment.

1.2 Thermal Comfort Issues of Existing Transitional Spaces

The previous sections have proven the significance and the escalating trend of transitional spaces developments in the building industry. In addition, it has been an interesting and fruitful topic about the impact of transitional spaces on the building thermal comfort (Hou and Tweed 2014). In spite of these facts, there are quite a number of issues revealed by previous research in existing building transitional spaces.

At the early design stage, transitional spaces can be easily designed with good visual impacts by providing the brightness and openness (Wang et al. 2014). However, thermal comfort issues of transitional spaces are often overlooked which may lead to high life time costs for operating building systems (Ahmad and Rasdi 2000). Although transitional spaces do not generally require a fine control of temperature or have comfort limits when compared to indoor spaces, maintaining an acceptable thermal comfort for such spaces is still a challenge to building designers (Pitts and Saleh 2007). Thermal comfort is an important topic for building developments because people may complain, or even may refuse to stay or work in an environment that their thermal comfort cannot be achieved (ASHRAE 2013; Wyon and Wargocki 2013). Moreover, improving comfort within transitional spaces is important for active businesses and quality of life (Raja and Virk 2001). In fact, there have been growing interests on thermal comfort and acceptable environment in the twenty-first century research and society (Wyon and Wargocki 2013).

Due to the interaction of heat and air flow, the ventilation inside the spaces is hardly predicted (Acred and Hunt 2013). Recent research has revealed that glazed façades lead to a strong interaction between external environment and indoor space, and thermal discomfort becomes a major issue (Abdullah et al. 2009; Hussain et al. 2012; Wang et al. 2014; Liu et al. 2018a). This may result in complaints from the building occupants.

As the interaction of transitional spaces with the external conditions is strong and the glazed envelope would lead to high solar radiation heat gain and thus significant buoyancy, considerable thermal stratification becomes an issue which is hard to manage (Abdullah et al. 2009). Similar problems were identified by Hussain et al. that high temperature regions and thermal stratification, which lead to thermal discomfort issue, are the unpleasant results of transitional spaces (Hussain et al. 2012). Research carried out by Wang et al. revealed even more serious problems discovered in a case building called Guangzhou International Textile City (GITC) that is located in Guangzhou, China. Due to the thermal discomfort problems, especially over-heating in summer time, the building received complaints from over three-quarters of the tenants of the building (Wang et al. 2014). Unfavourable conditions can be generated by all these thermal problems which may result in considerable discomfort for the building occupants (Moosavi et al. 2015).

Moreover, there is still a lack of research evidence relating to the thermal environment of transitional spaces (Monterio and Alucci 2007; Hui and Jiang 2014; Rupp et al. 2015). The majority of previous research on the comfort environment of dynamic states, including transitional type spaces, such as corridors and atria, were conducted in climatic chambers, with only a few of them being validated through fieldwork studies (Palma 2015). Most of them only considered the human thermal response to stable environment conditions (Liu et al. 2014). This may be the reason why transitional spaces are still not clearly addressed in the current comfort standards (Van Hoof 2008), and why there are no recommended acceptable indoor temperature ranges specified for thermal comfort in transitional spaces (Yu et al. 2015).

1.3 Research Questions

Based on the revealed issues of transitional spaces, the following questions have formed the basis of this research:

1. What comfort condition does a transitional space require?

2. Does a transitional space require a fine temperature control to maintain its acceptable thermal comfort?

3. Would the people in building transitional spaces adjust their clothing when the indoor air temperature and outdoor air temperature changes?

4. How do people in building transitional spaces react to overcome uncomfortable situations?

5. Is there any difference between preferred temperature and neutral temperature for people in cold climate?

6. Can thermal comfort situation be improved by just altering the passive designs such as windows / doors opening of a transitional space under extreme weather conditions?

7. How should a transitional space be properly designed to improve its environmental performance?

1.4 Hypothesis

The research hypothesis is that the range of thermal comfort of building transitional spaces falls in between that of the indoor environment and outdoor environment. Moreover, because the average time people spend within a building transitional space is much shorter than indoors and people have thermal adaptability to their thermal environment, the requirement for thermal comfort of building transitional spaces is less stringent than for the indoor spaces. Fanger's PMV model, which is widely adopted to predict the thermal environment in indoor spaces, will have less correlation with the actual people's thermal environment in transitional spaces than indoor spaces because the model was developed specifically for office type of environment which is well controlled. Knowing that there are a variety of factors that affect thermal comfort, another hypothesis of this research is that questionnaire surveying could help to identify the acceptable range of thermal comfort within building transitional spaces and the relationships between environmental factors and thermal comfort; and computational simulation could help generate ideas of potential impacts of building / system designs on thermal environment.

1.5 Aim, Objectives and Scope

1.5.1 Research Aim

The aim of this research is to investigate thermal environmental performance and adaptive comfort of transitional spaces in order to achieve acceptable thermal comfort level by identifying the thermal comfort ranges, people's adaptive behaviours and means to improve thermal comfort.

1.5.2 Research Objectives and Scope

To achieve the research aim, the research topic has been established as "Optimised Model for the Thermal Environment of Transitional Spaces", where the followings are the list of research objectives:

1. To establish the current knowledge about thermal comfort of transitional spaces in terms of modelling techniques and study scenarios;

2. To establish the methodologies to evaluate the thermal environmental performance of transitional spaces;

3. To select three representative existing buildings with transitional spaces for detailed study;

4. To develop structured questionnaire surveys to collect subjective responses from the occupants of the selected case buildings;

5. To carry out field studies which include questionnaire surveys and physical measurements in the selected case buildings;

6. To identify the acceptable comfort ranges and adaptive comfort behaviours within building transitional spaces

7. To set up computational models and identify improvement strategies for transitional spaces to achieve acceptable thermal environmental performance of building transitional spaces.

In order to accomplish the aim and objectives of the research, this thesis is composed of six chapters. Chapter 2 and Chapter 3 are the literature review and research methodology respectively which are aimed to establish the basis for the whole research by developing an understanding of the current knowledge and research status of thermal comfort in building transitional spaces and by establish a robust methodology to conduct the research. Chapter 4 and Chapter 5 are the core chapters that present the research findings of the field studies and computational simulation respectively. The last Chapter is the conclusion session for the whole research which summarises the key accomplishment of the research aim and objectives and recommendations for further research.

Chapter 2. LITERATURE REVIEW

2.1 Introduction

From Chapter 1, it is known the importance of transitional spaces in nowadays building developments, where about 10% to 40% of total volume of different types of buildings is occupied by transitional spaces (Pitts and Saleh 2007), and the revealed problems of the existing transitional spaces that are related to thermal discomfort and high energy consumption. This chapter is aimed to present the whole picture of previous research studies of transitional spaces in relation to the architectural developments, thermal comfort and energy performance, in order to establish the fundamentals and better understanding of transitional spaces. This includes the current and future development trends, critical theories, relationships among different important factors of such spaces and existing cases around the world. All these will provide the basis for the research hypothesis and justifications for the methodologies to be undertaken in this research.

This chapter involves four main sections – the evolution of transitional spaces, the overview of architectural designs, the relationships among different factors that have influences on the performance of transitional spaces and performance evaluation methods of transitional spaces. The first section discovers the historical development of transitional spaces from the very beginning in 3000 BC to present days. This helps to review the changes of architectural designs and design rationale of transitional spaces throughout the decades. This leads to the other section which summarises different architectural forms of transitional spaces being adopted in the nowadays industry. After that, the third section reviews the relationships among the three main factors of transitional spaces, which include architectural form, energy performance and thermal comfort. The final section of the chapter covers the evaluation methods that are commonly-used to evaluate thermal comfort performance.

2.2 Evolution of Transitional Spaces

The development of transitional spaces can be traced back to climate sensitive and social use of a central courtyard in ancient design (Li 2007). This section summarises the review of the historical background of transitional spaces, including the development ideas and concepts and their changes in architectural forms and functional uses throughout the years. The whole history of the development of transitional spaces is divided into four periods –

- **3000 BC – 18th Century** – this is the era of idea development of transitional spaces in the forms of courtyard and central room, where some researchers called it as Antique Origins (Bednar 1986; Saxon 1994; Li 2007);
- **19th Century** – the use of steel and glass started to be significant components in architecture (Kim and Kim 2010);
- **20th Century** –new ideas and improvements, such as more focus on sociability, have been incorporated into the old design of transitional spaces;
- **Present** – the modern design concept has been introduced to enhance the aesthetics, economy and environmental conditions.

3000 BC – 18th Century

Transitional spaces have been used in building design for about 5000 years (Fathy 1986; Oliver 2003). The incorporation of transitional spaces in building originates from House of

Ur, Mesopotamia in 3000 BC, where it appeared as a form of courtyard in the building (Bednar 1986). In Figure 2-1 below, the section and plan of the courtyard and its building are illustrated. At that time, the courtyard design in building was claimed as an important innovation (Franco 2009). The original ideas of the courtyard design, as illustrated in Figure 2-2, were to serve as a climate modified and central social function space, where some of the courtyards were designed as an air well to provide natural ventilation for the internal spaces (Ahmad and Rasdi 2000).

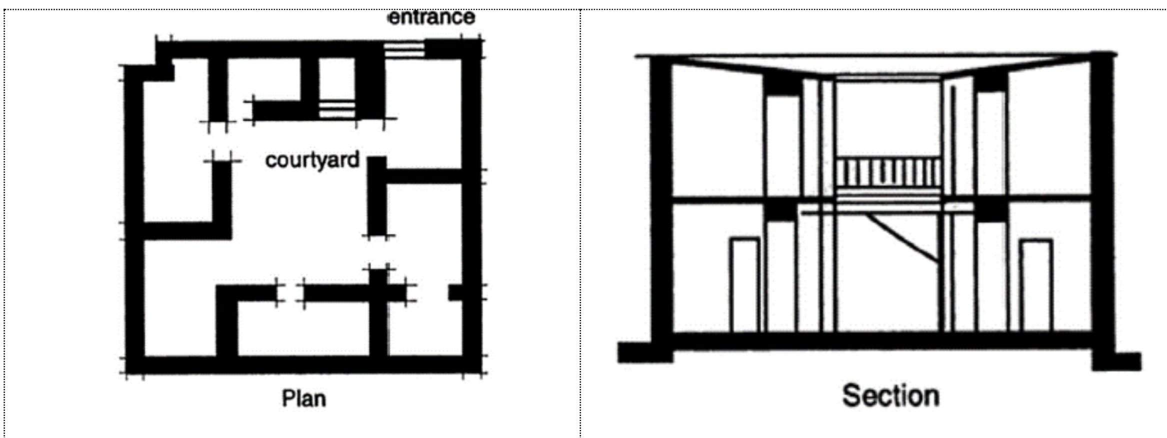


Figure 2-1 Section and Plan of Courtyard in House of Ur, Mesopotamia (Ahmad and Rasdi 2000)

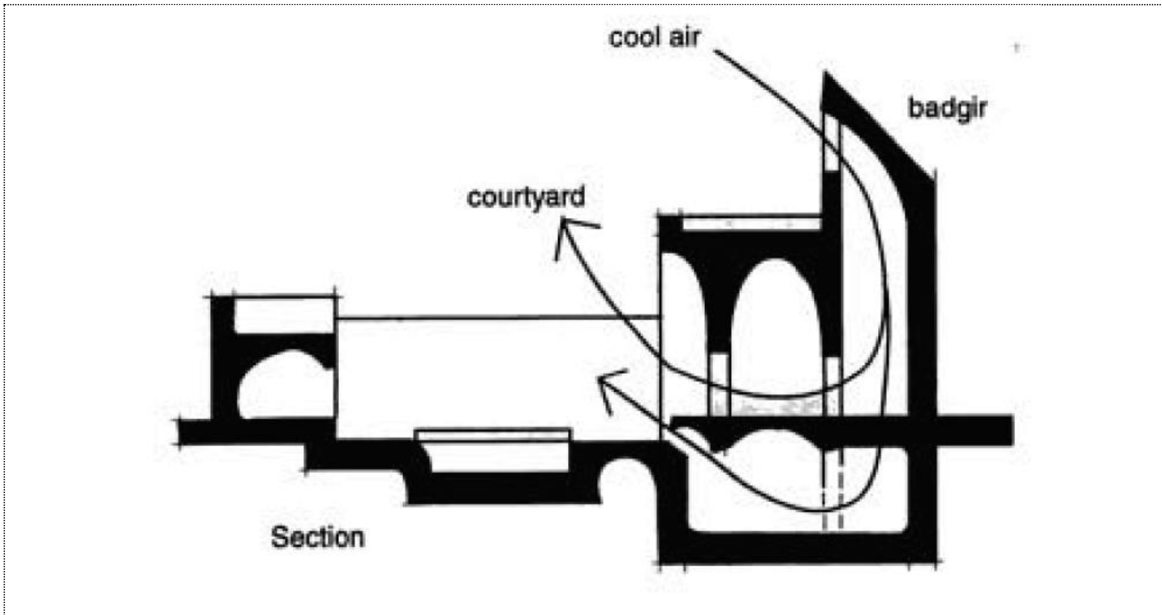
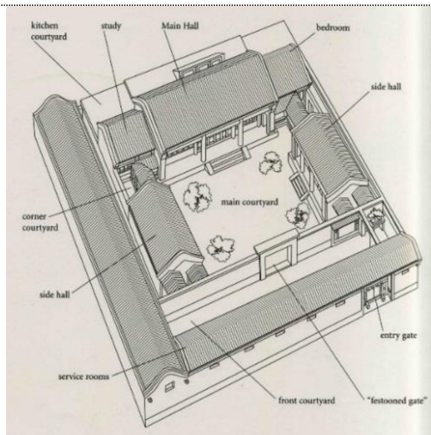


Figure 2-2 Section of Persian House Showing the Use of Courtyard as an Air-well (Ahmad and Rasdi 2000)

In China, courtyard house, named Siheyuan, has also been a common core element of dwelling between 11th and 10th century BC (Knapp 2000). The courtyard house found at that period of time is similar to the design of House of Ur. Mesopotamia. The similar elements include north-south axis, quadrangular layout, and the central open spaces (Knapp 2000).

Later in 14th century (Ming Dynasty), the layout of courtyard houses were found to be more optimised (Li 2009). Being in the centre of the house, they provide natural, comfortable, private open space for family members to have gathering (Li 2009). Some of the courtyards may also be decorated with plants, rocks and flowers, which form an enjoyable space for the house occupants. Figure 2-3 shows one of the examples of the traditional courtyard houses in China – Mei Lanfang (Susan 2007), where it demonstrates how the courtyards can act as the transitional spaces to connect different compartments of the house and the entrance. Similar ideas were later found in Palazzo della Cancelleria (1513) and Palazzo Farnese in Rome (1541). The central courtyards served as civic squares and social space for staff and the general public (Ahmad and Rasdi 2000). Examples are shown in Figure 2-4.



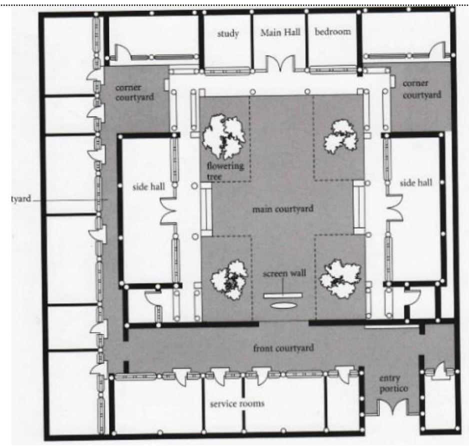
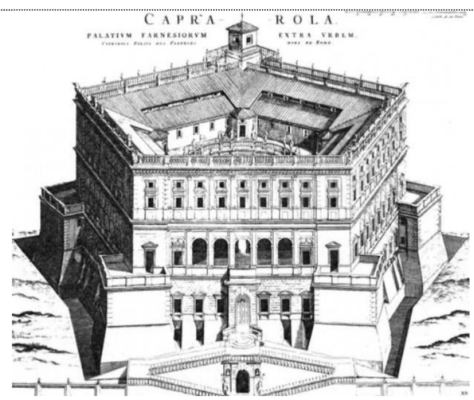


Figure 2-3 Examplar of Traditional Chinese Courtyard House – Mei Lanfang's Siheyuan

Palazzo della Cancelleria, Rome



Palazzo Farnese, Rome

Figure 2-4 Examplar of Traditional Courtyards in Rome

Then, later in the 18th century, other central courtyards were found in ancient Roman and Greek houses (Moosavi et al. 2014), where the term atrium originates from (Hung 2003). They formed the central room of the building, connecting to all the other chambers (James et al. 2009). As shown in Figure 2-5, the central opening (the courtyard) was designed to allow daylight and air to enter the building (James et al. 2009). Most of this kind of houses were single-storey building although some had two stories and the typical courtyard was open to the sky, which served as a catch basin to collect and store rainwater (Bensalem 1991). This architectural feature also enables evaporative cooling for the building (James et al. 2009).

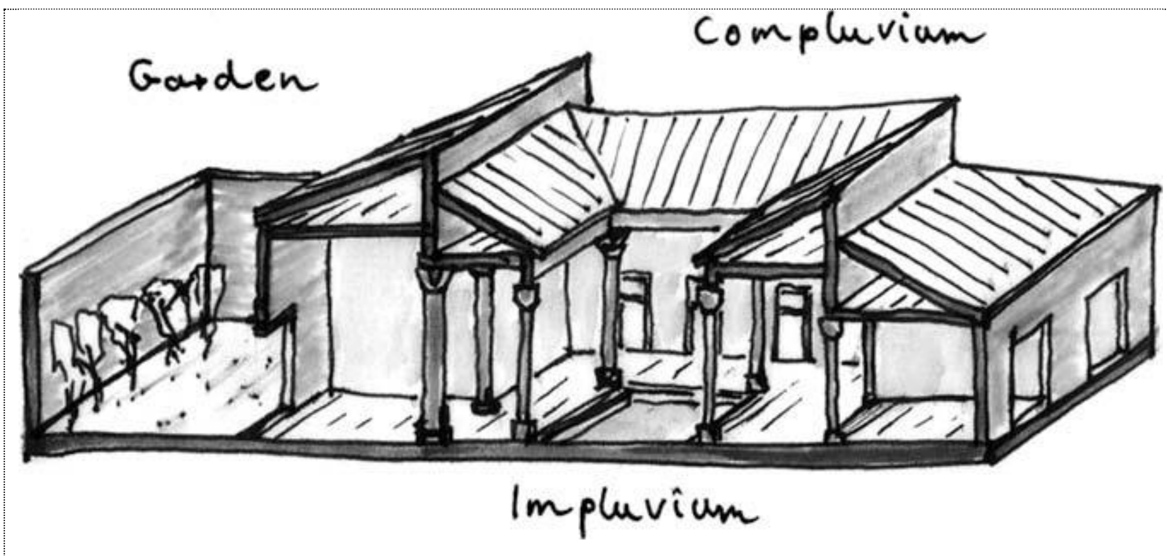


Figure 2-5 Roman Atrium House (James et al. 2009)

19th Century

Atrium buildings have been increasingly popular since the industrial revolution (Saxon 1983). As the technology of manufacturing iron and glass became more developed in the 19th century, a new form of courtyard, which is now known as atrium, was created (Kim and Kim 2010). At that time, designers and builders were excited in demonstrating their skills and ability in creating structure with glass and iron, which has created the basis for the atrium development (Tabesh and Sertyesilisik 2015).

Beginning from the development of Galleria in Milan, which was a popular development in Europe in 1867 in Italy, more buildings such as public buildings, hotels, shops and offices, have adopted the design of atrium to serve as lobbies, circulation centers or even big social spaces (Tabesh and Sertyesilisik 2015). More examples can be found in Attingham Park in Shropshire (1806) designed by John Nash, Westminster Arcade in Providence (1828) designed by Warren and Buklin and Reform Club in London (1837) designed by Charles Barry (Saxon 1983). The concept of atrium was once uncommon (Moosavi et al. 2014), because it was extremely costly to build such an enormous interior space in buildings, which reduced the total area of useful spaces (Saxon 1983).

Westminster Arcade, Providence

The Reform Club, London

Figure 2-6 Examplars of Atrium Developments in early 19th century

Later in late 19th century, John Root made use of atrium design to create a grand lobby space for the 11-storey The Rookery Building in Chicago (1885), where memorable views and viewpoints were revealed with the circulation stairs (Saxon 1983). Few years later in 1893, a newer idea was created by George Wyman in atrium design of Bradbury Building, which was described as "circulation into dramatic prominence" (Saxon 1983). The atrium environment was surrounded with open iron elevators cages and stair-towers in the 4-storey space (Saxon 1983). However, towards the end of 19th century, such transitional spaces designs, due to the changes of architectural styles and forms, began to be less popular (Briggs 1989).

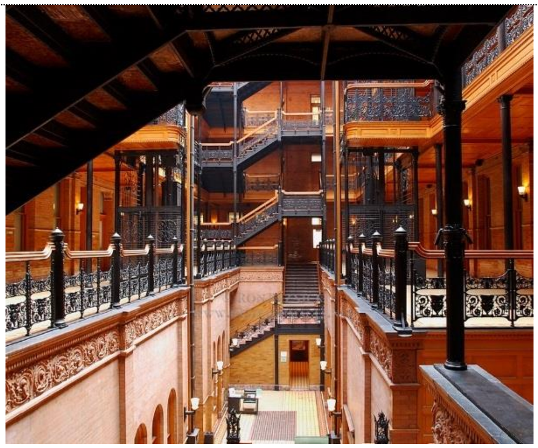
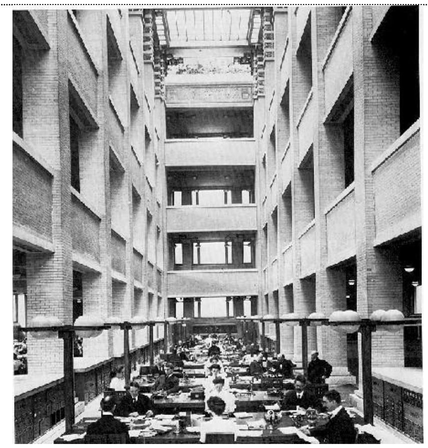
	
Bradbury Building, Los Angeles	*Rookery Building, Chicago*

Figure 2-7 Examplars of Atrium Developments in late 19th century

20th Century

In the early 20th century, on the basis of earlier European experiences, the United States started using heavy masonry construction with iron, steel and glass to develop atrium buildings (Tabesh and Sertyesilisik 2015), which resurged the popularity of atrium designs (Briggs 1989). Examples include Larkin Building in Buffalo (1903), Johnson Wax Headquarters in Racine (1936) and Guggenheim Museum in New York (1959). Most of the atrium developed in this period of time were either square or rectangular in shape (Bednar 1986).



Johnson Wax Headquarters, Racine	Larkin Building, Buffalo

Figure 2-8 Examplars of Atrium Developments in early 20th century

Starting from the mid-20th century, apart from enhanced floor-to-floor flow within buildings, the socially stimulating environment has been more emphasized in atrium designs and its application has been extended to enclosed shopping malls (Saxon 1983), such as Southdale Centre in Minnesota (1956), Midtown Plaza in Rochester (1962), Rødovre Centrum in Copenhagen (1966), Ford Foundation Headquarters in New York (1968), Lyngby Storcenter in Lyngby (1973) and Bateson State Office Building (1981). As shown in Figure 2-9, the focus of the atrium space has been put on the social and public event, where there were greenery plants located in different locations of the space.

When it past the mid-20th century, atrium space in building was treated as the focal space which drew the attention from people (Tabesh and Sertyesilisik 2015). Besides, it can be found from these building exemplars that a new era of transitional space designs has started.

As illustrated in Figure 2-10, in addition to providing public space and meeting place and creating a corporate image, linkage between the city outside and indoor space can be found.

	
Deere & Company Corporate Headquarters	*Bateson State Office Building*

Figure 2-9 Examplars of Atrium Developments in mid-20th century

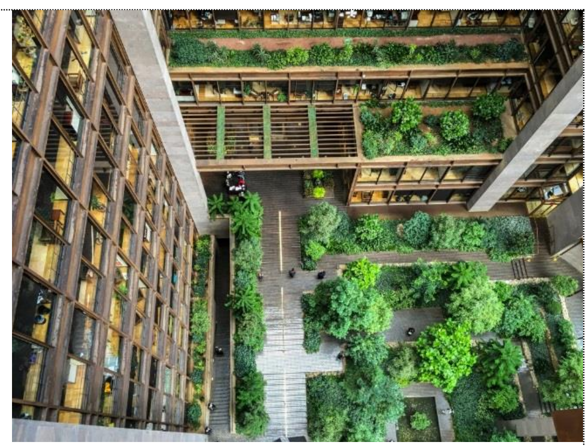
 

Figure 2-10 Ford Foundation Building, New York

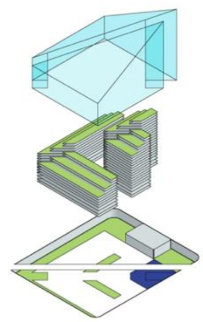
Until 1970s and early 1980s where energy crisis occurred, atrium, because of its environmental advantages on building, was considered as a new building element that can reduce building energy consumption (Ahmad and Rasdi 2000). Benefits on building energy such as passive heating and ventilation and cooling were brought by the atrium design by utilising the glazed façade feature and the openings of atrium (Abdullah et al. 2009).

Present

Over the past decades, because of the advanced technologies such as new materials including glazing and structure and computational modelling (Samant 2011), transitional spaces have been evolved into different types, serving different purposes in a building. Transitional spaces in the form of atrium have now become a dominant feature in built environments in different part of the world of different climates and culture (Samant 2011). These cover a variety of different forms, ranged from a balcony and a corridor to a courtyard or atrium (Taleghani et al. 2014). They can be attached or detached from a building; located at building peripheral or middle portion of a building connecting one end to the other (Hui and Jiang 2014).

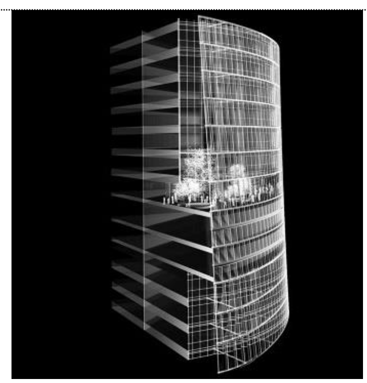
Not only transitional spaces can provide a more comfortable environment, by acting as a thermal buffer zone that reduces the thermal shock for occupants moving into and out of the spaces, for a building development (Pitts and Saleh 2007), they are also an aesthetic physical character and a potential means to save energy (Chun et al. 2004). Recent exemplar buildings with transitional spaces, as illustrated in Figure 2-11, demonstrate these features. In addition, they also show that transitional spaces are no longer necessarily mean “centroidal” and "interior" spaces. Parkview Green in Beijing (2012) has demonstrated the new idea of modern transitional spaces in the form of atrium, which provides strong linkage between different buildings themselves and with the urban climate. It is expected atrium design in commercial and service buildings, such as shopping malls and school buildings, will continue to be developed in various degrees and applied in modern architecture, especially in large-scale buildings (Danielski et al. 2016).

Beijing Parkview Green, 2012



Anatomy of Beijing Parkview Green

Shanghai Tower, 2015



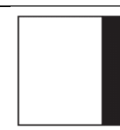
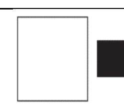
Anatomy of Shanghai Tower

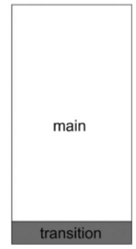
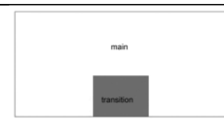
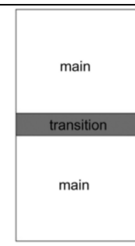
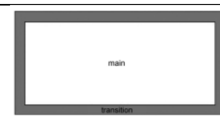
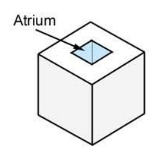
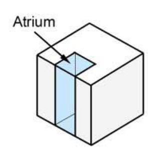
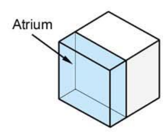
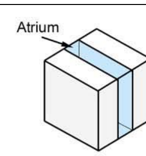
Figure 2-11 Recent Exemplar Buildings with Transitional Spaces in Present Century

2.3 Architectural Forms of Transitional Spaces

As the transitional spaces evolve, there are different geometric designs in nowadays building developments. These spaces can be attached or detached to a building (Monterio and Alucci 2007). Other than being "centroidal", they can be located in the building perimeter, connecting two ends of a building in a linear shape, or located at the building entrance as a foyer, etc. Table 2-1 below briefly summarizes different classifications of transitional spaces (Chun et al. 2004; Pitts and Saleh 2007) and that in the form of atrium (Hung 2003) from the recent researches. Depending on the locations of the transitional spaces in a building development, these spaces may provide natural ventilation and daylight by the connection of the internal area with the external one (Khan et al. 2008).

Table 2-1 Summary of Different Geometric Designs of Transitional Spaces

Author	Category	Configuration
Transitional Spaces		
Chun, Kwok & Tamura (Chun et al. 2004)	Type 1 – transitional spaces contained within a building (e.g. Hotel lobby, entry atrium)	
	Type 2 – transitional spaces attached or connected to a building (e.g. Balcony, porch, corridor, covered street or arcade)	
	Type 3 – transitional spaces unattached to a building (Pergolas, bus stations, pavilions)	

Pitts & Saleh (Pitts and Saleh 2007)	Type A – linear foyer space	
	Type B – foyer area set into the middle portion of the loner facade of a building	
	Type C – circulation corridor set across the shorter facade	
	Type D – external perimeter corridor running around the outside of a building	
Transitional Spaces in the Form of Atrium		
Hung (Hung 2003)	Type a – centralized	
	Type b – semi-enclosed	
	Type c – attached	
	Type d – linear	

In general, there are three broad types of transitional spaces, namely entrance zones, circulation zones, and longer-term occupancy zones (Pitts 2013). Entrance zones are normally the entrance areas and other spaces that have strong connections to the exterior environments. The activity level of occupants at entrance zones likely to be walking pace level and the time period of residence is likely to be short, typically 5 minutes. Circulation zones are typically the spaces where people move from one space to another within an interior environment. Examples include an open circulation area adjacent to a café and staircase, an entrance foyer of a library, a lift lobby circulation space; and a linking covered walkway between two buildings. The activity level of occupants at circulation zones likely to be slower walking pace or standing and average time spent in such zones is slightly longer, typically 5 – 10 minutes. Longer-term occupancy zones normally mean interior spaces that have functionality. Atria is one of the typical examples of such spaces. They are normally within an enclosed space with a glazed roof and/or often one or more glazed walls. The range of activity level of occupants within such spaces is wider than the other two spaces, but normally people have relatively low activity level, likely to be seating. The residence time of occupants in longer-term occupancy zones is likely to be longer, depending on the mode of use and the function of the space, typically 10-30 minutes.

2.4 Relationships among Architectural Form, Thermal Comfort and Energy Performance of Transitional Spaces

Knowing from the historical review that the major design rationales of building transitional spaces development are to provide thermal comfort and improve energy performance of the spaces, this section would review the relationships among the architectural form, thermal comfort and energy performance. By understanding the relationships between these factors, this would help to establish investigation directions of this research.

2.4.1 Impacts of Architectural Form on Thermal Comfort in Transitional Spaces

2.4.1.1 Overview

"*Transitional spaces are potentially and traditionally efficient ways to moderate indoor climate with the free sources available from nature*" – Taleghani et al. (Taleghani et al. 2014)

Architectural form of transitional spaces, in the form of courtyard, play an important role in controlling its thermal environments (Al-Naimi 1989; Abdulkareem 2016), as it provides desired shade, especially during summer period, for its spaces and surrounding rooms (Al-Naimi 1989). In addition, its orientation and materials are also the important factors that have impacts on the thermal and visual performance of the spaces (Poggi et al. 2014). Abdullah & Wang suggested that apart from the aesthetic effect, atrium, a type of transitional spaces, can also lead to different environmental implications, such as solar gain, daylight and thermal comfort, to its building spaces and adjacent spaces, including solar gain, daylight and thermal comfort (Abdullah and Wang 2012). These environmental conditions depend directly on the interaction between the atrium's construction materials, its architectural forms and the external weather conditions (Atif 1992).

2.4.1.2 Influencing Factors of Architectural Forms

Aldawoud's study identified the difference of thermal performance between square and rectangular atria, which is related to the climate, glazing type and atrium's architectural form (Aldawoud 2013). An effective architectural form of transitional spaces can help to reduce thermal shock and thus the energy loss for the buildings, especially the ones in extreme climatic conditions (Chun et al. 2004).

There are various researches conducted in the past years on the impacts of architectural form on the comfort level of transitional spaces. Their studies can be classified into the following three major aspects:

1. Ventilation
2. Daylight
3. Solar

Ventilation

Transitional spaces can be treated as an air channel that enhances convective airflow through and around the adjacent buildings, which forms, in the other words, a part of natural ventilation system (Khan et al. 2008).

Haw et al. conducted a research on a full-scale experimental building with a venturi-shaped wind-induced ventilation tower in Malaysia, from which they revealed that an air flow rate generated by a venturi-shaped roof tower can be approximately eight times greater than the normal cross-ventilation in a hot, humid climate. This was explained by the aerodynamic performance of the venturi-shaped roof which can produce the low pressure that is required to induction of fresh air from outdoor into building interiors (Haw et al. 2012).

Besides, the size of the transitional spaces is also the influencing factor for the ventilation performance of the spaces. Li et al. concluded from their research that the increase in atrium size for the square form would lead to the improvement in ventilation performance and thus cooling (Li et al. 2010). Taleghani et al. added that the size of courtyard have positive impact on the ventilation performance, which can be employed for natural ventilation (Taleghani et al. 2012).

When it comes to natural ventilation by the means of transitional spaces, Shi quantified the optimal settings of courtyard in terms of ventilation performance. From the research, investigation of the impact of architectural form of courtyard on natural ventilation was conducted by using CFD as an analytical tool, from which it was concluded that width-to-length ratio of 1.0, and north building height to south building height ratio of 1.2 – 1.4 are the optimal settings to achieve natural ventilation (Shi 2013).

Daylight

Transitional spaces provide daylight and passive solar gains (Baker and Steemers 2003) and there are many factors influencing the daylighting performance, where the main architectural factors include architectural shapes (both plan and cross-sectional), geometry properties, roof cover and surface properties of the materials (Aizlewood 1995; Sharples and Lash 2007; Samant 2011). The impacts of these factors of atrium on the daylight performance have been investigated by many researchers (Yunus et al. 2010).

In terms of daylight performance attribution, atrium form is the key factor in the preliminary stage (Yunus et al. 2010). As the orientations and architectural shapes of courtyards affect the daylight distribution, the microclimate inside the spaces is also affected. In order to determine the degree of sky view factor (SKF) of the courtyard, which has an impact on daylight and thus solar heat intake, the aspect ratio of the courtyard shall be calculated (Reynolds 2002). Muhaisen found that the greater the aspect ratio (which is = area of the courtyard floor / (average height of surrounding walls)^2), the greater is the would exposure to the sky and this affects the thermal performance of the indoor spaces because of the heat transfer between the transitional spaces and the external environment, which includes reflected radiation, short-wave radiation, long-wave radiation, and evaporative exchanges (Muhaisen 2005). These will turn out affecting the occupants' thermal comfort.

Depending on the design of atrium roof, the daylight transmittance may vary from 20% to 80% (Rennie and Parand 1998). The major factor on the daylight transmittance as well as the daylight distribution is the roof structure and glazing bars (Littlefair and Aizlewood 1998). Sharples & Lash investigated the daylight transmission through the atrium fenestration and roof structure by adopting on-site measurements and virtual validation using various sets of weather conditions which combined with different settings of atrium geometry. The research showed that the impact of roof structure on daylight performance was significant, but they suggested that further investigation were required (Sharples and Lash 2007).

Solar

It is agreed by a several researchers that there is an impact of architectural forms of transitional spaces on the solar radiation penetration into the spaces. Muhaisen & Gali opined that the architectural forms and the solar position are the major factors that influence the solar radiation penetration and thus the thermal performance of the courtyard (Muhaisen and Gadi 2005). Assadi et al. added that the glazing height, apart from atrium size, had a significant impact on the solar radiation (Assadi et al. 2011).

Sectional shape of atrium has impacts on the solar radiation penetration and thus the thermal environment. To reduce the solar penetration and increase the stack effect, "A" form sectional shape is suggested for atrium design; however, to increase the solar radiation penetration, which is advantageous for buildings in cold climate regions, "V" form sectional shape shall be used (Lin et al. 2004; Wen, C; Wang 2006).

In order to reduce the thermal impact on the transitional spaces, less daylight and thus solar radiation shall be reduced (Al-Azzawi 1984). It is found that one of the approaches to reduce the daylight / solar heat penetration and thus the temperature impact is to design deeper transitional spaces (Almhafdy et al. 2013). However, Muhaisen & Gali opined that this is only for shading in summer. To provide more heating in winter, shallower transitional spaces shall be designed (Muhaisen and Gadi 2006). Martinelli & Matzarakis also agreed that the increase of courtyard height is more favourable on thermal comfort for summer periods. They explained this with Sky View Factor (SVF) of the courtyard, where the higher the SVF, the higher is the solar penetration. The assessment of thermal comfort their research based on was the Physiologically Equivalent Temperature (PET), which was calculated by the RayMan model (Martinelli and Matzarakis 2017).

Abdulkareem provided similar point of view on limiting solar radiation penetration for providing satisfactory thermal comfort during summer. He suggested maximising the height of courtyard to minimise the direct exposure of its floor and walls to the solar radiation

(Abdulkareem 2016). This can actually be done by adding more floors to the courtyard during design stage (Al-Azzawi 1984).

In addition to the careful design of the architectural form of the transitional spaces, installation of shading devices, such as internal and external solar blinds, is the alternative approach to reduce solar gain and thus improve thermal environment on their occupied level (Abdullah and Wang 2012). In terms of lighting and thermal performance inside an atrium space, installing external blind could be more influential than internal one as the latter would probably trap the warmed air beneath the roof cover which increases the air temperature of the top layer of the atrium. However, if internal blind is to be installed, it is suggested to install interior shading with blinds at about 3-5 m below the roof cover for better thermal and visual comfort (Wang et al. 2014).

2.4.1.3 Downside of Improper Design of Architectural Form

Improper design of architectural form of transitional spaces could lead to overheating issue and thus thermal discomfort issue. Pan et al. pointed out that especially in the tropics, where the solar position is at high altitude, the solar radiation penetrating through the glazed envelop can lead to high temperature within the atrium space and thus severely worsen the in indoor thermal environment (Pan et al. 2010b). Abdullah et al. and Wang et al. explained that overheating issue within the atrium space is normally caused by excessive solar gain.

Mitigation measures such as installing shading devices or external evaporative cooling system can be considered to control the solar gain (Abdullah et al. 2009; Wang et al. 2009).

2.5 Evaluation of Thermal Comfort in Transitional Spaces

Having established the basic understanding among the architectural forms, thermal comfort and energy performance of transitional spaces, this section is aimed to evaluate the thermal comfort study for built environments by reviewing the previous research studies. The overview of thermal comfort in built environments is first discussed, followed by the review of current knowledge gap of thermal comfort evaluation in transitional spaces. This then leads to the review of thermal comfort in indoor and outdoor spaces respectively in terms of the international standards and the fundamental principles for the widely-adopted comfort prediction models so that the influencing factors for different comfort prediction models can be identified.

2.5.1 Overview of Thermal Comfort in Built Environments

"(Thermal comfort is) that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation" – ASHRAE Standard 55 – 2013

(ASHRAE 2013)

Since a long time ago, a variety of strategies have been adopted in built environments, including private houses and public places, to achieve the desirable level of indoor thermal comfort (Elaiab 2014) because of the importance of thermal comfort. Raw & Oseland concluded from their research that the knowledge of thermal comfort can provide the following five advantages for building designs (Raw and Oseland 1994), which include:

1. provision of guidance for design of building and enclosed environments;
2. better control over environments which are too extreme for the building occupants;
3. improvement on indoor air quality;
4. reduction of carbon production; and
5. increased productivity of building occupants.

Occupant's health and well-being has been the focus (Shrubsole 2016), especially after the WELL Building Certification scheme has been launched recently in 2016 (International WELL Building Institute 2016). In the recent years, there are a number of researches that have proven the positive impacts of thermally comfortable environment on occupants' well-being and productivity (Wyon 2005; Akimoto et al. 2010; Lan et al. 2011; Elaiab 2014; Al Horr et al. 2016). Therefore, some international standards and guidelines, including ASHRAE 55 (ASHRAE 2013), CIBSE TM 52 (CIBSE 2013) , BS EN ISO 7703 (ISO 2005), EN 15251 (CEN (European Committee for Standardization) 2007), have introduced the thermal comfort requirements for proper building design. Due to the importance of thermal comfort in built environments, it is also revealed that the research interest in thermal comfort, as shown in Figure 2-12, has been increased dramatically in the past decade (Rupp et al. 2015). Rupp, et al. also generally classifies thermal comfort into three categories: outdoor, indoor and transitional (semi-outdoor) spaces (Rupp et al. 2015). The current knowledge of thermal comfort in transitional spaces is explicated in the following sub-section, which forms the basis for this research study.

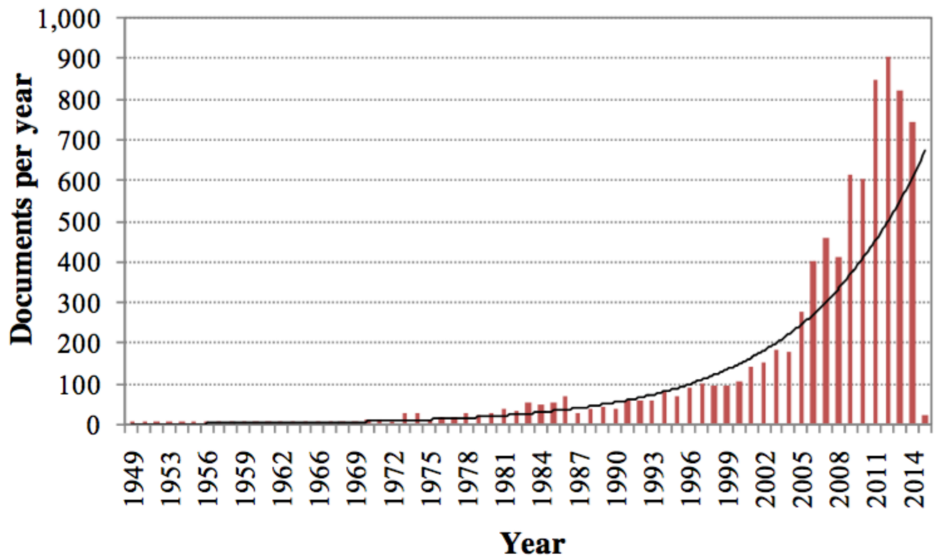


Figure 2-12 Number of articles in the field of thermal comfort published per year – Scopus (Rupp, Vasquez, & Lamberts, 2015)

2.5.2 Knowledge Gap of Thermal Comfort in Transitional Spaces

The conditions in transitional spaces are complicated due to the glazed façade designs, which lead to temperature differentials, solar radiation, wind and localized microclimate (Raja and Virk 2001), and may result in significant air exchange with outside environment (Pitts and Saleh 2007).

In the recent years, some researches were conducted to investigate the dynamic interactions between the environmental factors and comfort level. Hwang & Lin carried out a field study to investigate the thermal comfort ranges in outdoor and semi-outdoor environments in Taiwan (Hwang and Lin 2007) and Lin et al. later investigated the impacts of seasonal thermal adaption (Lin et al. 2011). Similar studies were also conducted in Wuhan, China (Zhou et al. 2013) and Nagoya, Japan (Wong and Chong 2010). Kwong et al. studied the importance of air velocity to maintain thermal comfort in transitional spaces in tropical climates like Malaysia (Kwong et al. 2014).

However, Monterio & Alucci and Hui & Jiang both agreed that there is still lack of research evidence on this field and thus the information of thermal environment of transitional spaces is still insufficient (Monterio and Alucci 2007; Hui and Jiang 2014; Rupp et al. 2015). It may be explained by Moosavi et al. that it is difficult to predict the thermal performance of such spaces due to the wide ranges of variables, including air changes, occupancy density, clothing and the time spent in these spaces, associated with them (Moosavi et al. 2014). Palma added that it is the dynamic interactions of these variables that make the accurate comfort prediction difficult (Palma 2015), where there were only few researches studied the dynamic relationships of environmental conditions on the thermal comfort in transitional spaces (Potvin 2000).

The majority of previous research on the comfort environment with dynamic states, including transitional spaces like corridor and atrium, were conducted in climatic chambers, and only a few of them have been validated through fieldwork studies (Palma 2015). Liu et al. pointed out that most of the previous researches covered human thermal response to stable environment conditions only (Liu et al. 2014). There are still lack of accurate prediction methods for evaluating human thermal comfort perception in dynamic state (Palma 2015). Nevertheless, transitional spaces are still not clearly addressed in the current comfort standards (Van Hoof 2008).

In addition, there is still no recommended acceptable indoor temperature ranges for thermal comfort of transitional spaces (Yu et al. 2015), although there were experimental investigations on human psychological and physiological responses to the steps changes of temperature (Zhang et al. 2014b) and humidity (de Dear et al. 1989). People in transitional spaces would experience different climate conditions due to the variety of factors affecting the thermal environment, which leads to an unpleasant comfort condition for the occupants in transitional spaces (Chun et al. 2004).

Since the transitional spaces are known as the physical connections between indoor and outdoor spaces (Hensen 1990; Hayashi et al. 1996; Zold 2000), it can be expected that the comfort requirements of such spaces would not exceed that of outdoor or indoor environments. Therefore, the thermal comfort in outdoor spaces and indoor spaces would be reviewed in next sections in order to identify the comfort standards, evaluation methods and fundamental principles of each methods. These will form the basis for this research to conduct further investigations on how to accurately predict the comfort conditions of transitional spaces and thus the recommended comfort range for different environmental parameters.

2.6 Thermal Comfort in Outdoor Spaces

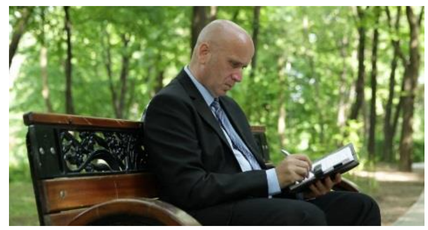
Outdoor spaces are important in improving public health and wellbeing of people and reduce government expenditure (Aljawabra 2014). In addition, good outdoor spaces can also benefit the communities economically and environmentally by providing spaces for people to have cultural activities (Madden and Schwartz 2000), which enable social activities between people (Gehl 2007). Previous research study in England found that around 9% early deaths and £900 million of government expenses could be saved every year for its country if 75% of people did meet the recommended exercise level, e.g. walking for 20 minutes five days a week (Roberst-Hughes 2013).

Outdoor spaces provide publicly accessible outdoor areas within cities such as parks, plazas, streets, community gardens, and greenways (Lynch 1972; Carré 1992). These spaces serve as meeting place, market place and connection space (Gehl 2007) and the activities of people in such spaces can be categorised into three types: necessary/functional, optional/recreational and social / resultant activities (Gehl 1996), which are briefly summarised in the

Table 2-2 below. People of all ages can be found using these spaces, which involve different activities that was essential to their lives (Aljawabra 2014).

Table 2-2 Definitions and examples of different categories of outdoor activities

Category	Definitions	Examples

Necessary/Functional Activities	People need these around the year under all circumstances. These are associated with walking. People have few choices on these activities.	 People walking to work / shop
Optional/Recreational Activities	These activities are more related to sitting and people would carry out them when place and time are suitable.	 People sitting at the park
Social/Resultant Activities	These cover all communal activities, where they would occur when people meet each other in a particular place	 People enjoying social time

In the outdoor spaces, people, who are directly exposed to the environment including solar radiation and wind (Chen and Ng 2012), tend to be more tolerant to the environmental changes that occur to their physical activities (Griffiths et al. 1987) and therefore people's comfort range in air temperature of outdoor spaces is wider than that of indoor spaces (Nikolopoulou and Lykoudis 2006). This may be explained that when people are in movement, their thermoregulatory system constantly changes according to the environmental changes to reach thermal equilibrium (Hwang et al. 2008). Emmanuel added from psychological point of view that people's different perception on the thermal environments may also lead to the difference in people's tolerance in the environmental changes (Emmanuel 2012).

2.6.1 Comfort Standards for Outdoor Spaces

Outdoor thermal comfort is not dealt with in the current comfort standards (Höppe 2002; Johansson et al. 2012). In addition, there are still no recommendations on neutral and preferred index temperature calculations for outdoor spaces; the current international standards guidelines are just developed for indoor conditions and/or working environments (Johansson et al. 2014). For instance, ISO 7730 only suggests specification of the thermal comfort conditions for indoor environments where the conditions are moderate (ISO 2005).

Although some indices such as PET are recommended in the new German guidelines for urban and regional planners (Verein Deutscher Ingenieure (VDI) 2008), it is used for the prediction of changes in the thermal component of outdoor climates (Honjo 2009). It, however, does not deal with the psychological instruments and methods, including field study protocols and questionnaires (Johansson et al. 2012).

2.6.2 Review of Comfort Prediction Models for Outdoor Spaces

In order to predict the thermal comfort condition in outdoor spaces, there have been a number of indexes developed in the past decades, where the Predicted Mean Values (PMV), Standard

Effective Temperatures (SET*), and Physiological Equivalent Temperature (PET) indices have been widely-used in recent outdoor thermal comfort studies (Yao 2016; Zhao et al. 2016b).

The PMV index, which is based on the actual thermal sensation by assessing a large group of people, adopts the ASHRAE 7-point scale of thermal sensation scale (Chen and Ng 2012; ASHRAE 2013); the SET* and PET indexes, which are based on analyses from climate chamber of the human heat balance, integrate the effects of air temperature (Ta), relative humidity (RH), mean radiant temperature (Tmrt) and air speed (v) (Zhao et al. 2016b). More details of these indexes are covered in the followings.

Predicted Mean Votes (PMV)

PMV was developed by Fanger (Fanger 1972), which is aimed to provide an index for ratings of thermal discomfort at different activity levels and clothing insulation for indoor climates. Although PMV is originally developed as an indoor comfort index, PMV has been widely adopted in outdoor thermal comfort studies to evaluate the comfort levels from large groups of people (Nikolopoulou et al. 2001; Thorsson et al. 2004; Cheng et al. 2012).

Matzarakis and Mayer used Greece as an example and calculated the PMV to develop a high-resolution map that reflects the average annual number of very hot days with PMV>3.0. They obtained the meteorological data from 12 Greek stations for the years 1980 to 1989 for the PMV calculations and the research outcome showed that a broad area was shown as high heat stress zones (Matzarakis and Mayer 1997).

Vu et al. (Ca et al. 1998) studied the thermal conditions inside the park by using PMV index and they found that the PMV for a walking person is 2.6. It was also found that the PMV is different for the same person for different wind directions, i.e. upwind/downwind. Although the results from this research showed that the PMV was not in a comfortable range, it was found that the presence of the park can improve the thermal environment.

Thorsson et al. also used the PMV index to study the relationship of thermal bioclimatic conditions and behavioral patterns of people in an urban park of Gothenburg, Sweden. They conducted field studies, including structured questionnaire surveys, site measurements and observations of behaviour of the people using the park. They compared the PMV and the actual perception vote (ASV) and identified some discrepancies between these values (Thorsson et al. 2004).

Grifoni, et al. assessed the outdoor thermal comfort by using the calculated PMV to study the relationship of the comfort level and the urban geometry. By using Mode Frontier as an integration platform, the researchers modified the urban geometry, i.e. the height-to-width (H/W) ratio of urban streets and correlated against the calculated PMV (Grifoni et al. 2013).

2.7 Thermal Comfort in Indoor Spaces

Due to the increase in the urban density of buildings as a result of urbanisation, where it is expected the urban centres will be occupied by over 70% of world population, the increase of people's time spent in indoor spaces is significant (Rupp et al. 2015). It is estimated that people spend approximately 90% of their time indoors (Wargocki 1999; Fisk 2000). Nevertheless, as it has proven that poor thermal comfort can lead to reduced occupants' productivity (Huizenga et al. 2006) and even sick building syndrome (Myhren and Holmberg 2008), there have been increasing interests in research on comfort-related building designs (ASHRAE 2013).

Occupants' perception of thermal sensation in indoor spaces is different from that in outdoor spaces (Potter and de Dear 2000), in terms of psychological, thermo-physiological and heat balance (Höppe 2002). Gómez-Azpeitia et al. conducted field studies and explained that the difference in thermal sensation is due to the different people's adaptation and expectation (Gómez-Azpeitia et al. 2011). Moreover, people in indoor spaces have more control over the surrounding environments that outdoor spaces (Aljawabra 2014), which have significant impacts on improvements of comfort and energy performance (Brager and de Dear 1998).

2.7.1 Comfort Standards for Indoor Spaces

"A standard is a document that provides requirements, specifications, guidelines or characteristics that can be used consistently to ensure that materials, products, processes and services are fit for their purpose" – ISO 7730:2005 (ISO 2005).

The determination of thermal comfort indices and the specification of thermal comfort conditions are the main focuses of the current standards (Parsons 2014). Current standards are essentially based on either heat balance or adaptive models (Toe 2013). There are three commonly used international standards that are specifically related to thermal comfort, namely ISO Standard 7730 (ISO 2005), ASHRAE Standard 55 (ASHRAE 2013), and CEN Standard EN15251 (CEN (European Committee for Standardization) 2007).

2.7.1.1 ASHRAE Standard 55

In the U.S., ASHRAE 55 specifies "*the combination of indoor thermal factors and personal factors that will produce thermal environmental conditions acceptable to a majority of the occupants within a space*." (ASHRAE 2013). In 1992, PMV-PPD method for thermal comfort evaluation was added to ASHRAE 55 in order to determine the comfort zone, which is considered to be more consistent with ISO 7730 (Oleesen and Brager 2004). Similar to BS EN 15251, predictive and adaptive models have set up the basis for ASHRAE 55, which provides recommendations for local thermal discomfort assessment.

In the 1960/70's, Fanger's model was developed, which is based on the fact that *"the human body employs physiological processes (e.g. sweating, shivering, regulating blood flow to the skin) in order to maintain a balance between the heat produced by metabolism and the heat lost from the body"* (Charles 2003). Thermal comfort is achieved if the heat gain and loss of the human body is balanced out (Fanger 1972). In this model, the human body exchanges energy with the surroundings by the means of:

1. Evaporation of sweat and/or water vapour diffusion through the skin.
2. Respiration.
3. Skin exchanges energy by convection and radiation.

These flows depend on six variables which vary over time (ASHRAE 2013):

- Two personal variables: clothing insulation level (Icl) and activity level (M).
- Four environmental variables: air dry-bulb temperature (Ta), mean radiant temperature (Tr), relative air velocity (Va) and relative humidity (RH).

Generally, predictive models should be used for the occupants' thermal comfort level assessments when a building is mechanically conditioned (Gauthier 2015). The single-node model has been recognised as a good indicator but it contains formulation and evaluation errors (Humphreys and Nicol 2000). This model is considered to be the most simplified evaluation of thermal comfort as the approximation of the human body is one-dimensional only and the transient thermal conditions or thermal regulation is not simulated (Jones 2002).

In ASHRAE standard 55, it is assumed that people prefer a moderate thermal sensation, which is named as "neutral" (a vote of zero on the 7-point ASHRAE thermal sensation scale), and discomfort is partly proportional to the difference between the measured temperature and the optimum temperature for comfort (ASHRAE 2013).

Adaptive Model

Alongside with the PMV model, adaptive model was introduced in ASHRAE Standard 55 in order to overcome the limitations of the PMV index (Kotsopoulos et al. 2013). This model applied a simple method to calculate the operative temperature to determine comfort temperature for indoor spaces (Eltrapolsi 2016). According to ASHRAE, "*The Standard specifies conditions acceptable to a majority of group of occupants exposed to the same conditions within a space*". The "majority" is defined as 80% overall acceptability, while the variation of specific discomfort limits depends on different local discomfort sources. The acceptable zones for indoor temperature can be estimated by the indoor operative temperature and average monthly outdoor air temperature. This is specified for naturally ventilated buildings (ASHRAE 2013). The following is the formula to evaluate the comfort temperature.

$$T_{comf} = 0.31 \cdot T_O + 17.8 \qquad \text{Eq. 1}$$

Where T_{comf} is the comfort temperature and T_o is the prevailing mean outdoor temperature.

Figure 2-13 shows the relationship of prevailing mean outdoor temperature and the indoor operative temperature, from which the comfort range is shown. Optimum ± 3.5°C and ± 2.5°C represent 80% and 90% of thermal acceptability respectively for all naturally-ventilated buildings (de Dear and Brager 2002).

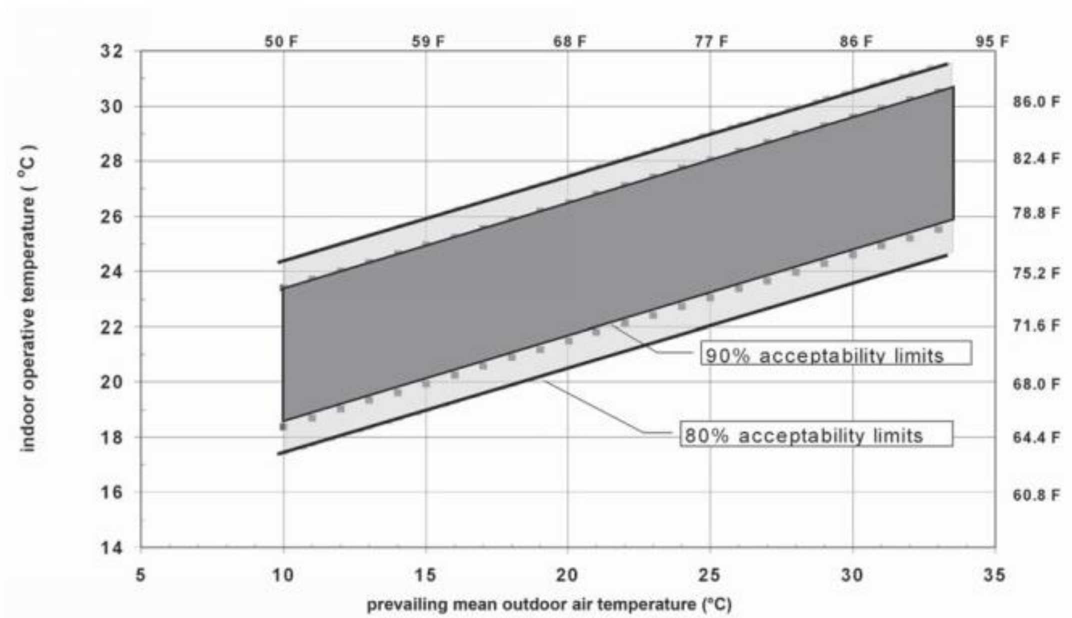


Figure 2-13 Acceptable Range of Indoor Operative Temperature (ASHRAE 2013)

Among all the international standards, the ASHRAE standard was the first to include an adaptive component, which is applicable to naturally conditioned building (Elaiab 2014). However, according to the standard, the application of the adaptive model requires the calculated prevailing mean temperature to be greater than 10°C (50°F) and less than 33.5°C (92.3°F), followed by some other requirements (ASHRAE 2013).

2.7.1.2 ISO 7730

The ISO standards on "*ergonomics of the thermal environment*" are used complementarily (ISO 2005). ISO 7730 is considered as the main thermal comfort standard developed by the International Standards Organisation (Olesen and Parsons 2002), which provides an analytical method for determining and interpreting thermal comfort (Gauthier 2015). The ISO 7730 standard is based upon the Heat Balance Model, which adopts Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) thermal comfort indices. The standard specifically categorised buildings based on their PMV ranges. The following table illustrates the different categories defined by ISO 7730:2005 (ISO 2005).

As shown in Figure 2-14, the standard has set up different categories for different thermal comfort level according to the PMV and PPD values (ISO 2005), where EN 15251 contains similar ones (CEN (European Committee for Standardization) 2007). ISO 7730 states that deviations in the PMV /PPD index may be caused by differences in age, ethnic, national-geographic location, and number of patients or disables. In addition, it applies to indoor environments with stable or moderately deviated thermal comfort (Olesen and Parsons 2002).

Cate-gory	Thermal state of the body as a whole		Operative temperature °C		Max. mean air velocity m/s	
	PPD %	PMV	Summer (0,5 clo) Cooling	Winter(1 clo) Heating	Summer(0,5 clo) Cooling	Winter(1 clo) Heating
A	< 6	-0.2 < PMV < + 0.2	23,5 – 25,5	21,0 – 23,0	0,18	0,15
B	< 10	-0.5 < PMV < + 0.5	23,0 – 26,0	20,0 – 24,0	0,22	0,18
C	< 15	0.7 < PMV < + 0.7	22,0 – 27,0	19,0 – 25,0	0,25	0,21

Figure 2-14 Different categories of thermal comfort environment defined by ISO 7730:2005 (ISO 2005)

There are five supporting standards, including ISO 13731 (vocabulary and symbols), ISO 8996 (determination of metabolic rate), ISO 9920 (estimation of clothing insulation level), ISO 7726 (measuring instruments), and ISO 10551 (subjective assessment). With respect to cold environments, assessment methods of human responses of contacting with cold surfaces have been the focus of ISO 13732. ISO 12894 reviews the medical supervision of individuals' exposure to extreme weather conditions, and ISO 11079 concentrates on determining and interpreting cold stress when using specified clothing insulation (IREQ) and local cooling effects.

2.7.1.3 prEN 16798-1 (superseded BS EN15251)

In Europe and the U.K., BS EN 15251 reviews the "*indoor environmental input parameters for design and assessment of energy performance of buildings*", and includes thermal environment. EN15251 was developed by the European Committee for Standardization (CEN), as a supporting document to the Energy Performance of Buildings Directive (CEN

(European Committee for Standardization) 2007). EN15251 was firstly published in 2007, where both the PMV/PPD model (Nicol and Humphreys 2010) and the adaptive comfort method were included (McCartney and Fergus Nicol 2002; Nicol and Humphreys 2002; Nicoil and Pagliano 2007). The adaptive comfort method was developed from the European SCATs project (Nicol et al. 2001). By then, a new code named prEN 16798-1 was released, which superseded the EN15251 (European standards committee 2015). The standard was established in response to the impact of indoor environment on energy consumption and productivity (work and learning performance), which is supported by studies that proved the cost of poor indoor environment is often significantly higher than energy consumption in the same building (Nicol and Wilson 2010). Therefore, the indoor environmental parameters that affect the building energy performance, such as indoor air quality, lighting, and acoustics, have been specified in the standard (Nicol and Wilson 2010).

In the new European standard prEN 16798-1, two changes have been made in the adaptive comfort method (Carlucci et al. 2018), which are (1) the lower limit of optimal operative temperature is 1 °C lower than the previous version; and (2) the available range of outdoor running mean temperature in correspondence with lower limit of thermal comfort zone changed from 15 to 30 °C to 10 to 30 °C.

The following equation is used to define the comfort temperature limits for building without mechanical cooling:

$$T_{comf} = 0.33 \cdot T_{rm} + 18.8 \qquad \text{Eq. 2}$$

Where T_{rm} is the exponentially weighted running mean of the outdoor temperature, which can be found by using the equation $T_{rm} = (1-\propto)_{ed\text{-}1}+\propto T_{rm\text{-}1}$, where the value of $\propto$ is 0.8.

The standard breaks new ground in recognising the different thermal expectations of occupants in naturally and air-conditioned buildings, and is addressed to the European Union members. Nevertheless, it does not widely spread around the globe (Nicol and Wilson 2011).

2.7.2 Review of Comfort Prediction Models for Indoor Spaces

Thermal comfort is one of the most essential elements of occupant's satisfaction and energy consumption in built environments (Milne 1995; Nicol et al. 2012). There are a great number of indices for standard thermal comfort models, which can be categorised into physical, physiological, and psychological systems (Auliciems and Szokolay 2009; Carlucci and Pagliano 2012).

From the review of the current standards, the proposed model can actually be classified into two types of models, which are the heat-balance-based predictive model, PMV, and the adaptive models, which are built on field study results. Both types of models are based on empirical studies under controlled environment (Gauthier 2015). As shown by field studies, people may adopt localised behaviour, and be satisfied with conditions outside the recommended boundary of the models (Tweed et al. 2014).

In this section, more details of these models are reviewed to set up a comprehensive theoretical basis in order for the later part of the research to select the most appropriate model for thermal comfort predictions in transitional spaces.

2.7.2.1 PMV

In the 1960/70's, Fanger's model was developed, which is based on the fact that *"the human body employs physiological processes (e.g. sweating, shivering, regulating blood flow to the skin) in order to maintain a balance between the heat produced by metabolism and the heat lost from the body"* (Charles 2003). Thermal comfort is achieved if the heat gain and loss of the human body is balanced out (Fanger 1972). This can be summarised in the following equations:

$$H - E_d - E_{sw} - E_{re} - L = K = R + C \qquad \text{Eq. 3}$$

$Where$:

$H\ is\ the\ internal\ heat\ production\ rate\ per\ unit\ area$ $(W/m2)$;

$Ed\ =\ the\ heat\ loss\ by\ water\ vapour\ diffusion\ through\ the\ skin$;

$Esw\ =\ the\ heat\ loss\ by\ evaporation\ of\ sweat\ from\ the\ surface\ of\ the\ skin$

$Ere\ =\ the\ latent\ respiration\ heat\ loss$

$L\ =\ the\ dry\ respiration\ heat\ loss$

K

$= the\ heat\ transfer\ from\ the\ skin\ to\ the\ outer\ surface\ of\ the\ clothed\ body$

$R\ =\ the\ heat\ loss\ by\ radiation\ from\ the\ outer\ surface\ of\ the\ clothed\ body$

$C\ =\ the\ heat\ loss\ by\ convection\ from\ the\ outer\ surface\ of\ the\ clothed\ body$

PMV, the index that predicts the mean value of the votes from a large group of people, is presented by seven-point thermal sensation scale (Butera 2007). An environment with PMV in the range of -0.5 and +0.5 is considered as comfortable. When the PMV is zero, it is the perfect case where the PPD is about 5%.

In order to quantify people's thermal sensation, Fanger's PMV-PPD model adopts a seven-point scale as illustrated in Figure 2-15 below, ranging from -3 (cold) to +3 (hot) where 0 is defined as neutral point (Fanger 1972). In this model, it is believed that even when the PMV is equal to 0 (neutral), 5% of people are still feeling dissatisfied with the thermal environment. Figure 2-16 illustrates the relationship between PMV and PPD.

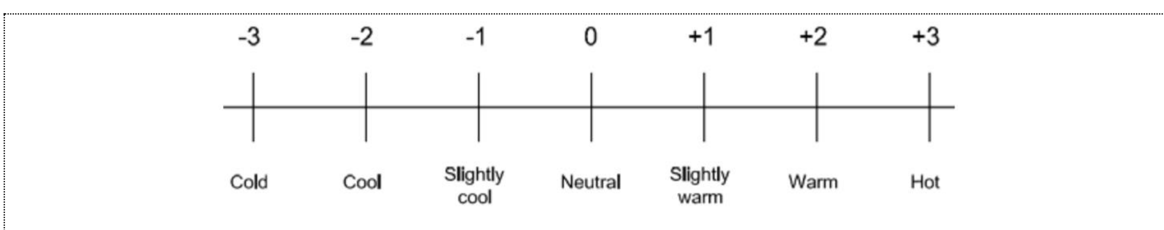


Figure 2-15 Fanger's Seven-point Thermal Sensation Scale

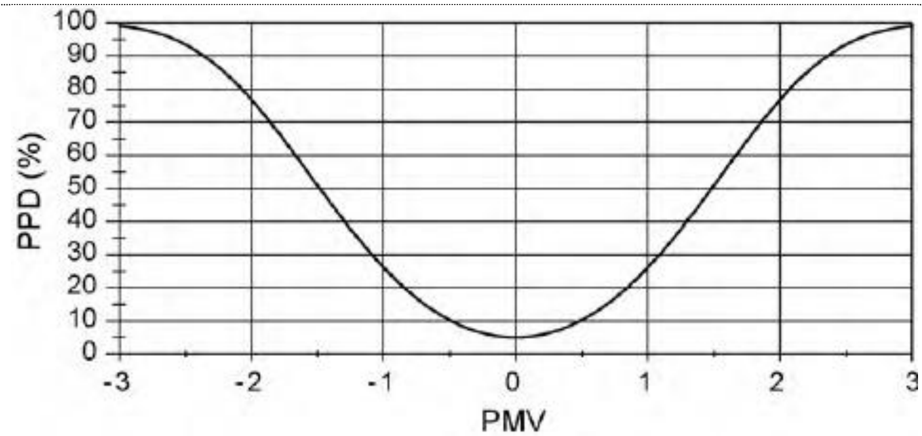


Figure 2-16 Relationship between PMV and PPD

The commonly used indices for this model are the Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) (Gauthier 2015), where PMV is defined as *"the index that predicts, or represents, the mean thermal sensation vote on a standard scale for a large group of persons for any given combination of the thermal environmental variables, activity and clothing levels"* (Fanger 1972).

The followings show the calculation method of PMV and PPD (ISO 2005):

$$PMV = (0.303e^{-0.036M} + 0.028) \cdot \{(M - W) - 3.05 \cdot 10^{-3} \cdot [5733 - 6.99 \cdot (M - W) - p_a] - 0.42 \cdot [(M - W) - 58.15] - 1.7 \cdot 10^{-5} \cdot M \cdot (5687 - p_a) - 0.0014 \cdot M \cdot (34 - t_a) - 3.96 \cdot 10^{-8} \cdot f_{cl} \cdot [(t_{cl} + 273)^4 - (\overline{t_r} + 273)^4] - f_{cl} \cdot h_c \cdot (t_{cl} - t_a)\} \quad \text{Eq. 4}$$

$$PPD = 100 - 95 \cdot e^{\left(-0.03353 \cdot PMV^4 - 0.2179 \cdot PMV^2\right)} \quad \text{Eq. 5}$$

Generally, predictive models should be used for the occupants' thermal comfort level assessments when a building is mechanically conditioned (Gauthier 2015). The single-node model has been recognised as a good indicator but it contains formulation and evaluation errors (Humphreys and Nicol 2000). This model is considered to be the most simplified evaluation of thermal comfort as the approximation of the human body is one-dimensional only and the transient thermal conditions or thermal regulation is not simulated (Jones 2002).

2.7.2.2 Adaptive Approach

On the basis of statistical analysis of empirical study results and an assumption that occupants prefer the variation of indoor temperature with outdoor weather conditions, adaptive models have been developed (Nicol and Humphreys 2002). Adaptive approach is indicated through an occupant's satisfaction with an indoor climate, with consideration of the actual thermal environmental condition prevailing at that point in time and space, and the occupant's thermal expectations of the indoor thermal (de Dear 1994).

Unlike the heat-balance method, neither clothing knowledge nor activity level of occupants is required (Gauthier 2015). Therefore, human behaviour may be varied with different seasons. If discomfort occurs, people would react differently to restore their comfort, which may be done by the change of clothing, activity of place. These actions can be classified as physiological, behavioural and the use of personal environmental controls (Nicol 1993; Rijal et al. 2002). People in buildings with natural ventilation are comfortable over a wide range of temperature due to the various adaptive actions (Nicol and Humphreys 2002; Wagner et al. 2007).

By nature, thermal adaptation is a dynamic process, an occupant may be accustomed to a range of comfortable indoor temperatures changing with time and through different spaces within a dwelling (Gauthier 2015). Previous studies reported that indoor temperature has a linear relationship with outdoor temperature (Humphreys 2008). In general, the adaptive model can be considered as regression equation that correlates the desired indoor temperature with the monthly average outdoor temperature. The only input variable is the average outdoor temperature, which the impact on human heat balance is indirect (Elaiab 2014). However, this model is only applicable for the following conditions (Gauthier 2015; Rupp et al. 2015):

- Naturally ventilated buildings.
- Occupants engaged in near sedentary physical activities (1.0 to 1.3 mets).
- T_o ranging from 10.0°C to 33.5°C.

In addition, it is essential that the occupants have the opportunity to adapt by changing their clothing, opening/closing windows, or by other means (de Dear et al. 1989).

2.7.3 Review of People's Adaptive Behaviours in Indoor Built Environment

When people are situated in an environment that they feel uncomfortable, they would take personal control to change or reverse the situations (Fisher 1990). In general, the adaptive actions may be grouped into two major categories, the "self-adaptive actions" and "adaptation to the environment". "Self-adaptive actions" may be defined as personal activities that individuals take to reduce the feeling of thermal discomfort; "adaptation to the environment" may be defined as activities that individuals take to adjust the settings of accessible and available building facilities and/or systems to improve the thermal environment. Macfarlane is one of the researches in early citations who introduced adaptive behaviour in built environment by addressing behaviour adjustments such as changing clothing and restraining physical actions (Macfarlane 1978). Changing or adjusting clothing levels may be one of the major "self-adaptive actions" that people would take to deal with thermal discomfort, where this kind of action is recognised by a number of researches (Brager and de Dear 1998; Humphreys and Nicol 1998; Goto et al. 2007; Liu et al. 2012). Humphreys and Nicol observed from their research that one of the people's adaptive behaviours is adjustment of activity level (Humphreys and Nicol 1998), which was supported by several other studies (Lyons et al. 2000; Cena and de Dear 2001; de Dear 2007). Benton and Brager evaluated the impacts of 'taking a break' or 'having a cold drink' on thermal comfort (Benton and Brager 1994). Brager and Baker found out that "moving to a cooler location" may also be one of the actions that people would take to prevent thermal discomfort (Brager and Baker 2009).

Other researchers found out that people would also take "adaptation to environment" actions to adjust their perceived comfort on the thermal environment, which include changing the settings of furniture, doors, windows, shades, fans or other building systems (Baker and Standeven 1996; Holopainen et al. 2014). Some other researchers identified that people may also opt for opening or closing building openings such as windows and doors to mitigate the uncomfortable situations (Brager and de Dear 1998; Edwards 2006; Rijal et al. 2007; Yun and Steemers 2007; Haldi and Robinson 2008; Peffer et al. 2011). Adjusting air conditioning system settings such as adjusting room temperature set points and air conditioning operation hours are also identified by a number of researchers that individuals may act to adjust the thermal environment to make themselves more comfortable (Brager et al. 2004; Zagreus et al. 2004; Lee and Brand 2005; Huizenga et al. 2006; Macmillan 2006; Peffer et al. 2011).

2.8 Review Of Improvement Strategies For Thermal Comfort In Building Transitional Spaces

There have been researches about different types of transitional spaces including building entrances, lobbies, train stations, corridors, airports and arcades. However, there is still a lack of research on this research topic about multi-functional transitional spaces that offer longer-term occupancy areas for building users by detailed analysis through fieldwork research and computational simulations. The following table summarises the main researches about transitional spaces and relevant spaces.

Authors	Year	Location	Space Type	Research Method
Potvin	2000	Cardiff, UK	Arcades	Questionnaires
Jitkhajornwanich and Pitts	2002	Bangkok, Thailand	Schools and Offices	Questionnaires and Physical Measurements
Nakano	2003	Waseda, Japan	Semi-outdoors Environment	Laboratory and Fieldwork
Spagnolo and de Dear	2003	Sydney, Australia	Outdoor and semi-outdoor space	Questionnaires
Chun et al.	2004	Yokohama, Japan	Lobbies, Balconies, Pavilions	Physical Measurements and Observation
Chun and Tamura	2005	Yokohama, Japan	Train Station, Passageway, Shopping Mall	Laboratory world and Fieldwork
Nakano et al.	2006	Tokyo, Japan	Train Station	Questionnaires
Bouyer et al.	2007	Paris, France	Stadium	Simulation
Kotopouleas and Nikolopoulou	2014	Manchester and London, UK	Airport Terminal	Questionnaires and Physical Measurements

Authors	Year	Location	Space Type	Research Method
Taleghani et al.	2014	Netherlands	Transitional Spaces of Low-rise Dwellings	Simulation
Hui and Jiang	2014	Hong Kong, China	Lift Lobby	Fieldwork and Simulation
Gloria Vargas	2016	Sheffield, UK	Lobby	Fieldwork

Table 2-3 Summary of Researches Related to Transitional Spaces

2.8.1 Application of Natural Ventilation in Building Transitional Spaces

Natural ventilation provides air exchange between outdoor and indoor environments without the use of any mechanical means such as ventilation fans and air conditioning process (Omrani et al. 2017). A building can be provided with fresh air, air circulation and dissipate internal heat with reduced energy usage by natural ventilation (Hughes et al. 2012). Not only natural ventilation may result in better air quality and thus healthier indoor environment by introducing fresh air from outside, but also the improved thermal comfort (Chungloo and Limmeechokchai 2007; Wang and Wong 2007; Moosavi et al. 2014). In addition, the application of natural ventilation in buildings, especially for those located in cold climate (Miller and Nazari 2013), can also save the energy and operating cost because mechanical systems are not required to maintain the desirable indoor environment (Aynsley 2007). Due to all these benefits for built environment, natural ventilation is widely used in building designs (Tian et al. 2018). Natural ventilation could be achieved by different techniques, including buoyancy, wind induction, solar assistance and night ventilation (Moosavi et al. 2014).

Natural ventilation is considered as an important passive design strategy and thus leads to great research interest (Khanal and Lei 2011). The impacts of atrium geometry on its ventilation and thermal performance were evaluated by Abdullah & Wang (Abdullah and Wang 2012). Hussain & Oosthuizen studied the ventilation performance of an atrium which was integrated with a solar chimney (Hussain and Oosthuizen 2012). Another study was carried out by Aldawoud which evaluated the natural ventilation performance under different atrium geometrical settings in terms of cross sectional aspect ratios, i.e. length to width (Aldawoud 2013). Holford & Hunt conducted a numerical analysis using CFD models to predict the steady stack-driven ventilation and thermal stratification of an atrium (Holford and Hunt 2003). Ding et al. investigated the performance of a solar chimney in an eight-story office building with an attached atrium by conducting a reduced scale experiments and CFD analysis (Ding et al. 2005). The field study carried out by Tanaka et al. showed that the use of double-skin facades in an atrium can enhance the natural ventilation performance by up to 25 ACH (Tanaka et al. 2009). Cook et al. evaluated the combined effects of wind-driven and buoyancy-driven natural ventilation flow in an enclosure (Cook et al. 2016).

2.8.2 Application of Passive Systems in Building Transitional Spaces

Building transitional spaces are usually constructed with high ceilings and large spans without partitions. Most of such spaces rely on mechanical systems for cooling and heating throughout the year (Tabesh and Sertyesilisik 2016). Occupants, in such a large space building, would just normally function in a lower zone, i.e. within a height of 2m from floor, while the upper zone is unoccupied (Zhao et al. 2014). The most common method to maintain the thermal comfort within these spaces is all-air jet ventilation which supplies air at a speed of 3.0-7.5m/s at a height of 3-5m from the floor (Wang et al. 2009; Zhihong et al. 2011). However, this method is found to have high overall energy consumption due to the fan operation (Yang et al. 2011).

In order to improve the building energy performance, passive systems such as natural ventilation and radiative heating / cooling systems, therefore, becomes a useful strategy to improve thermal comfort (Toe and Kubota 2015). The advantage of using radiant heating / cooling systems is that the space thermal requirement can be fulfilled with low-temperature media (Ren et al. 2010). Occupants in a space with radiative heating / cooling systems can enjoy the same level of thermal comfort in both winter time and summer time as the surface temperature can be adjusted (Olesen 2008). During the past decades, the application of radiant heating / cooling systems has become increasingly popular and widely adopted in commercial and residential buildings in different regions of the world such as South Korea, Japan, and Europe (Olesen and Parsons 2002; Bean et al. 2010; Rhee and Kim 2015). There is a growth of research interest in investigating radiant heating / cooling systems for large space buildings (Simmonds et al. 2000; Olesen 2002; Olesen 2008). The feasibility of such system applications in built environment has also been demonstrated in the research conducted by Kabele et al. (Kabele et al. 2011). Chu et al. studied the air distribution and thermal comfort in an atrium space with radiant floor heating (Chu et al. 2017). Zhao et al. conducted an on-site investigation of a radiant floor cooling system in Xi'an Xian Yang International Airport (Zhao et al. 2014). Feng et al. developed a new design method of a radiant floor cooling system with solar radiation (Feng et al. 2016).

Therefore, with the considerations of the advantage and popularity in building applications, the impacts of natural ventilation and underfloor radiant heating / cooling systems were investigated in this research. The three surveyed buildings presented in the previous research (Tse and Jones 2019) were used and apply these strategies. The effects on the thermal comfort by these systems under the average and extreme conditions were studied. The overall purpose was to give an idea of how a building transitional space can be designed appropriately in order to provide an acceptable thermal environment for its occupants. As to simulate the worst-case conditions, the natural ventilation was assumed to be carried out at no-wind situation. In other words, the wind pressure at the façade openings was set as 0 Pa.

2.8.3 Application of Underfloor Air Distribution (UFAD) System in Building Transitional Spaces

Underfloor air distribution (UFAD) is one of the mechanical ventilation systems that supply conditioned air at a floor level by pressurising the plenum between the structural floor and the raised floor (Atienza-Márqueza et al. 2018). There are a number of benefits using UFAD system over the traditional overhead systems, especially in a large-volume space (Atienza-Márqueza et al. 2018). One of the most common identified benefit by using UFAD system is better energy efficiency (Allan Daly 2002), as the conditioned air is delivered directly at the occupied zones. Yoon et al., by using TRNSYS simulation program, proved that UFAD systems can improve the energy performance by 12-18% (Yoon et al. 2013). The research conducted by Lian and Ma showed that UFAD system can reduce 25-50% energy consumption when compared to traditional overhead air conditioning systems (Lian and Ma 2006). Besides, UFAD can also improve the thermal comfort level and ventilation efficiency (Alajmia and El-Amer 2010). Better indoor air quality (IAQ) can also be maintained because of the stratification from the lower zone to the upper zone where the occupied zone can be kept cool and fresh due to the low level supply of conditioned air (Bauman and Webster 2001; Zhang et al. 2016). The web-based survey carried out by Zagreus et al. (Zagreus et al. 2004) showed that about 95% of the surveyed people felt thermally comfortable for a space using UFAD system, and nearly 66% of them indicated the preference for UFAD system rather than traditional overhead air conditioning systems. Because the heat and contaminants air can be brought to the unoccupied zones due to the flow patterns, UFAD system can provide a better IAQ and ventilation performance at the breathing level (Bauman and Webster 2001). In addition, the better thermal comfort and IAQ in the occupied zone can also lead to improved occupant productivity and health (Zhang et al. 2014a).

In the study, UFAD system, taking into account the list of benefits it brings to an indoor space, was chosen to be a supplementary system to the other proposed strategies, i.e. natural ventilation and passive systems, to maintain the required thermal comfort level under both average and extreme conditions for all the three surveyed buildings.

2.9 Conclusion

In this chapter, the historical development of transitional spaces was reviewed first. Beginning from 3000BC to the present, the changes of transitional spaces in terms of architectural forms, applications in built environments, functionality and interactions with other internal spaces were explored. Then, the different architectural forms that exist in the industry were summarised. This forms an important basis for the research in terms of case selections. After that, the identification of the relationships among architectural forms, thermal comfort of transitional spaces. It was revealed that a poor design of transitional spaces can lead to thermal comfort issues due to excessive solar gain, daylight penetration and ventilation. As thermal comfort is considered as an important factor for design of transitional spaces, the evaluation methods of thermal comfort for such spaces were then reviewed. It was concluded from several researchers that there are still lack of clear methods, guidelines, recommendations or acceptable temperature range for evaluation of thermal comfort in transitional spaces. As transitional spaces are defined as the spaces in-between outdoor and indoor environments, it was believed that the thermal comfort requirements would be somewhere in-between these spaces. This will form the basis for detailed comparison of the accuracy of different prediction models in thermal comfort evaluation for transitional spaces in the research. Therefore, further review on the thermal comfort prediction methods, theoretical fundamentals and improvement strategies were conducted to establish the basis for the further investigation in this research. In general, the improvement strategies in relevant spaces include natural ventilation, radiant floor system, and under-floor air distribution system. These may be considered in this research on the impacts of the strategies on the thermal environment of multi-functional transitional spaces. There are some researches that investigated transitional spaces, but there are only a few of them covering multi-functional transitional spaces, where longer-term occupancy areas are provided for building users, and there is a lack of thorough investigations by both fieldwork (questionnaires and physical measurement) and simulation that studied the people's experience in such spaces and the potential improvement strategies to provide thermal comfort for its occupants.

Chapter 3. RESEARCH METHODOLOGY

3.1 Introduction

The literature review, as detailed in Chapter 2, has established a solid understanding of the current situations of research and knowledge gaps of building transitional spaces, and led to the needs to further analyse the occupants behaviour to its thermal environment within building transitional spaces. This chapter presents the methodology constructed for this research in order to understand and investigate the thermal environmental performance of transitional spaces, people's reaction to thermal discomfort, and potential improvement strategies for transitional spaces. In order to optimise the approach for the field studies, a case building in Cardiff University named the Optometry Building was selected as to carry out a pilot study. The methodology is optimised after reviewing the whole process of the pilot study, including the setups of questionnaire survey form, techniques of engaging survey respondents, and physical measurements setups. In addition, findings from literature review on computational simulation techniques on thermal environmental analysis are also presented in this Chapter, which will form the basis of how the research to be conducted.

3.2 Research Methodology Framework

A research methodology framework is designed to ensure the research is carried out in a robust and systematic manner through selecting appropriate case buildings, collecting important building information, and conducting field studies and computational simulations. A simplified methodology framework developed for the research is presented in Figure 3-1. It would then lead to a detailed version of the methodology, which would be discussed in later sections of the chapter.

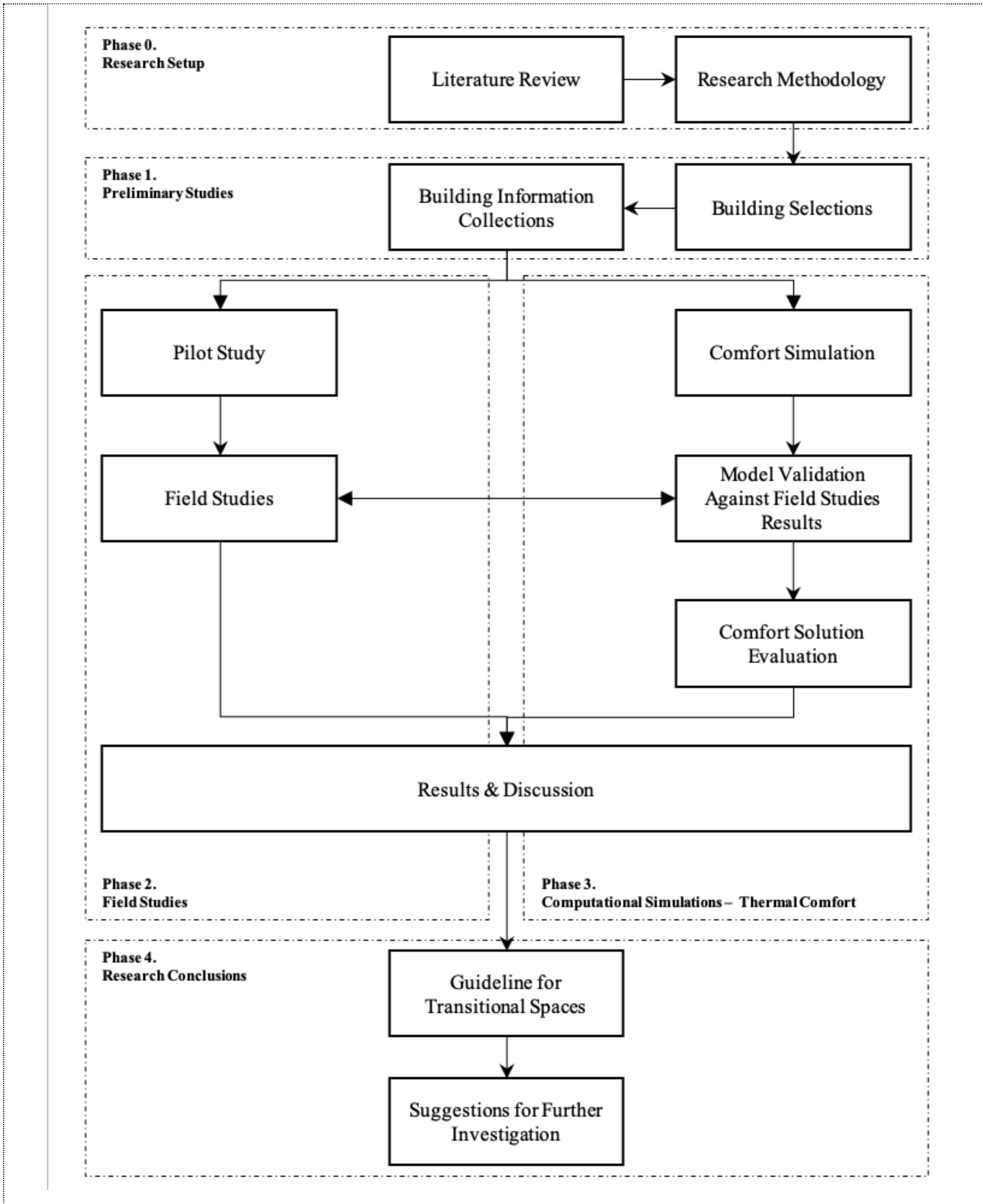


Figure 3-1 Simplified Research Framework

3.2.1 Overview of the Proposed Research Methodology

The simplified research methodology framework is illustrated in Figure 3-1. In Phase 0, literature review and development of research methodology would be conducted. The idea is to first set up the research basis and to confirm that the proposed research is able to generate new knowledge in the research area of environmental performance of building transitional spaces.

In Phase 1, real case examples, based on some selection criteria, would be selected to carry out the pilot study and field studies. The aim of this phase is to ensure appropriate selection of case buildings and to collect the necessary building information for further analysis in later phases. For each selected case, primary information would be collected, which includes site location, walk-through observations of the selected case itself and the surrounding environments, meteorological data, building basic information such as architectural layouts, systems design and building materials and properties. All the information gathered in this phase will be fed as an input to field studies and computational simulations in later phases.

In Phase 2, a pilot study is proposed in order to find out the optimised setups for the main field studies. Actual operational data of the transitional spaces in the selected case buildings would be collected. The aims of this phase are to measure the external and internal environmental data, to collect the subjective thermal responses from the building occupants, and to define thermal comfort and thus prediction of thermal comfort for transitional spaces.

The results from this phase would then be used to validate the simulation model to ensure the model accuracy and to further analyse solutions to improve the thermal environment of transitional spaces.

In Phase 3, computational simulations would be carried out to investigate the environmental performance of the transitional spaces that are selected for field studies. The aim of this phase is to identify the optimal settings for transitional spaces to achieve acceptable thermal comfort. Based on the physical measurement data collected from the selected cases, preliminary simulation would first be conducted, which would be compared against the real data gathered from Field Studies. The model, if necessary, would be fine-tuned to ensure the simulation accuracy. The validated model would then be used to study the environmental performance of transitional spaces under different scenarios. Environmental performance would first be evaluated. If thermal comfort cannot be met, common systems including passive system designs and active systems would be tested to see if how they can be applied to such spaces to maintain acceptable thermal comfort level.

The results from Phase 2 to 3 would then be summarised and discussed individually, from which mathematical analysis would be carried out to quantify the relationships among different factors and elements of transitional spaces. Optimal solutions for transitional space designs would be suggested based on the analysis outcomes.

In the final phase (Phase 4), a guideline would be created, which would provide suggestions for building designers including architects and building engineers to design transitional spaces that can achieve acceptable thermal comfort. Finally, further research investigations would be suggested so that continued improvements in such area can be carried on by future researchers.

3.2.2 Detailed Description of the Research Methodology Framework

Having had a general overview of the proposed research methodology framework, this section will review the rationale behind and the detailed process of the proposed phases 1 - 4 and will describe the relationships between theses phases. The detailed research methodology framework is presented in Figure 3-2.

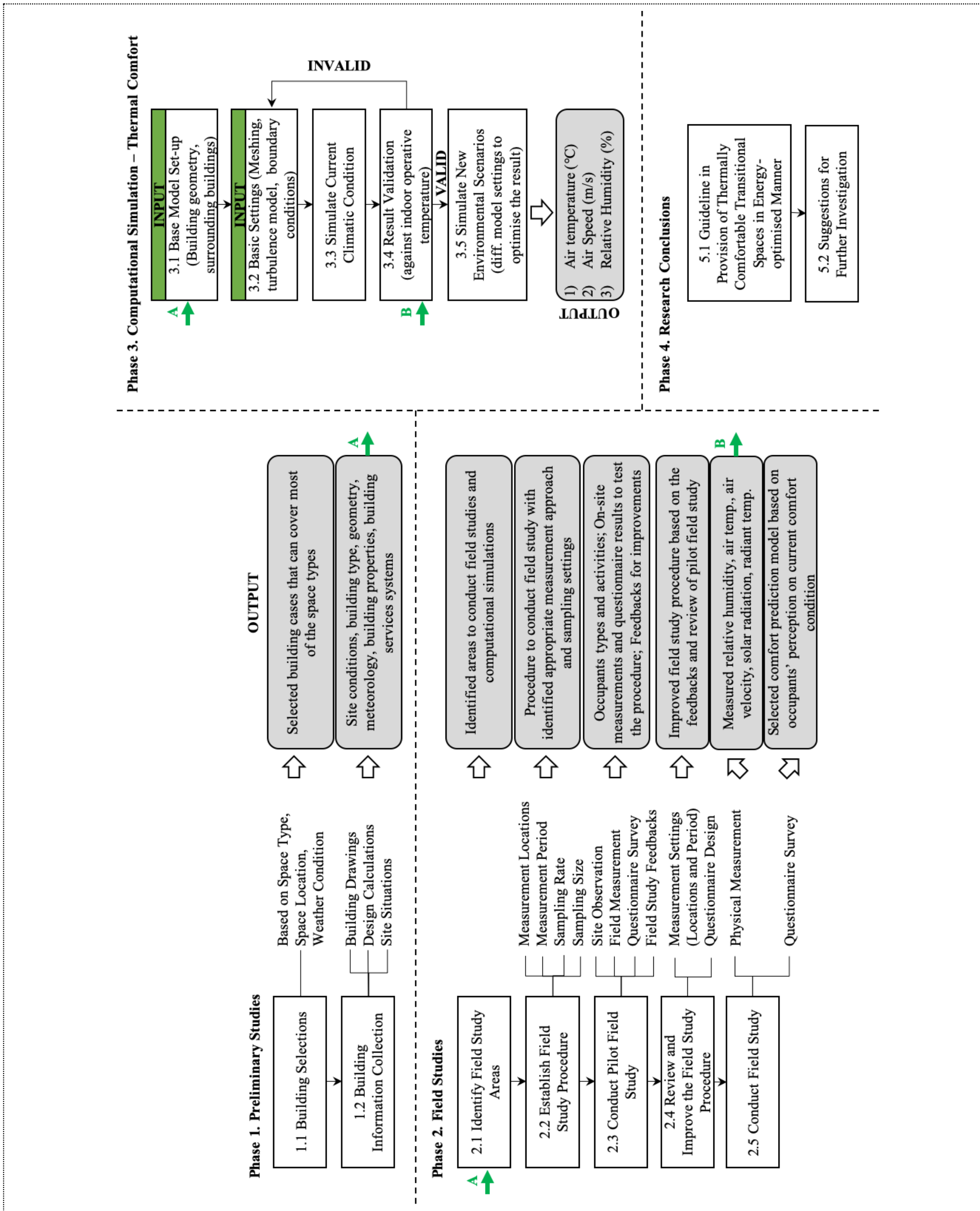


Figure 3-2 Detailed Research Methodology Framework

3.2.2.1 Phase 1 – Preliminary Studies

In this phase, real buildings with transitional spaces would be selected for the field studies in the later phase. A single outdoor weather station, which was installed on the rooftop of the Bute Building, the Architectural School of Cardiff University, was used in the study. The case buildings shall be located within 3km from the weather station to ensure the representativeness of the data collected.

Therefore, an institutional building was selected for the pilot study, and three existing buildings, namely, the National Assembly for Wales Senedd (NAfW), the Hadyn Ellis Building (HEB) and the Royal Welsh College of Music and Drama (RWCMD), were selected for the main field studies. These buildings were located at a distance from the weather station between 0.1km and 2.8km.

Then, the primary building information for the individual selected building cases would contribute as the input parameters for the Phase 2 and Phase 3 respectively (see indicators "**A**" in the Figure 3-2). For Phase 2, the information would be used to identify the appropriate locations of the field study area with reference to the architectural layout of the selected transitional spaces; for Phase 3, the information would be used as inputs for the model set-up for the computational simulation model.

3.2.2.2 Phase 2 – Field Studies

To convert theoretical knowledge into explicit knowledge, it is useful to conduct case study, which allows researchers to learn more about the actual performance of the subjects being investigated (Elaiab 2014). It is because case study provides opportunity for the individual researchers to have in-depth study on particular problems within a limited time scale (Bell 2005). Therefore, Yin described case study as “an empirical investigation into contemporary phenomenon operating in a real-life context” (Yin 2008). He added that the case study is the preferred strategy when it is to answer "how" or "why" questions because it allows researcher to identify what happened and why it happened (Yin 2008). In addition, researchers, through case study, can also gain rich understanding of the context and explore existing theory (Saunders et al. 2009).

The information collected from the selected building cases in the previous phase would be reviewed, from which the transitional spaces may be divided into different areas based on the space usages. Moreover, based on the layout plans, the locations for physical measurements would also be identified. Prior to the main field studies, a pilot study would first be conducted.

Pilot Study

A pilot study is a small-scale trial before the main investigation is carried out to assess the adequacy of the field study design and the measurement equipment to be used for data collection (Sapsford and Jupp 2006). It is desirable to conduct a pilot study before carrying out the formal questionnaire survey (Bryman 2015). Regarding the sampling size of pilot study for questionnaire survey, Babbie suggested that at least five candidates should be piloted (Babbie 2012), while Fink advised 10 or more candidates (Fink 2011).

In order to ensure or improve the appropriateness of the field study, a considerable number of researchers had opted to conduct pilot study before the final surveying were developed (Lakeridou 2010; Yan 2013; Aljawabra 2014; Alznafer 2014; Gauthier 2015; Palma 2015; Wu 2015; Heiselberg 2016; Teli et al. 2016). The purposes of performing a pilot study, with reference to these researchers, can be summarised in the followings:

1. to test the reliability and limitations of the proposed methodology in order to improve the major field study procedure and decision making (Alznafer 2014; Gauthier 2015; Palma 2015; Wu 2015; Teli et al. 2016);

2. to evaluate the comprehensiveness of the questionnaires or data collection process (Lakeridou 2010; Palma 2015; Heiselberg 2016);

3. to examine the equipment requirements and setup including the installation position of the sensors (Lakeridou 2010; Palma 2015; Heiselberg 2016);

4. to detect unanticipated problems during the surveying process (Palma 2015; Wu 2015);

5. to conduct preliminary data analysis (Yan 2013; Palma 2015; Heiselberg 2016);
6. to validate the computational model that is set up for evaluating the performance under different environmental settings (Alznafer 2014); and
7. to review the surveying team coordination (Palma 2015).

In short, the major objective of conducting a pilot study is to improve the quality of the field study to reduce the unnecessary needs of resources including time and cost by optimising the study procedure. A pilot study was carried out in a selected building in Cardiff University, named the Optometry Building. During the pilot study, the procedure including questionnaire survey, physical measurements, site observations such as identifying the general occupants' activities and the major use of the transitional space, would be examined. At the end of each questionnaire survey, the respondents' feedbacks would be collected and analysed in order to identify the room for improvements and optimise the field study procedure and the questionnaire set-ups.

Field Study

One of the most effective methods for investigation of thermal comfort in a particular region is field studies, other than the chamber studies (Kwok 1998). They are more realistic than chamber experiments when it comes to human activities and their psychological expectations (Zhang et al. 2017). Wu added that field studies are the straightforward methods to investigate occupant's thermal perception efficiently (Wu 2015). More importantly, it is also acknowledged by researchers that field studies are the most reliable way for the observation and investigation of human thermal comfort, particularly when human responses to the thermal environment are studied (Gabril 2014). Humphreys explained that this is because practical data can be obtained from field studies, which can lead to accurate estimate of favourable environmental of a particular group of people in a particular building at a particular time (Humphreys 1981). Example may be referred to Humphrey's 36 thermal comfort field studies conducted in 1975, from which he was able to draw a solid conclusion about the relationship between the environmental preference and the climate conditions from more than 200,000 observations (Humphreys 1981).

In order to create a more comprehensive picture, Mishra & Ramgopal (Mishra and Ramgopal 2013) and Kwong et al. (Kwong et al. 2014) have reviewed the applications of field studies on different climate zones and different occupied areas in the past decades. In general, field studies compose of two main sections – the field measurements for collecting the meteorological conditions; and questionnaire surveying for investigating participants' thermal responses for certain environmental conditions (Yao 2016). In order to enhance the reliability of the field studies results, a large sample size shall be targeted due to the highly variable and complex conditions in real transitional spaces (Zhang et al. 2017)

Therefore, having finalised the procedure and methods for the field study, comprehensive field study, which is composed of physical measurement and questionnaire survey, would be conducted in order to collect the on-site information for further investigations in later phases.

Field Study – Physical Measurement

In order to predict thermal comfort, measurements of environmental parameters around participants shall be conducted to establish the database, which is useful to build am empirical model for further investigation (Gabril 2014; Yao 2016). Besides, the database can be used to investigate the ventilation statistics and building thermal performance (Wu 2015). Although climatic chamber is the alternative means for data collection and it provides controlled environment with fewer confounding variables, a number of researches have has demonstrated the importance of field studies in order to investigate the human thermal comfort (de Dear and Brager 2002; Nicol 2004; Rijal et al. 2007; Palma 2015).

In general, it has been widely accepted that the measurements of the environmental data shall be carried out by locating the measuring equipment at a reference height of 1.5m (Spagnolo and de Dear 2003; Chen and Ng 2012). With reference to Ajawabra, the physical measurements shall include estimation of activity level and clothing insulation of the participants and monitoring of the environmental variables of the microclimate (Aljawabra 2014). Wu explained more explicitly that the environmental variables shall cover both indoor and outdoor environments, which include dry bulb air temperature, relative humidity and air speed and the window state (Wu 2015). Mahgoub added that solar radiation and globe temperature shall also be measured to collect the physical parameters affecting thermal comfort (Mahgoub 2015).

To summarise from the experience of the abovementioned research references and to collect enough environmental data to estimate the comfort level of the selected space by different identified available comfort prediction models (see Chapter 2), the physical measurement to be conducted in this phase would collect all the relevant environmental data, including indoor and outdoor dry bulb air temperature (in °C), relative humidity (in %), air speed (in m/s), and black-globe temperature (in °C). These measured data would be used to validate the computational simulation models for thermal comfort (Phase 3) to ensure the model accuracy (see indicators "**B**" in the Figure 3-2).

Field Study – Questionnaire Survey

"(Questionnaire) survey *is the key to understand the true nature of people's interaction with their environment*" (Nicol 1993)

Due to the facts that the actual thermal sensation heavily relies on the individual characteristics (Nikolopoulou and Steemers 2003), questionnaire surveying shall be conducted at the time when physical measurements are being performed (Mahgoub 2015). The survey can provide subjective evidence from the reported responses from the participants or observers (Brager and de Dear 1998). It is suggested that thermal comfort surveying is a widely-applied approach around the world (Chen and Ng 2012).

Questionnaire surveying is a widely-adopted approaches by researchers to investigate the subject about thermal comfort. Different questionnaire surveys in the previous research works were developed to serve different particular purposes. The followings summarise the usual development aims of questionnaire surveys from the recent researches (Givoni et al. 2003; Nikolopoulou and Lykoudis 2006; Yun and Steemers 2008; Palma 2015; Wu 2015; Yao 2016):

1. To establish occupants' thermal comfort perception that is related to the environmental conditions;
2. To identify the relationship between occupants' thermal comfort and environmental conditions;
3. To identify the comfort range of any given participant in a particular location and season;
4. To determine how occupants would react to the change of environmental conditions such as global radiation, temperature, humidity and air speed;

Similarly, the procedure to be set up for the questionnaire surveying is also different according to different occasions, such as the nature of information needed to collect, the overall available resources including cost and time, and the targeted interviewers of the research project (Stathopoulos 2006; Yao 2016).

Despite of the popular applications of the questionnaire surveying, it is criticised that the results collected from the questionnaire surveys are subjective and may be prone to bias (Gauthier 2015), e.g. the participants may provide over-desirable responses to 'please' the interviewers, or the observers may provide inaccurate interpretation of the results (Bryman 2015). In order to tackle underlined 'problem' of questionnaire surveying and ensure the representativeness of the collected information, Francis et al. suggested that the sample size should be as large as financially feasible and every participant should only be interviewed once (Francis et al. 2010).

However, the complexity of the questionnaire survey is usually limited by the availability of resources such as time and budget; therefore, the survey shall be developed with considerations of the available resources, what is aimed to find out and how accurate the result needs to be (Preston 2009; Nicol et al. 2012).

Therefore, knowing the importance and typical purposes of questionnaire survey in terms of comfort investigations, questionnaire survey would be conducted in the research whilst the physical measurements are being conducted. The data collected from the participants, including their comfort perception and their personal factors such as clothing value and activity level, would be correlated with the environmental data gathered from the physical measurement. Different available comfort prediction models in the industry would also be used to predict the comfort level for the selected case, from which the most appropriate comfort prediction model can be selected for further investigations of comfort in transitional spaces (see indicators "**C**" in the Figure 3-2).

3.2.2.3 Phase 3 – Computational Simulation – Thermal Comfort

Computational fluid dynamics (CFD) is claimed to be an effective tool for predicting the air ventilation and identifying indoor and outdoor environmental improvement (Versteeg and Malaskekera 2007; Nielsen 2015). It is very useful in optimising building systems design and operation of indoor environment (Hui 2007). Therefore, CFD is widely applied for thermal comfort studies in different climatic conditions (Kwong et al. 2014). It is also found that the application of CFD in built environments has been increasingly popular for the past 15 years, especially in the studies of room air motion, air quality and smoke conditions (Stamou et al. 2008).

CFD can provide numerical calculation results of fluid flow with respect to space and time, which can deal with different problems of fluid physics such as air flow, heat transfer and air turbulence (Yao 2016). CFD, being considered a valid tool to estimate airflow characteristics, can offer an adequate prediction of wind environment (Blackman et al. 2015). CFD can generate flow field results in both two- and three- dimensional flow patterns (Yao 2016). The useful comfort-related parameters that can be predicted by using CFD include air temperature, air velocity and air ventilation performance such as air change (Kwong et al. 2014).

CFD is often applied due to the limitations of measurement techniques, spatial coverage, resources such as manpower and time (Yao 2016), as CFD can assess different scenarios that are too expensive to carry out experimental study or impossible to investigate (Wakes et al. 2010). In short, CFD models are flexible, efficient and cheaper alternative to experimental setups (Alhajraf 2004; Parsons et al. 2004). This is why there have been a number of researchers who applied CFD in their studies.

Li et al. conducted a survey and applied CFD to investigate the performance of natural ventilation in single-zone buildings with large openings (Li et al. 2000). Richtr et al. investigated the best discharge angle of the air conditioning systems in a computer room and the thermal comfort in terms of temperature and air speed profiles by using CFD (Richtr et al. 2001). Cheong et al. adopted CFD simulation to evaluate the thermal comfort and air velocity conditions of a lecture theatre that is air-conditioned in Singapore (Cheong et al. 2003). Lin et al. compared displacement and traditional mixing ventilation systems by simulating the thermal comfort conditions in different buildings in subtropical Hong Kong with the use of CFD models and they found that the former system can give a better comfort result (Lin et al. 2005). Evola and Popov concluded from his research that renormalization group theory (RNG) is more appropriate to predict comfort conditions of buildings with wind-driven natural ventilation by comparing it with the two-equation k-ε model using CFD technique (Evola and Popov 2006). Chiang et al. studied the indoor environment of a selected office building that adopts radiant cooling system by cooling panels by using CFD, which the maximum error was validated to be about 1.62% only, and they concluded from the research that thermal comfort can be achieved with an air temperature of 24 °C with a possible energy reduction of 13.2% (Chiang et al. 2012).

Due to the problems in defining the actual boundary conditions and different possible adaptation and acclimatisation of occupants to the thermal environments, there are always some discrepancies between the CFD model and experimental results (Kwong et al. 2014). Therefore, there is a strong need for model validation by comparing the simulated data from CFD with the experimental data in order to reduce the error introduced by numerical approximations, choice of turbulence models and boundary condition set-up (Yao 2016).

Therefore, in this research, CFD modelling would be adopted to investigate the impacts of architectural design and systems operation on the environmental performance of transitional spaces. Based on the primary building information gathered in Phase 1 (see indicators "**A**" in the Figure 3-2), the base model would be set up in the CFD, in which the conditions would be modelled in accordance with the existing environmental conditions. The results generated from the first simulation attempt would then be validated against the on-site physical measurement results conducted in Phase 2 (see indicators "**B**" in the Figure 3-2). Model modification would be carried out until an acceptable accuracy can be achieved. The validated model would then be used to simulate a wider range of scenarios, e.g. different air temperature, occupants' activities and climatic conditions, so as to identify the optimal range of settings for achieving acceptable comfort level in transitional spaces.

3.2.2.4 Phase 4 – Research Conclusions

The findings from the previous phases would be summarised in this phase. The outcomes would be gathered, from which suggestions for building designers would be concluded in a guidance in order to for them to design a thermally comfortable transitional space with minimal use of energy. The guideline would include the suggested comfort predict model, suggested comfort criteria and design concerns of thermal comfort and energy performance of transitional spaces. Finally, as this research cannot cover all the possible situations in the world, suggestions would be drawn for other researchers in the future who are interested in this subject area to carry out investigations.

3.3 Pilot Study

In order to optimise the proposed methodology before carrying out the main study, a pilot study was conducted in a selected building in Cardiff University, which was the Optometry Building. During the pilot study, apart from physical measurements and questionnaire surveys, feedbacks of the questionnaire form and interviewer's performance were also reviewed with the respondents. These were all contributed to the final proposed methodology which was then undertaken in the main study. The followings will first introduce the pilot study research design, the observations and results gathered from the pilot study will then be discussed.

3.3.1 Pilot Study Design

With the consideration of building access, architectural design and availability of building information, The Optometry Building in Cardiff University was selected to conduct the pilot study, which included physical measurements and questionnaire surveys. The study was carried out on 21st July 2017 from 12:20 to 16:20. In order to optimise the research methodology for the main study, the pilot study procedure and method structure were structured.

3.3.1.1 Building Description

The Optometry Building was located on Maindy Road, off Cathays Terrace. It was about 0.5km away from the weather station which was located on the rooftop of the Bute Building. Figure 3-3 illustrates the physical locations of the Optometry Building and the weather station. The weather station measured the external environmental parameters including air temperature, relative humidity, wind speed, and wind direction.

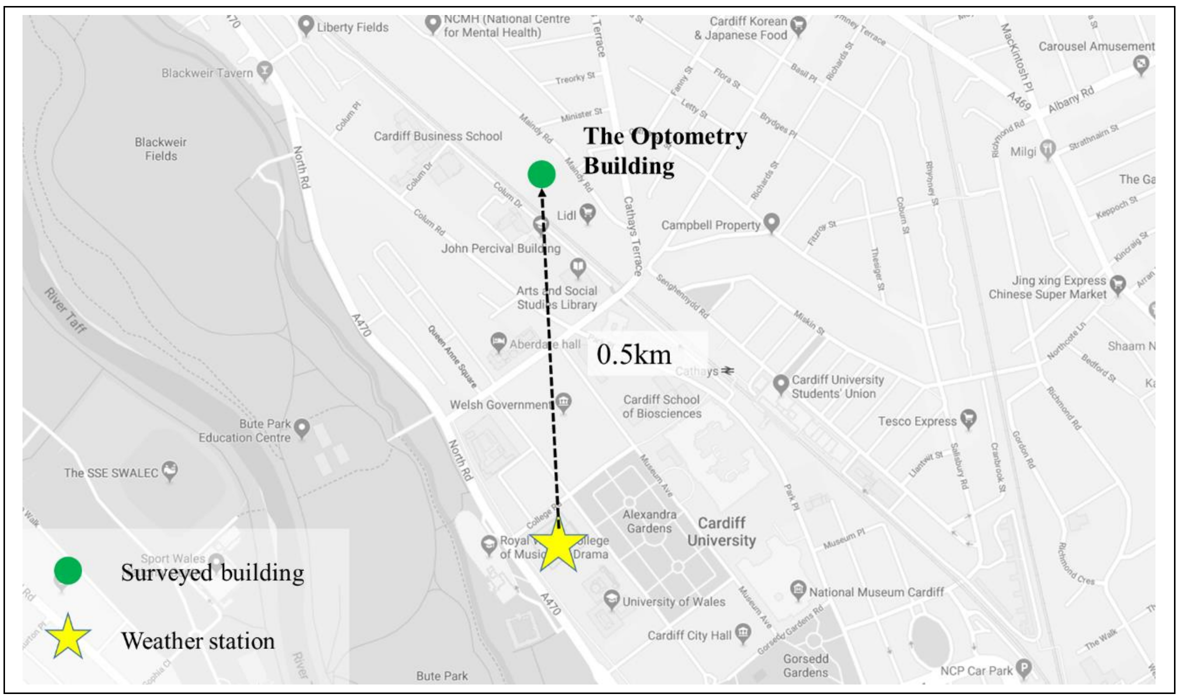


Figure 3-3 Location of the Optometry Building and weather station

The building was an institutional building which brings research, teaching and patient clinics together in one place. There was a level access into the building via automatic main entrance doors. Through the second set of automatic doors, there was a two-storey atrium, as shown in Figure 3-4, which serves as a transitional space linking the indoor environment with the external environment. Right next to the atrium, an open café area was provided for seating, resting and eating.

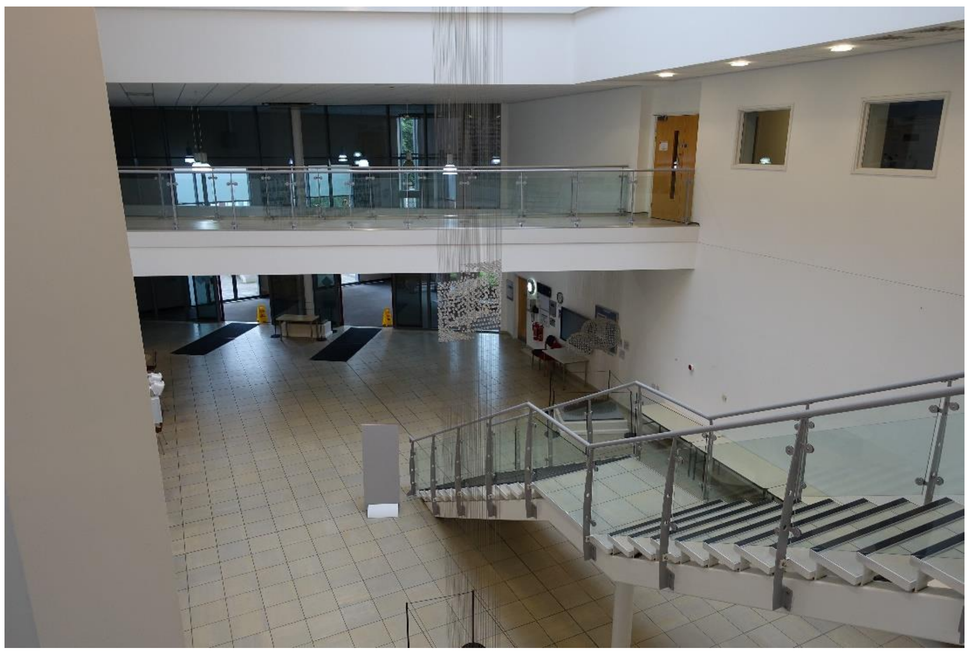


Figure 3-4 Indoor environment of the Optometry Building

3.3.1.2 Study procedure

Prior to the pilot study, a procedure was established to collect the necessary data in order to achieve the optimisation of the research methodology. As shown in Figure 3-5, a 7-step procedure was designed for the pilot study.

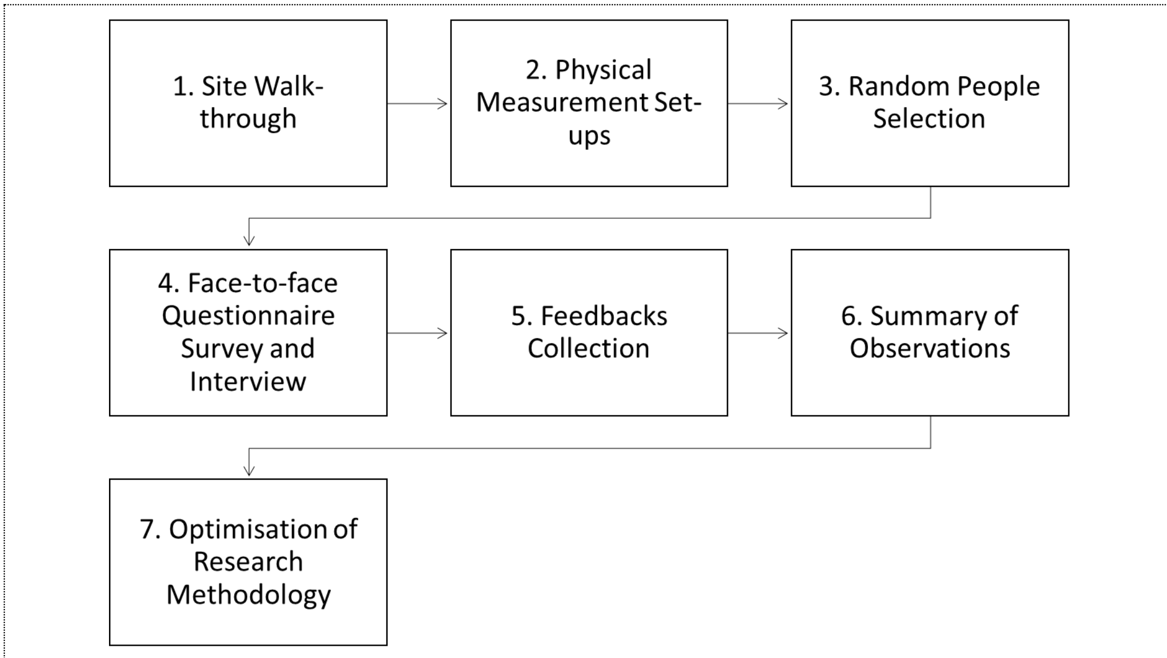


Figure 3-5 Pilot study procedure

Prior to the pilot study, a site walk-through was conducted to familiarise the surrounding environment of the building, including the outdoor weather condition, surrounding buildings and facilities, indoor built environment, and general occupants' behaviour within the building. Then, the measurement equipment, as illustrated in Figure 3-6, was placed at different locations within the transitional spaces, including the café area, atrium space and entrance lobby. The measurement equipment was set up to measure the indoor dry-bulb temperature, indoor relative humidity, black-globe temperature, and air speed. For the outdoor weather conditions, the data were extracted from the measured records by the outdoor weather station that was installed on the rooftop of the Bute Building of Cardiff

University. As the memory space of the indoor data logger was limited, the measurement was taken at 10-minute intervals. The outdoor weather data were recorded every five minutes.

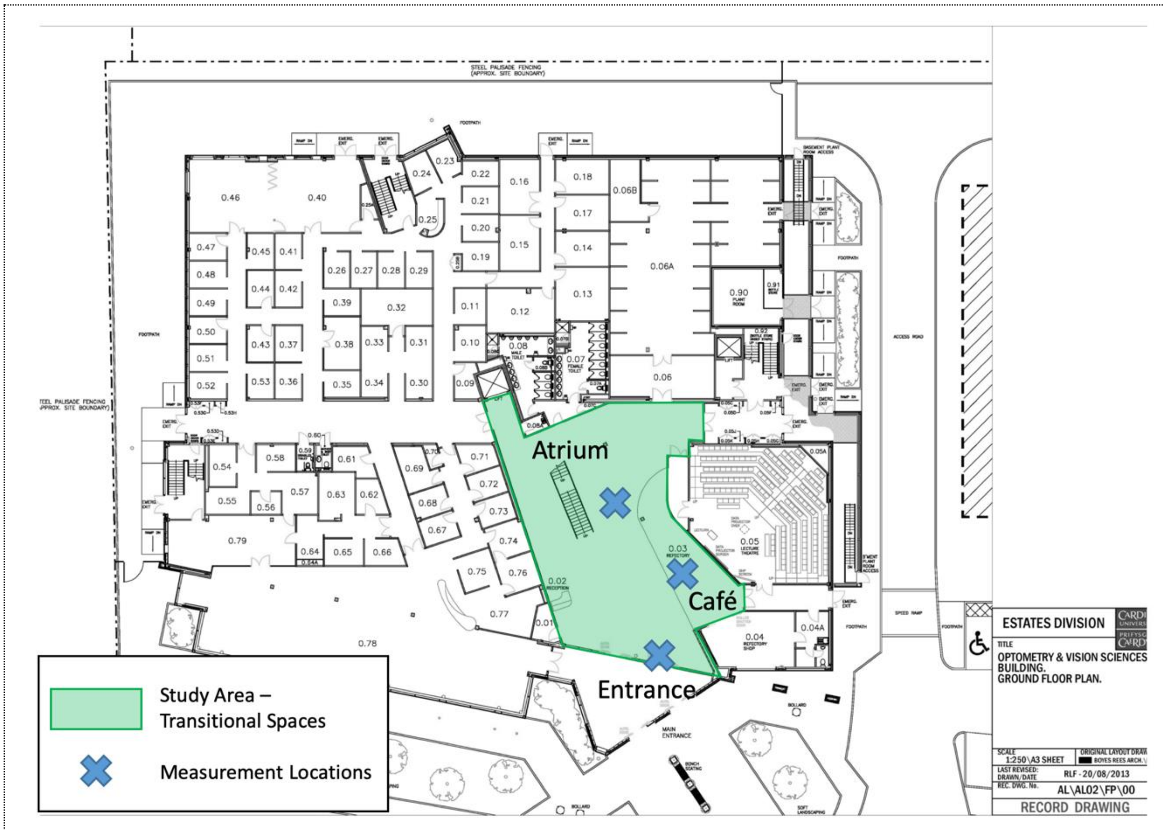


Figure 3-6 Measurement locations

Once the measurement equipment was installed and ensured they were well-functioned, people using the transitional spaces were randomly selected for questionnaire surveys. To ensure that the participants understand the questionnaire forms, the surveys were conducted face-to-face so that necessary clarifications can be made immediately to prevent mis-understanding. The average time the participant spent to complete the form was about 10 minutes. Depending on whether the participants would have spare time, feedbacks were collected from the participants about their experience of the whole process of questionnaire survey. Some general questions were asked, for example, "do you find any difficulty of understanding the questionnaire form?", "is there any improvement suggestion on the form design?", and "can you think of any additional comfort-related question that could be added to the form?".

After all, the responses collected from the questionnaire form were input to a spreadsheet and correlated with the measured environmental conditions at the same time when the questionnaire form was filled in. The data and the whole procedure adopted to conduct the questionnaire surveys were thoroughly reviewed, from which the improvement areas were identified.

3.3.2 Observations from the Pilot Study

After the thorough review of the whole pilot study process, some observations from the physical measurements and questionnaire surveys were concluded. They are summarised in the followings:

3.3.2.1 Physical measurements

The major improvement aspects for the physical measurements in the main study include the measurement intervals and the time required for accurate measurements.

1. Measurement intervals

   Throughout the pilot study, only 50 numbers of readings were recorded for each data logger and there were plenty of memory space available after the measurement. Therefore, in order to have a more precise measurement, the measurement could be taken at 1-minute intervals, instead of 10-minute interval in the main field studies. This could also reduce any errors due to interpolation as it assumed that the relationship between one recorded datum from another was linear, which it might not reflect correctly the real case.

2. Time required for accurate measurements

   As the measurement equipment was carried from outside, where there was a temperature difference between outdoor and indoor environment, a surge in the measured temperature by the data loggers was observed. The temperature was compared to the ones measured by the hand-held anemometer. It was found that the data loggers shall take about 10 minutes to accurately measure the indoor thermal environment.

3.3.2.2 Questionnaire surveys

Based on the observations and interactions with the participants, the improvement of the field study can be summarised in to "questionnaire form design" and "additional questions" in order to optimise the whole approach for the main study.

1. Questionnaire form design

   During the questionnaire survey, it was observed that some participants found difficulties in filling in the thermal sensation and preference sections. Some of them asked for clarification directly and some filled in a different answer than what they verbally described. Taking the sections 2 – 3 as illustrated in Figure 3-7, where there were more participants found difficulties at, for example, 7-point scale and 5-point scale were adopted for the perceptions and preferences respectively. People normally got lost with the whole group of boxes provided. By consulting the participants' opinions, a scale shall be provided next to each box to prevent confusion. For example, for overall feeling, "-3" shall be marked next to the box for "very unpleasant" and "0" shall be marked next to the box for "neutral".

Section 2 - THERMAL SENSATION
Please tick the best description about your current feeling using the below scale.

Overall Feeling	Unpleasant	☐	☐	☐	☐	☐	☐	☐	Pleasant
Comfort Level	Cold	☐	☐	☐	☐	☐	☐	☐	Hot
Humidity	Dry	☐	☐	☐	☐	☐	☐	☐	Humid
Air Movement	Still	☐	☐	☐	☐	☐	☐	☐	Draughty
Your preference	Cooler		☐	☐	☐	☐	☐		Warmer

Section 3 - SUN PENETRATION

Please tick what you prefer about sunlight:	Less		☐	☐	☐	☐	☐		More

Figure 3-7 Original form design for sections 2 – 3

2. Additional questions

Based on the conservation with the participants, some interesting questions were found to be worth being added to the questionnaire form for main field studies. These may have some correlations among the other parameters. In summary, the additional questions included:

a. "Are you a regular user of this space?" – throughout the pilot study, some participants who claimed to be a regular user of the space tried to recall their previous experience in the space when they filled in the form. Therefore, it would be interesting to see the relationship between it and the thermal sensation.

b. "Have you had any meal during the last hour?" – the author found the thermal sensation changed when he felt hungry. This question was added so as to investigate whether the status of hungriness would have impacts on the thermal sensation.

c. "How would you overcome uncomfortable situation, if any" – it was observed that some people would change their clothing when they entered the transitional spaces from outdoor. It helped generating an idea to evaluate the people's adaptability to their thermal environment, and to investigate what actions people would take to overcome the uncomfortable situations.

d. "If you have been to this space before, what is the best thermal description about your previous experience in this space?" – it may be interesting to add this question as some of the participants tried to compare their current feelings with what they felt before at the same location. Therefore, this question was added to evaluate weather this may be the significant parameter that would have impacts on people's current thermal sensation.

3.4 Field studies set-ups

The field studies carried out in the three selected buildings were comprised of physical measurements and questionnaire surveys. The following sections demonstrate how they were set up the collect the necessary data from the field studies. As to collect the environmental data and personal subjective comfort responses, on-site measurements and questionnaire survey were conducted at the same period of time. When the participants were filling out the survey, the indoor and outdoor environmental conditions were measured. In this section, the set-ups for the on-site measurements and questionnaire survey are discussed.

3.4.1 Physical Measurements

Questionnaire surveys were carried out at the same time as the indoor environmental parameters were measured, including air temperature, relative humidity, air velocity and black globe temperature. The accuracy of the instrumentations used for the field studies complied with the requirements of ASHRAE 55-2013 (ASHRAE 2013). Table 3-1 summarises the details of the instruments that were used in the field studies. The state-of-art equipment was tested and calibrated in the Welsh School of Architecture (WSA) laboratory before the field measurements. The setup of the equipment and data retrieval were conducted based on the user's manual accordingly.

Table 3-1 Measurement range and accuracy for the instruments used for the field studies

Parameter	Instrumentation model	Range	Accuracy	Accuracy requirements ASHRAE 55
Air temperature	Tinytag Ultra 2 Temperature and Relative Humidity Logger	-25°C - 85°C	±0.5°C (for range 0-40°C)	Minimum: ±0.5°C Ideal: ±0.2°C
Relative humidity	Tinytag Ultra 2 Temperature and Relative Humidity Logger	0% - 95%	±3% (at 25°C)	±5%
Black-globe temperature	Tinytag Talk 2 Temperature Logger (with 40mm black table-tennis ball)	-40°C - 125°C	±0.4°C (for range 0-70°C)	Minimum: ±2°C Ideal: ±0.2°C
Air speed	Lutron AM-4204 Anemometer	0m/s - 20m/s	±0.05m/s (for up to 1m/s)	±0.05m/s

Measurements were conducted at different locations across the indoor transitional spaces, including entrance lobby area, atrium area and café area. In order to ensure that the readings were representative throughout the surveyed area, and to identify the best measurement locations, a range of measurements was taken at different locations within each space. The average of the measured air temperatures at these locations were then calculated. The location where the measured air temperature was closest to the average air temperature was selected to place the measurement instruments. The air speed was measured at 15-minute intervals and all the other parameters were monitored at one-minute intervals. Each measurement location was set at 1.1m height from the floor. For the outdoor environmental parameters, data were recorded every five minutes by a weather station, which was installed on the rooftop of the Bute Building, the Architectural School of Cardiff University. The weather station data were recorded by a Campbell Instruments CR10 data logger. The air temperature and relative humidity were respectively measured by a Rotronic temperature and humidity probe with a radiation shield. More information of the weather station can be found on the website of Cardiff University[1]. Figure 3-8 and Figure 3-9 illustrates the setups for the weather station and indoor measurement instruments.

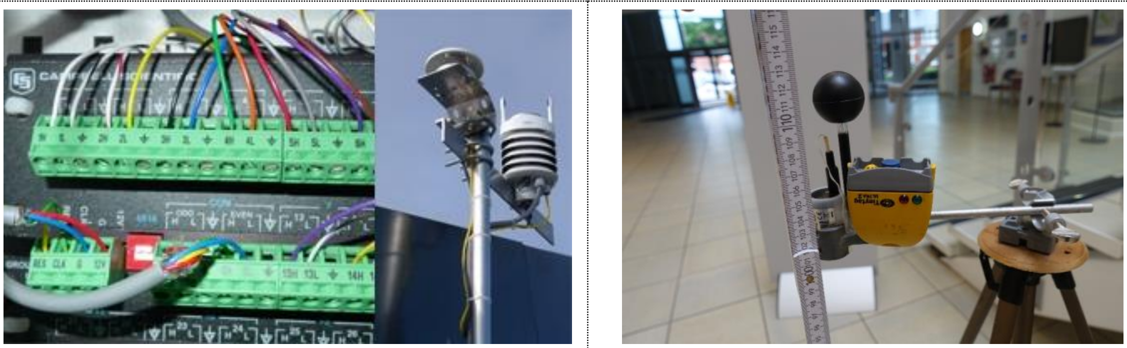


Figure 3-8 Instrument setups for outdoor (left) and indoor (right) environments

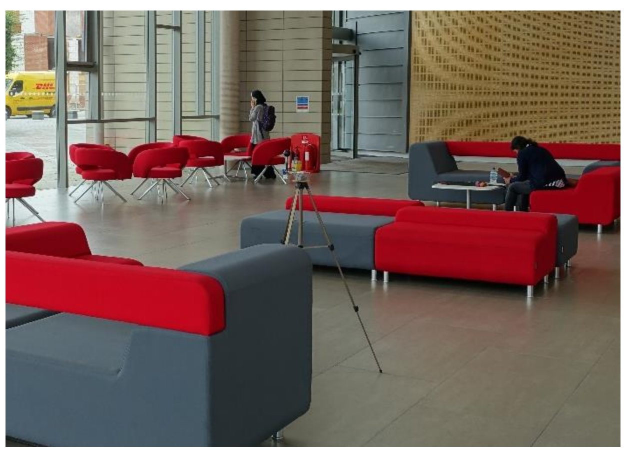


Figure 3-9 Indoor physical measurement set-ups

[1] Information of Meteorological Station on the roof of the Bute Building. https://www.cardiff.ac.uk/architecture/about-us/facilities/environmental-lab/meteorological-station. Accessed in Jun 2017.

3.4.2 Questionnaire Surveys

The questionnaire survey was developed to collect two major information – the personal parameters and the subjective responses of participants on the current environmental conditions. With reference to a number of questionnaire survey designs in the similar previous researches (Xavier and Lamberts 2000; Cheong et al. 2003; Spagnolo and de Dear 2003; Zhang et al. 2007; Dili et al. 2010), the questionnaire form was designed to be simple and user-friendly that each interview would take about 10 minutes, while the important information can be obtained from the participants.

Both open and closed questions were designed in the questionnaire. Open questions can obtain participants' own answers, while closed questions provide a set of fixed options for participants to choose as the answer(s) (Bryman 2015). Each of the question types has it pros and cons but closed questions are preferred in general for questionnaire survey (Hou and Tweed 2014). Two major advantages of closed questions were pointed out by May – (1) they are easier to use and analyse; and (2) they permit comparability between participants' responses (Langford and May 2006). Considering these advantages of closed questions and that coding is a problem when processing the answers from open questions (Bryman 2015), majority of the questions in the proposed questionnaire for this research were designed to be closed questions.

A standardised questionnaire was developed to collect subjective data from the building occupants for comfort evaluation in the specified locations of the surveyed buildings. The questionnaire form used in the field study is attached in the Appendix A**.** 24 questions were included in the questionnaire, which adopted a combination of open-ended, partially closed-ended and predominantly closed-ended questioning approaches. 7-point scale and 5-point scale methods were used for the thermal sensation questions and thermal and sunlight preference questions respectively, as presented in Table 3-2. In order to understand people's adaptability to their thermal environment, an open question "how would you overcome uncomfortable situations, if any" was included in the questionnaire.

Additional data collected from the questionnaire included the demographic data, purpose of using the spaces, activity level, clothing insulation, time spent at the interviewed location, previous space locations and time spent in previous space, and feedbacks and previous thermal experience in the interviewed location. Some subjective data such as clothing insulation and activity level were collected by giving a list of pre-set options with an open option which allowed respondents to fill in the answer that was out of the options. Building users were randomly selected within the transitional spaces of the surveyed buildings to carry out the questionnaire survey. In order to ensure the respondents had sufficient time to experience the thermal environment within the surveyed buildings, people who just entered the buildings from outdoor spaces would not be chosen for interviews. They were interviewed at least 5 minutes after they entered the buildings. The average period of stay in the transitional spaces for the respondents in NAfW, HEB and RWCMD were 26.5, 65.1 and 37.6 minutes respectively. Each survey was carried out by a means of a structured interview which took approximately 10 minutes to complete.

Table 3-2. Sensation and preference scale used in the survey

Scale	Overall Thermal Feeling	Thermal Comfort Sensation	Humidity Sensation	Air Movement Sensation	Thermal Preference	Sunlight Preference
+3	Very pleasant	Hot	Very humid	Very draughty	-	-
+2	Moderately pleasant	Warm	Moderately humid	Moderately draughty	Much warmer	Much more
+1	Slightly pleasant	Slightly warm	Slightly humid	Slightly draughty	A bit warmer	A bit more
0	Neutral	Neutral	Neutral	Neutral	No change	No change
-1	Slightly unpleasant	Slightly cool	Slightly dry	Slightly still	A bit cooler	A bit lesser
-2	Moderately unpleasant	Cool	Moderately dry	Moderately still	Much cooler	Much lesser
-3	Very unpleasant	Cold	Very dry	Very Still	-	-

After optimising the questionnaire survey form based on the observations and feedbacks collected from the participants during the pilot study, the survey was composed of 6 sections and most the questions were designed to be convertible to empirical data for result analysis and parametric correlations in later phases. The followings describe the purposes and the rationale behind each of the sections.

3.4.2.1 Section 1 – Personal Information

The purpose of this section is to collect the basic information from the participants and time and location of the questionnaire being taken. Figure 3-3 illustrates the section 1 of the questionnaire form. The information of the questionnaire location, time and date would be used to correlate with the recorded environmental data from the on-site measurements in order to identify the quantified relationships between different parameters. The questions about participants' gender and age, their purpose of using the transitional spaces, and whether they are regular users and whether they had any meal during the last hour were also included in the questionnaire form. This would help to understand whether these parameters would have any impacts on the participants' perceived thermal comfort on the transitional spaces.

Section 1 - PERSONAL INFORMATION

Location: ______________________________

Time: ____________ **Gender:** M / F

Date: ____________ **Age:** ____________________

What are you here for: Working / Dining / Shopping / Resting / Waiting / Other: ___________

Are you a regular user of this space (your current location): Yes / No

Have you had any meal during the last hour: Yes / No

Figure 3-10 Questionnaire Survey – Section 1 – Personal Information

3.4.2.2 Section 2 – Thermal Sensation

The purpose of this section is to collect the personal subject responses to the current environmental conditions of the transitional space. As presented in Figure 3-11, this covered the participants' perception on the current thermal conditions, including overall feeling of the environment and their subjective responses to the comfort level, humidity and air movement, and their preference on the current environmental conditions of the interviewed location.

Section 2 - THERMAL SENSATION

Please tick the best description about your **current feeling** at this space (your **current location)** using the below scale.

Overall Feeling	Unpleasant	☐ -3	☐ -2	☐ -1	☐ 0	☐ 1	☐ 2	☐ 3	Pleasant
Comfort Level	Cold	☐ -3	☐ -2	☐ -1	☐ 0	☐ 1	☐ 2	☐ 3	Hot
Humidity	Dry	☐ -3	☐ -2	☐ -1	☐ 0	☐ 1	☐ 2	☐ 3	Humid
Air Movement	Still	☐ -3	☐ -2	☐ -1	☐ 0	☐ 1	☐ 2	☐ 3	Draughty
Your thermal preference	Cooler		☐ -2	☐ -1	☐ 0	☐ 1	☐ 2		Warmer

Figure 3-11 Questionnaire Survey – Section 2 – Thermal Sensation

3.4.2.3 Section 3 – Sun Penetration

The purpose of this section is to understand the personal subjective preference on the sun penetration. As shown in Figure 3-12, 5-point scale was adopted to gather the participant's preference on the sunlight penetration. The collected results could be compared with the comfort level that the participants answered in Section 2 and this can help to identify the improvements on building facades / roof design of the transitional spaces in order to provide the preferred sunlight to the occupants.

Section 3 - SUNLIGHT PENETRATION

Your sunlight preference at this space	Less	☐ -2	☐ -1	☐ 0	☐ 1	☐ 2	More

Figure 3-12 Questionnaire Survey – Section 3 – Sun Penetration

3.4.2.4 Section 4 – Clothing

The purpose of this section to collect the clothing information from the participants. This is one of the important parameters to predict comfort by using heat balance approach. As illustrated in Figure 3-13, participants were required to report all the clothing that they were wearing during the questionnaire survey. A space was also provided for the participants to fill in their current garment(s) that was/were not included in the options provided. The options chosen by the respondents were then converted into quantitative figures according to ASHRAE Standard 55-2013 (ASHRAE 2013) and ISO 7703:2005 (ISO 2005). For example, a person wearing a short-sleeve shirt (0.15), shorts (0.06) and shoes (0.02) would have a clothing value of 0.23 (0.15+0.06+0.02).

Section 4 - CLOTHING

Please select **ALL** the correct descriptions of what you are **currently** wearing.

Clothings:	Trousers:	Footwear / Accessories:
☐ Short-sleeve shirt	☐ Shorts	☐ Shoes / Sandals
0.15	0.06	0.02
☐ Long-sleeve shirt	☐ Straight trouser	☐ Boots
0.20/0.30 ☐ thin ☐ thick	0.15/0.24 ☐ thin ☐ thick	0.1
☐ Sleeveless sweater	☐ Sweatpant / Jogger	☐ Gloves
0.13/0.22 ☐ thin ☐ thick	0.28	0.05
☐ Long-sleeve sweater	☐ Overalls	☐ Socks
0.20/0.35 ☐ thin ☐ thick	0.3	0.02/0.03/0.06 ☐ankle ☐calf ☐knee
☐ Jacket	☐ Skirt / dress	
0.25/0.35 ☐ thin ☐ thick	0.15/0.24 ☐ thin ☐ thick	Others: ____________
☐ Coat / Winter jacket	☐ Winter dress	
0.60	0.33/0.47 ☐ thin ☐ thick	____________

Figure 3-13 Questionnaire Survey – Section 4 – Clothing

3.4.2.5 Section 5 – Activity

The purpose of this section is to understand the activity level after the participants have entered the space. Similar to the clothing values, the answered activity level can be converted to quantifiable metabolic rate. The activity levels would be quantified according to the suggested values from ASHRAE 55-2013 (ASHRAE 2013). As it is hypothesised that the period of time that a person has stayed in a space has impact on the personal comfort responses to the given environment, this question was also designed in this section. The section is illustrated in Figure 3-14.

Section 5 - ACTIVITY AT THE CURRENT LOCATION
Please circle the best description of your major activity after you have entered this space (your **current location**).

Sleeping 0.7 Sitting 1.0 Standing 1.2 Walking Normally 2.0 Walking Quickly 2.6
Rushing 3.8 Other: ______________
How long you have stayed in this space: ______ hours ______ minutes

Figure 3-14 Questionnaire Survey – Section 5 – Activity

3.4.2.6 Section 6 – Previous Space

The purpose of this section is to collect the data about the participant's pervious activities. It is hypothesised that thermal experience of a person would have impacts on the comfort subjective responses to the current environment. Therefore, the data collected from this section would be used to correlate with the current comfort status that the participants have answered in Section 2. The questions designed for this section is shown in Figure 3-15.

Section 6 - PREVIOUS SPACE

Where were you before entering this space: Indoors Outdoors

How long did you stay at the previous space: ____ hours ____ minutes

Comfort Level at the previous space: Cold ☐ -3 ☐ -2 ☐ -1 ☐ 0 ☐ 1 ☐ 2 ☐ 3 Hot

Figure 3-15 Questionnaire Survey – Section 6 – Previous Space

3.4.2.7 Section 7 – Feedback / Previous Experience of this Space

The purpose of this section is to understand the participant's adaptability to their thermal environment and to understand their previous experience in the interviewed space if they have been to the space before. Since the answers may be different from a participant to another, an open question style, as illustrated in Figure 3-16, was adopted for the general feedback on the thermal environment and adaptive actions that participants would take to overcome the uncomfortable situation. For the previous experience, 7-point scale was applied to gather the data.

Section 7 - FEEDBACK / PREVIOUS EXPERIENCE OF THIS SPACE

Any feedback about thermal environment for this space: ____________________

How would you overcome uncomfortable situation, if any: ____________________

If you have been to this space before, what is the best thermal description about your previous experience in this space:

Summer Time Cold ☐ -3 ☐ -2 ☐ -1 ☐ 0 ☐ 1 ☐ 2 ☐ 3 Hot

Winter Time Cold ☐ -3 ☐ -2 ☐ -1 ☐ 0 ☐ 1 ☐ 2 ☐ 3 Hot

Figure 3-16 Questionnaire Survey – Section 7 – Feedback / Previous Experience

3.4.3 Data Analysis

The data collected from the field studies were first compiled into spreadsheets and then analysed using the Statistical Package for Social Sciences (SPSS) version 23. Data were separately analysed according to surveyed buildings and specified locations within the buildings. In order to assess the correlation between pairs of variables, Pearson correlation coefficients were computed. The outcomes were analysed based on two significance levels, which were interpreted as average statistical significance ($p<0.05$) and high statistical significance ($p<0.01$).

3.5 Computational Simulation

3.5.1 Review of CFD Application in Built Environment

CFD is an effective tool for predicting the air ventilation and identifying indoor and outdoor environmental improvement (Versteeg and Malaskekera 2007; Nielsen 2015). It is useful in optimising building systems design and operation of indoor environment (Hui 2007). Enabling to perform comparative analyses based on different scenarios is the major advantage of this kind of numerical simulation (Arnfield 2001; Souch and Grimmond 2006). Moreover, it can also provide a platform for researchers to investigate different variables in the entire computational domain, while field studies in general can only generate a limited set of database (Rizwan et al. 2008; Moonen et al. 2012; Blocken 2014). As opposed to the field measurements, CFD simulation may generate exhaustive airflow patterns and thermal environment in a more economic manner for investigations of indoor thermal comfort (Shan et al. 2019). Therefore, CFD is widely applied for thermal comfort studies in different climatic conditions (Kwong et al. 2014). It is also found that the application of CFD in built environments has been increasingly popular for the past 15 years, especially in the studies of room air motion, air quality and smoke conditions (Stamou et al. 2008).

Due to the motivation of more advanced computer developments (Arnfield 2001) and the limitations of measurement techniques, spatial coverage, and resources such as manpower and time, there is a growing popularity of using CFD in the industry (Yao 2016; Toparlar et al. 2017). CFD may also be used to investigate different scenarios of an experimental study that may be too expensive or even impossible to be conducted (Wakes et al. 2010). In short, CFD models are flexible, efficient and cheaper alternative to experimental setups (Alhajraf 2004; Parsons et al. 2004). Through CFD modelling, numerical calculation results of fluid flow with respect to space and time can be provided and different problems of fluid physics such as air flow, heat transfer and air turbulence can therefore be analysed (Yao 2016). CFD, being considered a valid tool to estimate airflow characteristics, can offer an adequate prediction of wind environment (Blackman et al. 2015). CFD can generate flow field results in both two- and three- dimensional flow patterns (Yao 2016). The useful comfort-related parameters that can be predicted by using CFD include air temperature, air velocity and air ventilation performance such as air change (Kwong et al. 2014). Solving the fundamental PDEs (partial differential equations) of conservation laws of continuity, momentum and energy is the core concept of using CFD simulations (Huizenga et al. 2006). Aiming to optimise the design of ventilation systems, CFD simulations have been extensively adopted in buildings for air movement predictions (Sun and Wang 2010; Li and Nielsen 2011; Chiang et al. 2012).

It has now been more common to use CFD simulations for indoor building applications including microclimate study (Nielsen 2015; Toparlar et al. 2017). Lin et al. compared displacement and traditional mixing ventilation systems by simulating the thermal comfort conditions in different buildings in subtropical Hong Kong with the use of CFD models and they found that the former system can give a better comfort result (Lin et al. 2005). A single room with different ventilation set-ups and heating systems such as radiators and underfloor heating were investigated by several studies (Myhren and Holmberg 2008; Chiang et al. 2012; Gilani et al. 2016). Risberg et al. conducted a study to compare the thermal effects of different heating systems including air heating with supply displacement ventilation ducts, radiators and underfloor heating (Risberg et al. 2015). Li et al. conducted a survey and applied CFD to investigate the performance of natural ventilation in single-zone buildings with large openings (Li et al. 2000). Catalina et al. used CFD to evaluate the thermal environment of a test room including mean velocity, temperature, and the PMV value (Catalina et al. 2009). Richtr et al. investigated the best discharge angle of the air conditioning systems in a computer room and the thermal comfort in terms of temperature and air speed profiles by using CFD simulations (Richtr et al. 2001). Cheong et al. adopted CFD simulation to evaluate the thermal comfort and air velocity conditions of a lecture theatre that is air-conditioned in Singapore (Cheong et al. 2003).

3.5.2 CFD Tool Selection

In this research, CFD code STAR-CCM+, which is a three-dimensional CFD tool, was selected to carry out the CFD simulations. The code was developed by CD-adapco, which is capable of simultaneously solving fluid flow and heat transfer problems. The advantage of this software was the more user-friendly interface and the provisions of almost all functions required for a CFD simulation including geometry, meshing, simulation, and post-processing (Kong et al. 2017). When compared with other CFD codes, STAR-CCM+ converges to equilibrium state in a more reasonable timeframe, providing steadier results (Youchison et al. 2010).

The software has been used much more frequently in recent years and well-performed when compared to other software (Peng, LeiPeng et al. 2016). Norton et al. developed predictive models with the use of Star-CCM+ for an indoor environment of a live-stock building under natural ventilation mode (Norton et al. 2010). Lee et al. investigated the indoor thermal environment which was served by a multi-sheet-type radiant panel heating system by conducting CFD modelling using Star-CCM+ (Lee et al. 2016). Hong et al. applied Star-CCM+ to calculate the indoor temperature distributions of an educations facility (Hong et al. 2017). CFD simulations were set up by Shi & An using Start-CCM+ to aid the optimisation design of a football stadium in China (Shi and An 2017). Yasa evaluated the effect of different glass façade designs on the thermal comfort in an atrium building using Star-CCM+ as a tool (Yasa 2015).

In order to take into the account of the impacts of internal surface temperature on the environmental situation, a coupling method was adopted between a dynamic simulation code using HTB2 and a CFD model using Star-CCM+. HTB2 is a software that was developed by the Welsh School of Architecture of Cardiff University (Alexander 1997). Taking into account the building location, building materials and construction, spatial attributes, and occupancy profiles, dynamic thermal simulation can be performed by using HTB2. With the application of HTB2, simulation was conducted with the use of the exported internal air temperatures from CFD. Building façade surface temperatures calculated by HTB2 were used as the boundary settings for the CFD models.

3.6 Conclusion

A robust research methodology framework was presented in this Chapter. In order to achieve the research aim and objectives, the research will be conducted by two major parts, which are the field studies and computational simulation. The Optometry Building in Cardiff University was selected for a pilot study so as to optimise the approach of field studies. A questionnaire form that includes 24 questions was fixed; and the physical measurement method was developed. Three buildings in Cardiff were selected to conduct the field studies, which included questionnaire surveys and physical measurements. Considering the representativeness of the outdoor measurement data, the furthest selected case building, which was the National Assembly for Wales (NAfW), was only 2.8km from the weather station which is located at the rooftop of Welsh School of Architecture of Cardiff University. In order to establish the analytical method for the data to be collected in the three selected surveyed buildings, the data analysis method, based on literature review, was also established. Lastly, computational simulation techniques would be adopted to identify the impacts of different systems on the thermal environment within building transitional spaces under average and extreme scenarios. With the considerations of the interaction of surface temperature and airflow and accuracy of the simulation, a coupling method was adopted between a dynamic simulation code using HTB2 and a CFD model using Star-CCM+. In short, a research framework, methodology and research techniques have been established for the main research work in the three selected buildings in Cardiff.

Chapter 4. FIELD STUDIES – MAIN STUDY

4.1 Introduction

The pilot study reported in the last chapter led to the optimised settings of the main study after a thorough review of the feedbacks that were obtained during the pilot study and the overall measurement and questionnaire surveying process. This chapter aims to aims to investigate the thermal environmental performance and people's adaptive comfort in transitional spaces, by conducting field studies, which include on-site questionnaire surveys and physical measurements. Field studies were carried out for three selected case study buildings in Cardiff, each having some forms of transitional space. They were the National Assembly for Wales Senedd, the Hadyn Ellis Building and the Royal Welsh College of Music and Drama. The total responses from the questionnaire surveys were 736 and 580, for all buildings, during the summer period in 2017 and the winter period in 2018 respectively. This paper first presents the findings from the field studies, followed by in-depth analysis of human adaptability to thermal environment. Strong correlations were identified between clothing value and indoor operative temperature. People's adaptability to the thermal environment is confirmed, with nearly 80% of the respondents opting for self-adaptive actions to overcome uncomfortable situations. The identified 90% acceptability comfort band (-0.5<TSV<+0.5) were 4.0°C and 4.2°C for the summer period and the winter period respectively, implying that a fine control of the indoor temperature to maintain an acceptable comfort level is not necessary.

4.2 Main Study Background

This section briefly summarises the background of the main study, which includes the selection criteria of the case buildings, and the descriptions of the selected buildings.

4.2.1 Selection of Case Buildings

The methodology adopted in this research included on-site questionnaire surveys and physical measurements in the transitional spaces of three existing buildings in Cardiff, namely, the National Assembly for Wales Senedd (NAfW), the Hadyn Ellis Building (HEB) and the Royal Welsh College of Music and Drama (RWCMD). They are shown in Figure 4-1. These buildings can be classified into two categories of transitional spaces as defined in Section 2.3 – the entrance zones and longer-term occupancy zones. Among these three selected case buildings, they have some similarities, including multi-functionality of the spaces (including entrance area, café and atrium spaces), having one or more glazed façade envelops, and the transitional spaces of them are located within an enclosed space. In order to optimise the proposed methodology for the main studies in these three buildings, a pilot study was performed in the transitional space of the Optometry Building of Cardiff University on 21st July 2017. The proposed methodology was then adjusted based on feedback from the pilot study, before carrying out the main studies. During the field studies, the indoor and outdoor environmental conditions were monitored at the same time as when the questionnaire surveys were carried out.

		
		
NAfW	**HEB**	**RWCMD**

Figure 4-1 Surveyed buildings and their indoor environments

The selected buildings were located in different locations in Cardiff. A single outdoor weather station was used in the study, and the distance from the outdoor weather station to the selected buildings, as shown in Figure 4-2 ranged from 0.1km to 2.8km. These buildings were selected based on the following major selection criteria:

1. The building shall be within 3 km from the weather station, in order to ensure the representation of the recorded weather data[2];
2. The selected buildings shall cover different functional types; and

[2] A radius of 15km from the weather station is recommended for temperature measurement in order to make the measurement representative. The closer the distance of the research subject to the weather station, the better is the accuracy (Plummer et al. 2003)

3. The buildings shall have large and publicly accessible transitional spaces where the response rate and thus representativeness of the questionnaire survey could be ensured.

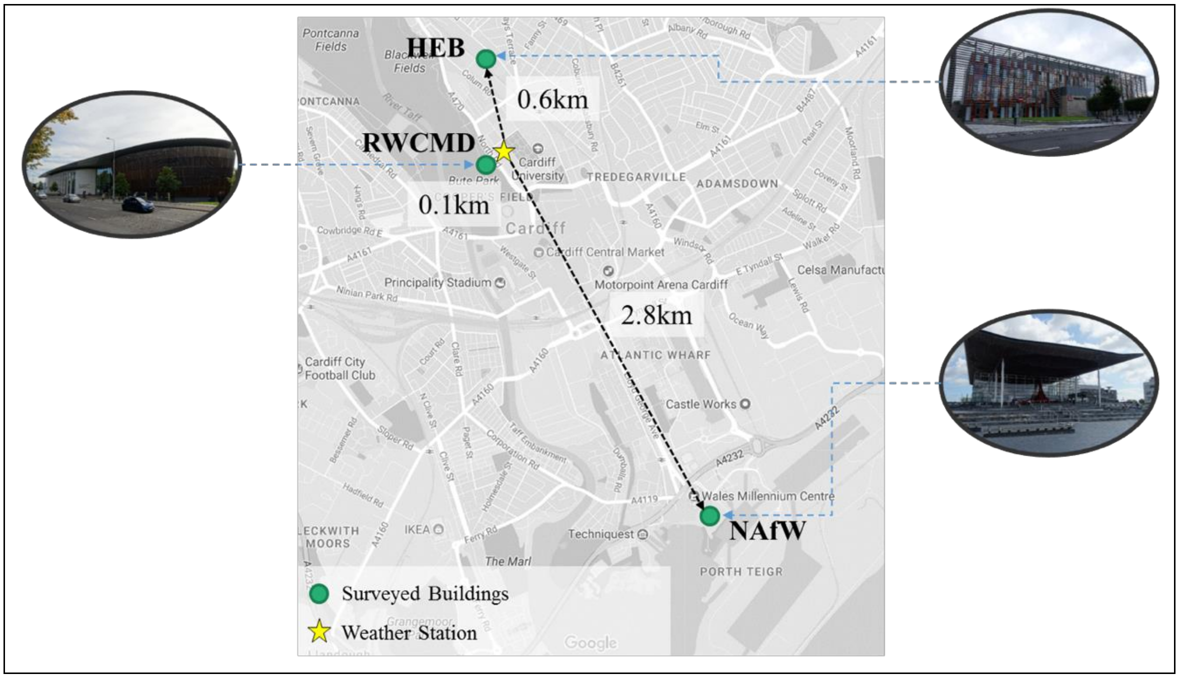


Figure 4-2 Locations of the surveyed buildings and their basic information

4.2.2 Descriptions of the selected buildings

The function of the surveyed buildings was quite different, but they were all open to the public during their opening hours. The windows of all the buildings were designed to be automatically opened under the control of Building Management System (BMS), which was aimed to enhance the ventilation during warm days so that a more desirable thermal comfort level could be maintained. In each of the selected buildings, field studies were carried out over a three-day period, in summer and winter. This included questionnaire surveys and physical measurements. Different ventilation modes were designed for each of these buildings, where the building can adopt natural ventilation or air conditioning mode to maintain the indoor comfort environment. Table 4-1 summarises the key characteristics of the surveyed buildings.

Table 4-1 Key characteristics of surveyed buildings

Surveyed building	**NAfW**	**HEB**	**RWCMD**
Building established	2006	2012	2011 (refurbished)
Building type	Public / Government	Academic	Academic / Cultural
Building area	5,120 m^2	9,740 m^2	4,400 m^2
No. of stories	3	5	3
Major façade type	Glazed	Glazed	Glazed
Windows open strategy	Automatic	Automatic	Automatic
Ventilation Mode	Mixed	Mixed	Mixed
Distance from weather station	2.8km	0.6km	0.1km
Survey dates (Summer Time)	19 August 2017 20 August 2017 26 August 2017	4 August 2017 8 September 2017 12 September 2017	20 September 2017 21 September 2017 22 September 2017
Survey dates (Winter Time)	6 January 2018 7 January 2018 13 January 2018	1 February 2018 2 February 2018 5 February 2018	20 January 2018 21 January 2018 22 January 2018
Survey period	10:30 – 16:30	08:30 – 17:30	08:30 – 19:00

4.3 Results and Analysis

4.3.1 Descriptive Analysis

The total number of responses collected from the questionnaire surveys were 736 and 580 during the summer period and the winter period respectively. Throughout the summer period, 282, 207 and 247 surveys were collected from the NAfW, HEB and RWCMD respectively; throughout the winter period, 198, 155 and 227 surveys were collected from the NAfW, HEB and RWCMD respectively. As the building functions and settings in the indoor transitional spaces of these buildings were different, the monitored and surveyed figures were different in different buildings.

The NAfW is a government building that is open to the public. During the summer period, because a special event "Poppies – weeping window" was held during the field study, a significant number of respondents were visitors to the building. Figure 4-3 shows the people's activities during the survey in the summer period. Since no special event was held during the survey in the winter period, the number of collected surveys was reduced. Guided tours took place regularly in the atrium space on the Ground Floor at designated times. The major purpose for visitors in the atrium was for the tours which led to lesser collected responses from the atrium part of the space. By contrast, the majority of responses were collected from the exhibition area and café area on the First Floor. The average activity level of the respondents was higher than the other two surveyed buildings, owing to a larger portion of people who walked or stood to watch the exhibition or to appreciate the building's architectural design or functional use. The measured indoor air temperature was lowest when compared to the other two surveyed buildings. For the summer period, the building was naturally ventilated. The windows were opened to keep the building ventilated at the time of the questionnaire survey. For the winter period, all the windows were closed and a trench heating system in the perimeter zones of the building was operated to maintain the indoor air temperature. However, even though the heating system was operating, the measured indoor temperature during the winter-time was lower than the other two surveyed buildings by at least 5.6°C. The major reasons were that the outdoor air temperature was lowest during the investigation period, in comparison with the other buildings, and that the space heat delivery was far away from the occupied areas and the measurement points.

Figure 4-3 People activities at NAfW

The HEB is an institutional research building that provides facilities such as offices, laboratories, meeting spaces, seminar, and lecture rooms for university students or researchers involved in various types of academic activities. As most of the respondents were undergraduate and postgraduate students, the average age of the respondents was lower than that of the NAfW. Since a higher portion of respondents used the transitional spaces for resting and dining, as shown in Figure 4-4, and there were more chairs and sofas set up for the building users, most respondents were seated. Therefore, the average activity level was lower than the NAfW. During the survey period in the summer-time, the windows were closed most of the time. On some occasions, when the temperature rose up, the windows were opened to adopt natural ventilation. In the winter-time, all the openings were closed during the survey period. During the survey period, an underfloor heating system was operated, with a floor surface temperatures ranged between 28°C to 30°C.

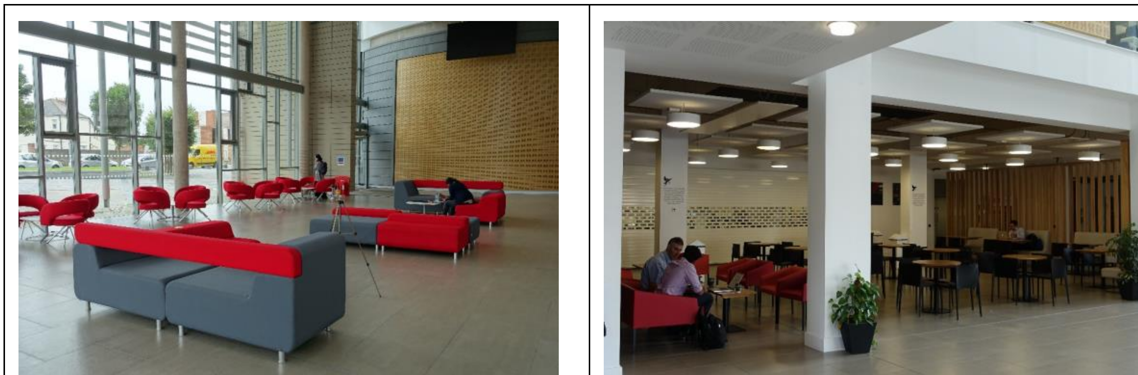


Figure 4-4 Interior settings at HEB

For the RWCMD, as the academic term had started when the questionnaire survey was carried out, even more respondents were undergraduate and postgraduate students, when compared to the HEB. Therefore, the average age of respondents from the RWCMD was the lowest among all the surveyed buildings. As illustrated in Figure 4-5, there were even a greater number of chairs and sofas provided for the building users in the atrium space and café area when compared to HEB. In addition, people in the transitional spaces tend to stay there for academic discussion, resting and dining. Therefore, the average activity level of the respondents was lowest among all the surveyed buildings where the respondents were mainly seated during the survey periods. Most of the respondents used the transitional spaces for waiting, resting and meetings. During the survey period in both the summer-time and winter-time, the windows were closed all the time. This may explain why the average monitored indoor temperature was higher than the other buildings during the summer time. A trench heating system and fan coil unit system were operated to provide heating to the atrium space and café area respectively during the winter-time. Therefore, even though the outdoor temperature was about 6°C during the survey period, the average indoor temperature could still be maintained at 21.6°C.

Figure 4-5 People activities at RWCMD

As the building functions and settings in the indoor transitional spaces of these buildings were different, the monitored and surveyed figures were different in different buildings. Table 4-2 summarises the key surveyed and monitored parameters collected during the surveys.

Table 4-2. Summary of the surveyed and monitored results

		NAfW		**HEB**		**RWCMD**	
		Summer	Winter	Summer	Winter	Summer	Winter
Total responses (N)		282	198	207	155	247	227
Male respondents		110 (39%)	90 (45%)	81 (39%)	56 (36%)	115 (47%)	83 (37%)
Female respondents		172 (61%)	108 (55%)	126 (61%)	99 (64%)	132 (53%)	144 (63%)
Age	Mean	42	43	32	29	26	26
	SD	18	18	10	11	10	13
Clothing value (clo)	Mean	0.50	1.18	0.60	0.92	0.60	0.84
	SD	0.17	0.33	0.20	0.32	0.20	0.30
Activity level (met)	Mean	1.44	1.67	1.30	1.31	1.18	1.27
	SD	0.48	0.47	0.47	0.48	0.46	0.53
Outdoor temperature (°C)	Mean	18.1	5.4	16.6	6.3	16.4	5.9
	SD	2.3	1.4	1.8	1.6	1.3	2.0
Indoor temperature (°C)	Mean	20.9	16.0	22.8	22.6	22.9	21.6
	SD	1.3	0.8	1.0	1.3	0.9	1.3
Relative humidity (%)	Mean	43.6	44.7	45.3	30.5	57.3	41.4
	SD	5.3	4.2	9.3	3.2	6.8	2.4

*** Temperatures shown were the record taken during the time when the questionnaire survey was conducted**

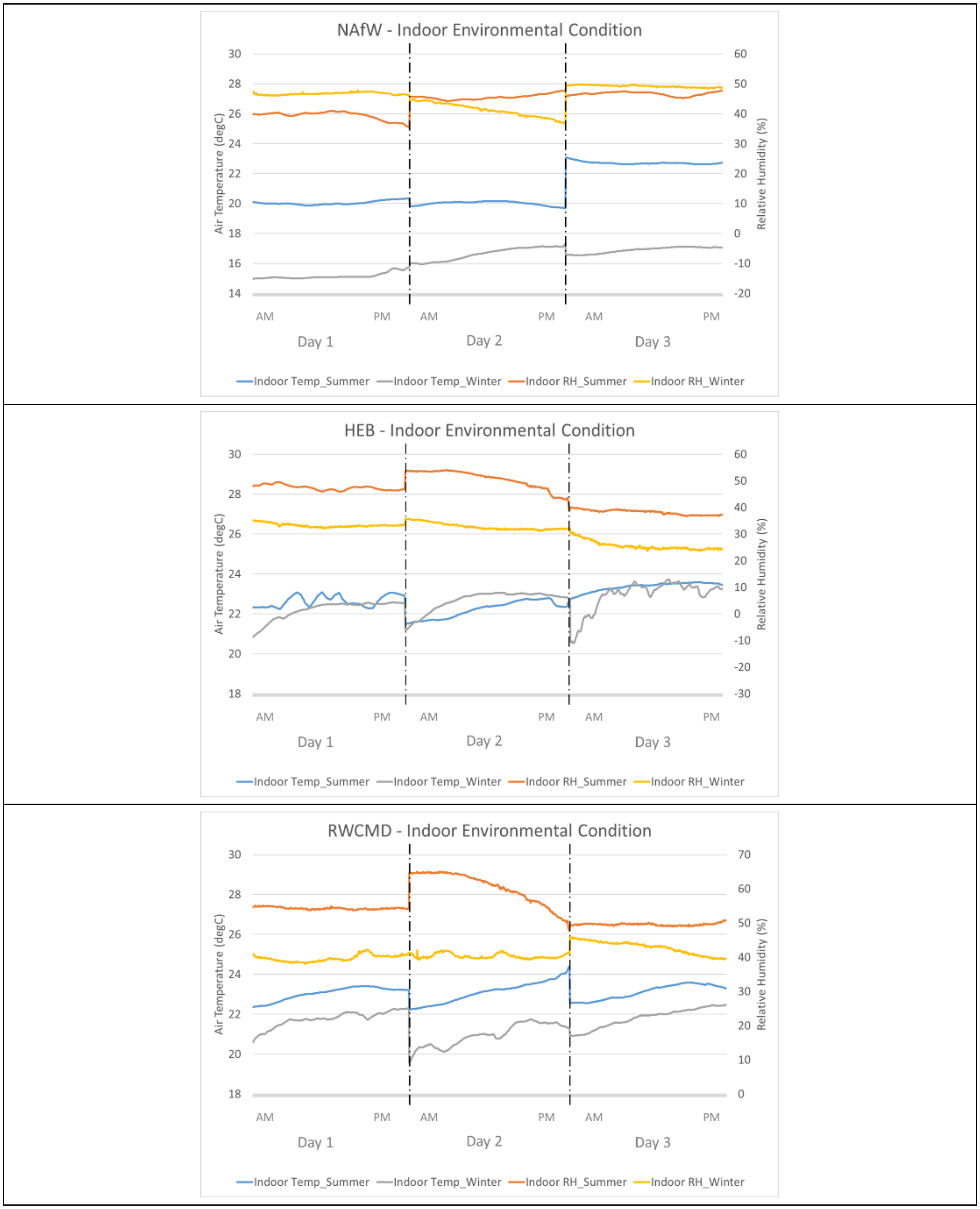
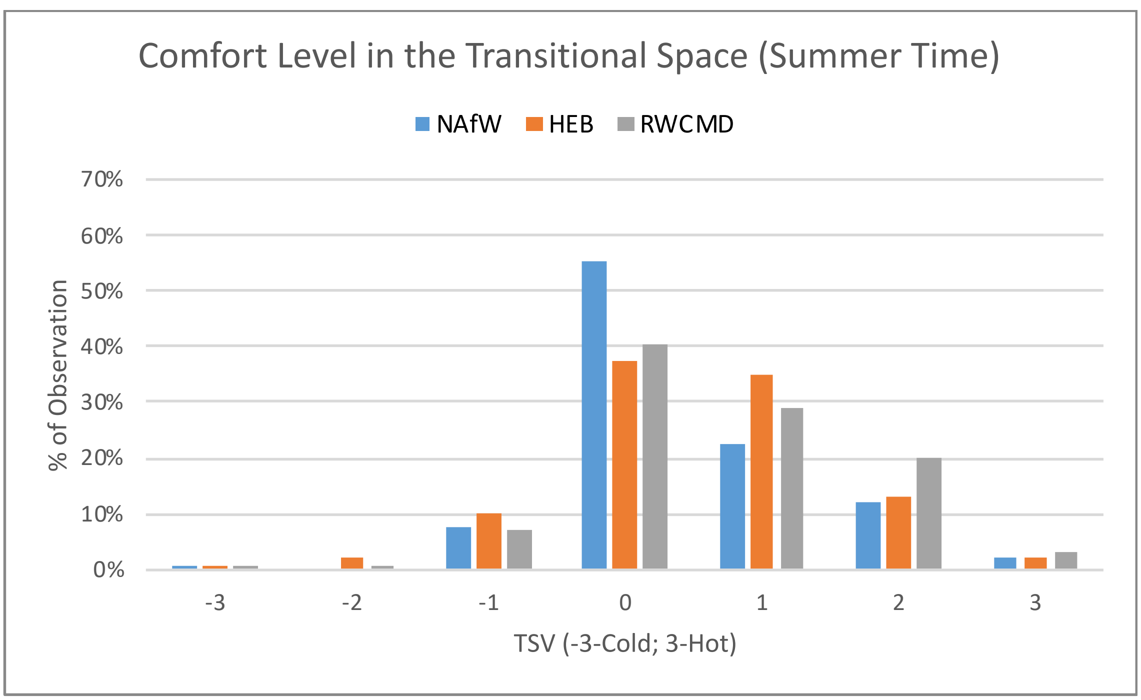


Figure 4-6 Physical measurement results for NAfW, HEB and RWCMD

Figure 4-6 illustrates the physical measurement results of the average indoor air temperature and relative humidity which were monitored during the field studies in both summer and winter time. Figure 4-7 illustrates the frequency distribution chart of the thermal sensation votes (TSV) that were collected from the questionnaire surveys from the three surveyed buildings. The thermal sensation distribution was similar among these buildings for both the summer and winter periods, where the majority of respondents voted for "neutral" and the others tended to have a warmer feeling (i.e. TSV>0).

For the summer period, some 85%, 83% and 76% of the respondents were found in the 80% acceptability comfort band ($-1 \leq TSV \leq +1$), as defined by ISO 7730:2005 (ISO 2005), for the NAfW, HEB and RWCMD respectively. In addition, for the question about the overall thermal feeling of the building, some 94%, 82% and 91% of the respondents felt pleasant (i.e. voted for +1 or higher), for the NAfW, HEB and RWCMD respectively. The average vote for the overall thermal feeling for the NAfW (mean: 2.25; SD: 0.96) was higher than that for the HEB (mean: 1.58; SD: 1.27) and the RWCMD (mean: 1.89; SD: 1.08). In summary, for all three surveyed buildings, people felt thermally comfortable in the transitional spaces during the summer period.

For the winter period, a slightly smaller number of respondents fell within the 80% acceptability comfort band when compared to the summer period, being some 82%, 81% and 78% for the NAfW, HEB and RWCMD respectively. Similarly, the number of respondents who felt pleasant about the overall thermal feeling of the buildings was also reduced, except for the HEB. Some 88%, 91% and 82% of the respondents voted for pleasant for the NAfW, HEB and RWCMD respectively. The average vote for the overall thermal feeling for the HEB (mean: 1.94; SD: 0.98) was higher than the other two surveyed buildings, that is, the NAfW (mean: 1.92; SD: 1.10) and the RWCMD (mean: 1.72; SD: 1.28). Even though the number of respondents who voted for an overall thermal feeling as pleasant was reduced, the portion was still over 80%. In summary, for the winter period all the three surveyed buildings were able to provide thermally comfortable transitional spaces for their occupants.



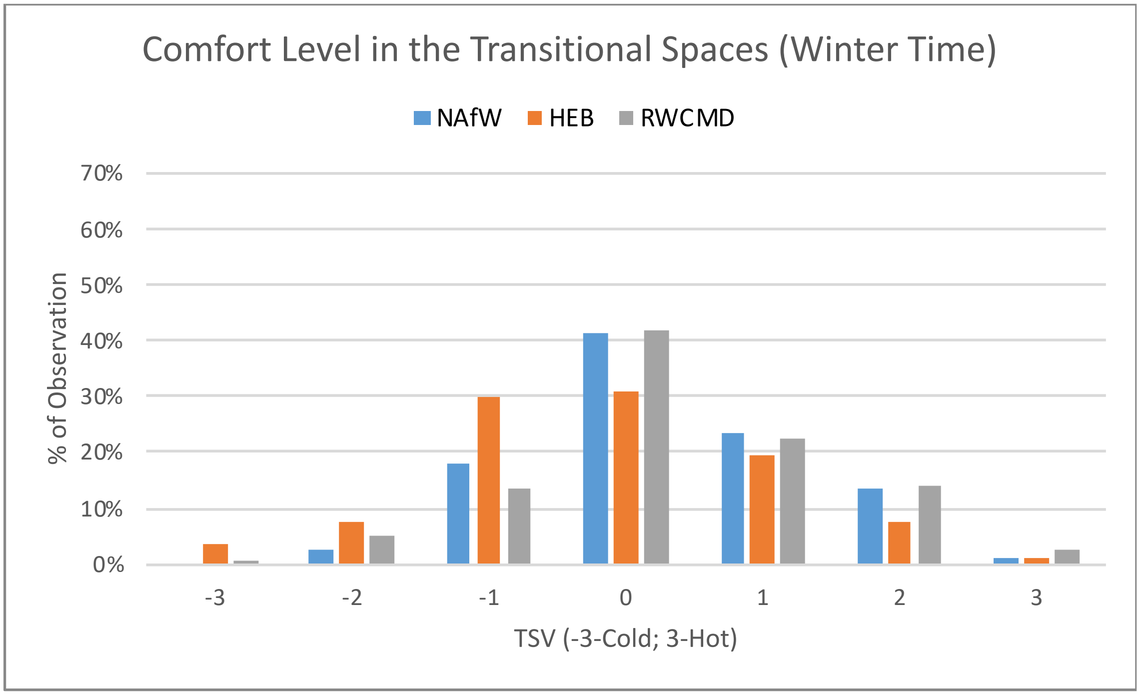


Figure 4-7 Frequency distribution of thermal sensation votes (TSV) in different transitional spaces during the summer (above) and winter period (below)

4.3.2 Correlation Analysis

In order to evaluate the correlation between different parameters and to filter out the appropriate parameters, a detailed analysis was carried out, using a Pearson (2-tailed) correlation analysis within the SPSS software. By inputting 39 parameters, including the questionnaire surveyed data (including date, location, time, gender, age, the reason of occupying the transitional space, whether the participant is regular user, whether the participant had meal within an hour before taking the questionnaire survey, overall feeling, comfort level, humidity feeling, air moving feeling, thermal preference, preference on sun penetration, total clothing, activity level, period of time the participant has stayed in the transitional spaces, whether the participant came from the indoor space or outdoor space, period of time the participant stayed at the previous space, comfort level at previous space, feedback on the thermal environment of the transitional spaces, how the participant would overcome any uncomfortable situation, the participant's previous thermal experiences on the transitional spaces in summer and winter time respectively if they have visited it before), the measured environmental parameters (including indoor air dry-bulb temperature, relative humidity, indoor globe temperature, indoor air speed, indoor surface temperature, outdoor air dry-bulb temperature, outdoor relative humidity, outdoor globe temperature and outdoor wind speed), evaluated environmental parameters (including mean indoor and outdoor radiant temperature, indoor and outdoor operative temperature) and the calculated comfort indexes (including PMV and PPD indexes), results were generated with a 1,482 Pearson correlation. Only the pairs of parameters that had a significant statistical correlation were then chosen for detailed analysis. These included the clothing value vs indoor operative temperature and outdoor temperature, and TSV vs indoor operative temperature and outdoor temperature. Another reason that these parameters were chosen for further analysis was that they are related to occupants' behaviour to their thermal environment. It may help to prove the correctness of the research hypothesis that people have adaptability to their thermal environment, i.e. people may have different thermal sensation and may change their clothing value according the surrounding temperatures. Table 4-3 and Table 4-4 below summarise the correlation results between clothing values and the temperature data, and between TSV and the temperature data respectively. The correlation was considered to have an average statistical significance when $p<0.05$; and a strong statistical significance when $p<0.01$. Although PMV and the actual thermal sensation vote (TSV) do not have statistical significance, this pair of parameters were selected for further investigation as PMV model is a widely adopted thermal prediction model for indoor environments.

It was found that clothing value correlated better with indoor operative temperature than with outdoor temperature. The relationship was stronger for the NAfW and the RWCMD during the summer period and the winter period respectively.

Table 4-3. Correlation results for clothing values of all surveyed buildings

	Clothing Value					
	NAfW		HEB		RWCMD	
	Summer	Winter	Summer	Winter	Summer	Winter
Indoor Operative Temperature	-0.384**	-0.145*	-0.260*	-0.185*	-0.145*	-0.312**
Outdoor Temperature	-0.386**	-0.144*	-0.072	-0.125	-0.107	-0.146*

***significant at p<0.05**
****significant at p<0.01**

In order to evaluate people's thermal adaptability, TSV against indoor operative temperature, indoor dry-bulb temperature and outdoor temperature, were filtered out respectively for further investigations. It was found that TSV had the strongest correlation with indoor operative temperature among the other comparisons, during both the summer and winter periods. Therefore, indoor operative temperature was selected for a detailed regression study.

Table 4-4. Correlation results for clothing values of all surveyed buildings

	Thermal Sensation Vote (TSV)					
	NAfW		HEB		RWCMD	
	Summer	Winter	Summer	Winter	Summer	Winter
Indoor Operative Temperature	0.162**	0.160*	0.165*	0.135**	0.135*	0.308**
Indoor Dry-bulb Temperature	0.153*	0.158*	0.131	0.128*	0.139*	0.245**
Outdoor Temperature	0.156**	0.088	0.133	0.036	0.032	0.002

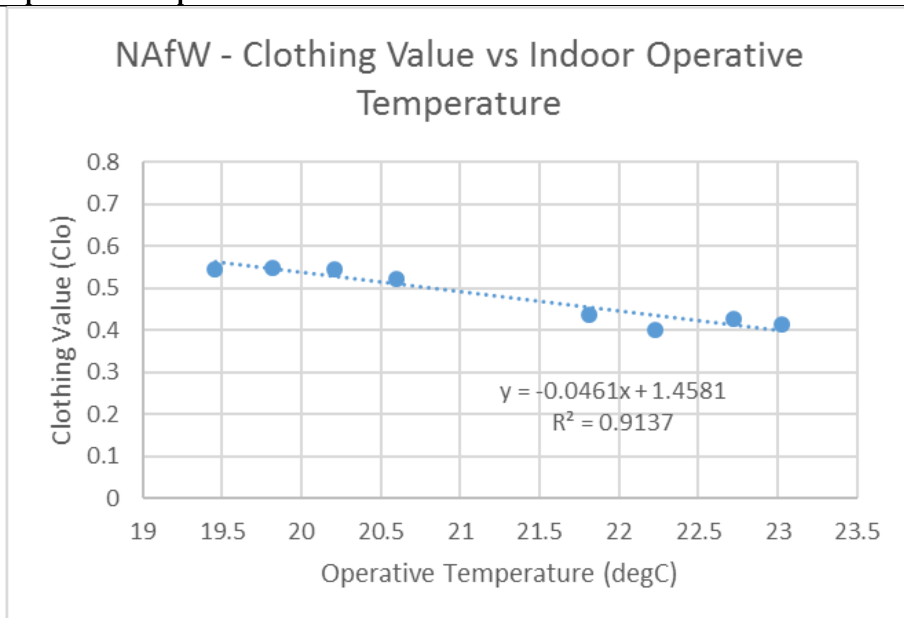
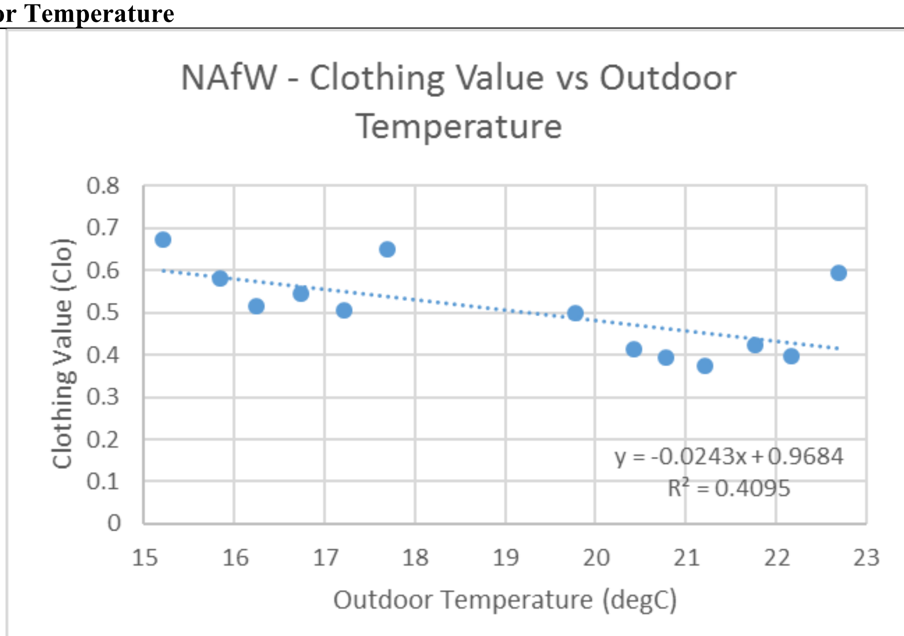
***significant at p<0.05**
****significant at p<0.01**

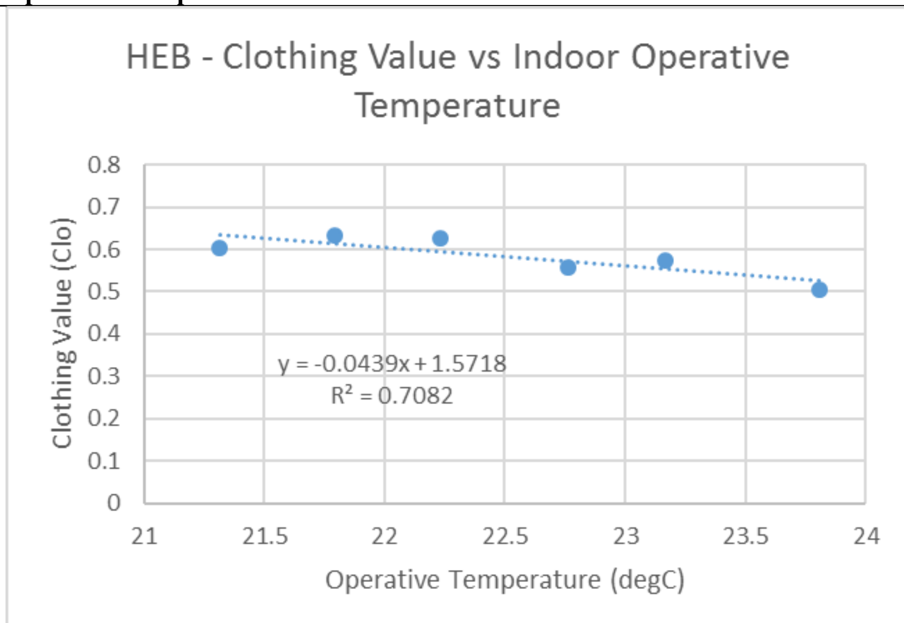
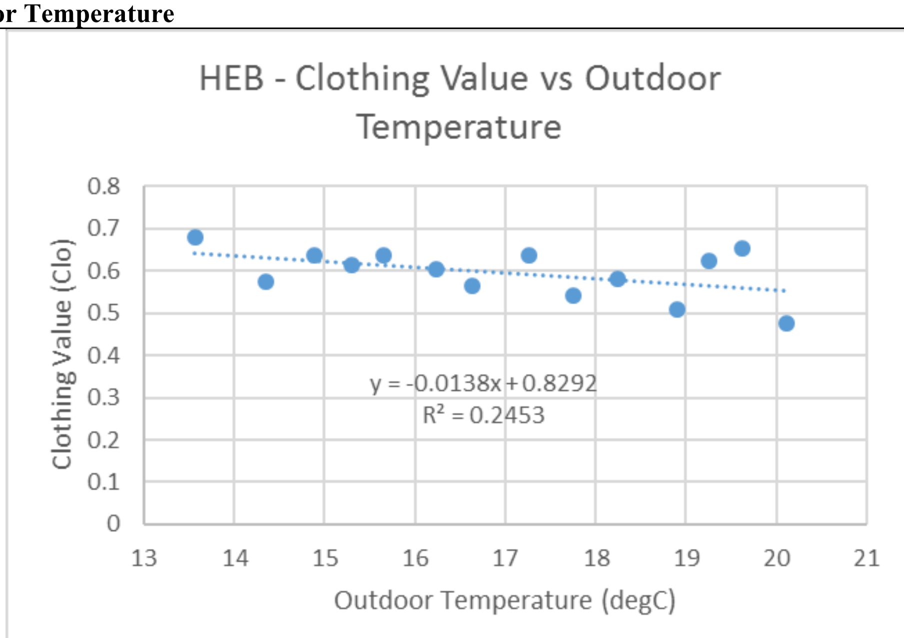
4.3.3 Investigation of Influence of Indoor Operative Temperature and Outdoor Temperature on Clothing Value

The reported respondents' clothing in the questionnaire surveys were converted into numerical values, with reference to ASHRAE Standard 55-2013 (ASHRAE 2013) and ISO 7703:2005 (ISO 2005). In order to reduce the impact of outliers in the database, a binning method, which is common in comfort research (Palma 2015; Khalid et al. 2019; Luo et al. 2019; Wu et al. 2019), was adopted by taking the weighted averages for every half-degree-Celsius bin. Figure 4-8 illustrates the linear regression plots between the average clothing value and the indoor operative temperature and outdoor temperature respectively for the summer period.

For the correlation of clothing value against indoor operative temperature, the linear relationship was found to be strong, with a coefficient of determination (r2) ranging from around 0.71 to 0.91. Negative gradients were identified for all the cases. In other words, the higher the indoor operative temperature, the lower was the clothing value.

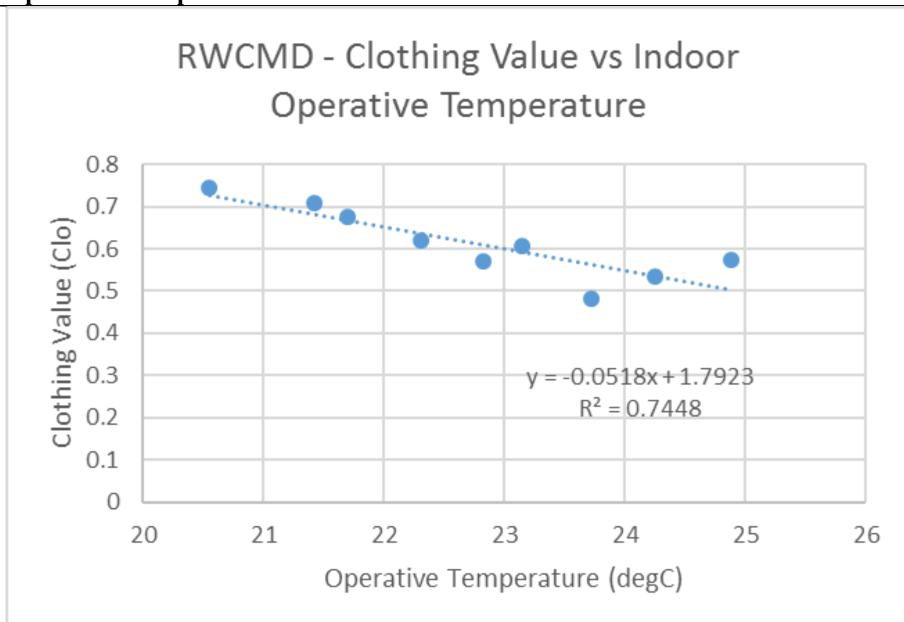
Similar correlations were conducted between clothing value and outdoor temperature. Similar relationships between outdoor temperature and clothing value were identified, only the correlation was weaker than the comparison with indoor operative temperature. The coefficient of determination (r2) ranged from 0.23 to 0.41. The identified gradients were the same, which were negative, as the correlations against indoor operative temperature.

Clothing Value
vs Indoor Operative Temperature

vs Outdoor Temperature

NAfW

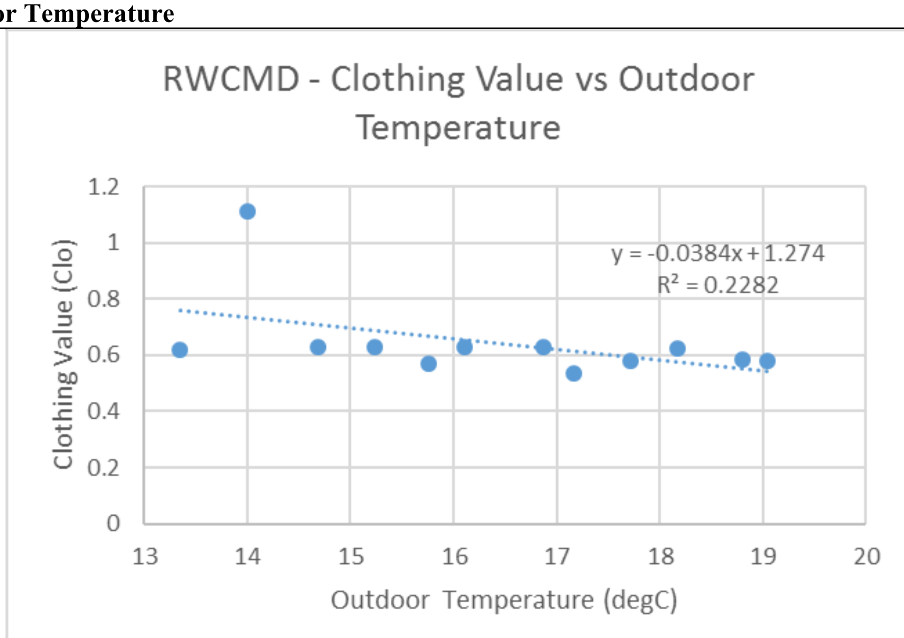
Clothing Value
vs Indoor Operative Temperature

vs Outdoor Temperature

HEB

Clothing Value

vs Indoor Operative Temperature



vs Outdoor Temperature



RWCMD

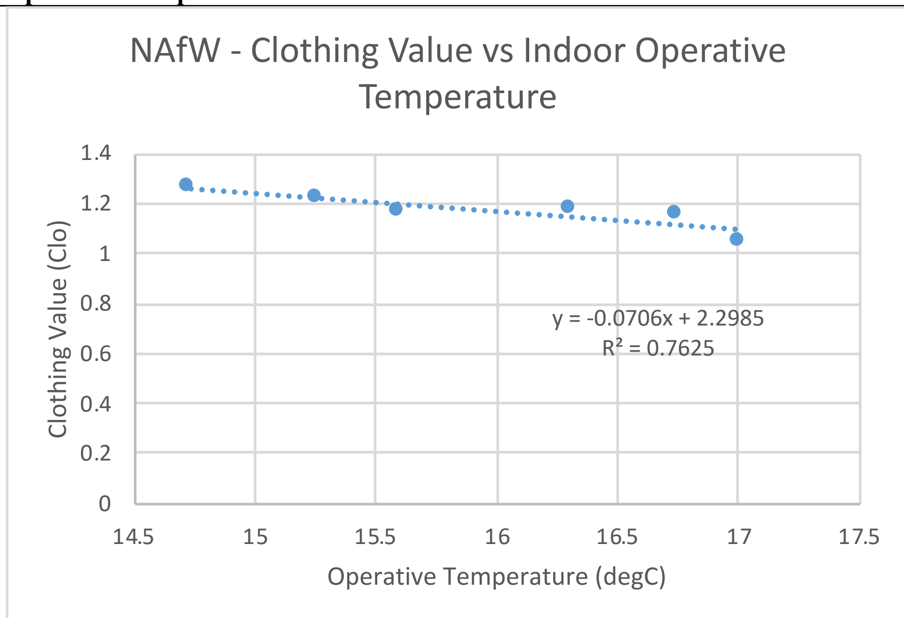
Figure 4-8 Influence of indoor operative temperature and outdoor temperature on clothing value (summer period)

The linear regression plots between the average clothing value and the indoor operative temperature and outdoor temperature respectively for the winter period are shown in Figure 4-9. The plot between the clothing value and indoor operative temperature was correlatively strong, with the coefficient of determination (r2) ranging from around 0.76 to 0.83. The gradients identified for all the cases were negative. In other words, the higher the indoor operative temperature, the lower was the clothing value.

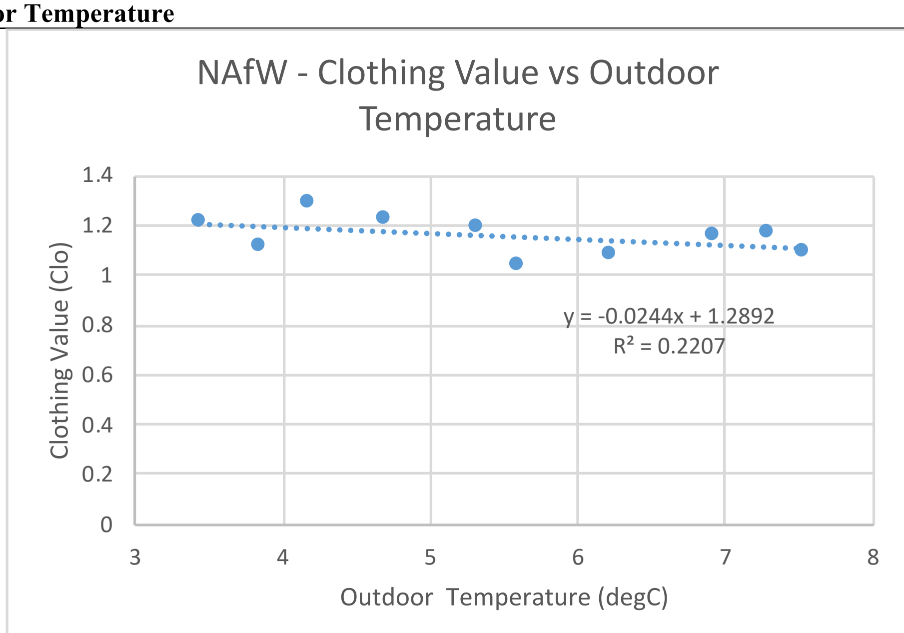
The relationships between outdoor temperature and clothing value were found similar However, the correlation was weaker than the comparison against indoor operative temperature. The coefficient of determination (r2) was ranged from 0.16 to 0.22. Similarly, the gradients of the linear relationship were negative.

Clothing Value

vs Indoor Operative Temperature



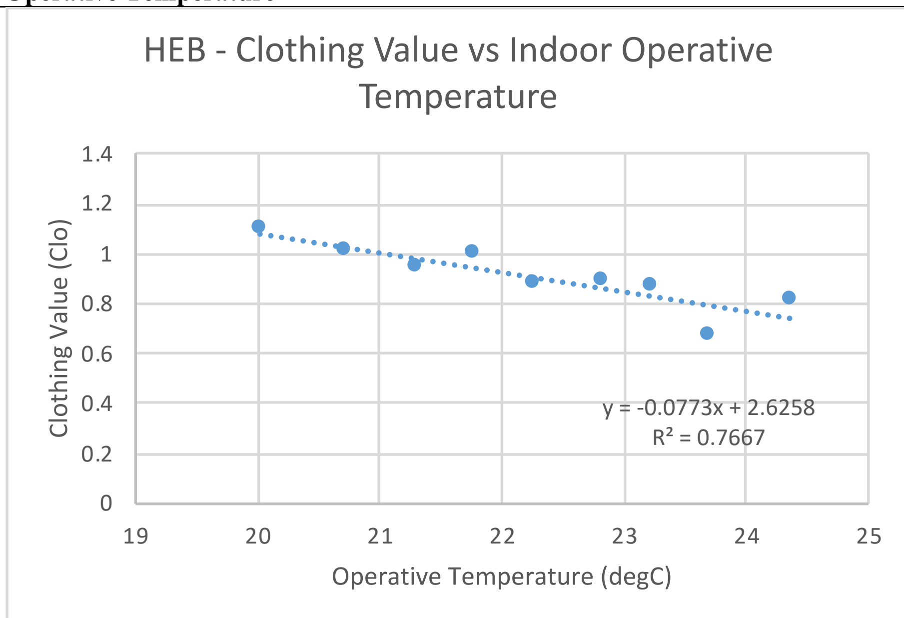
vs Outdoor Temperature



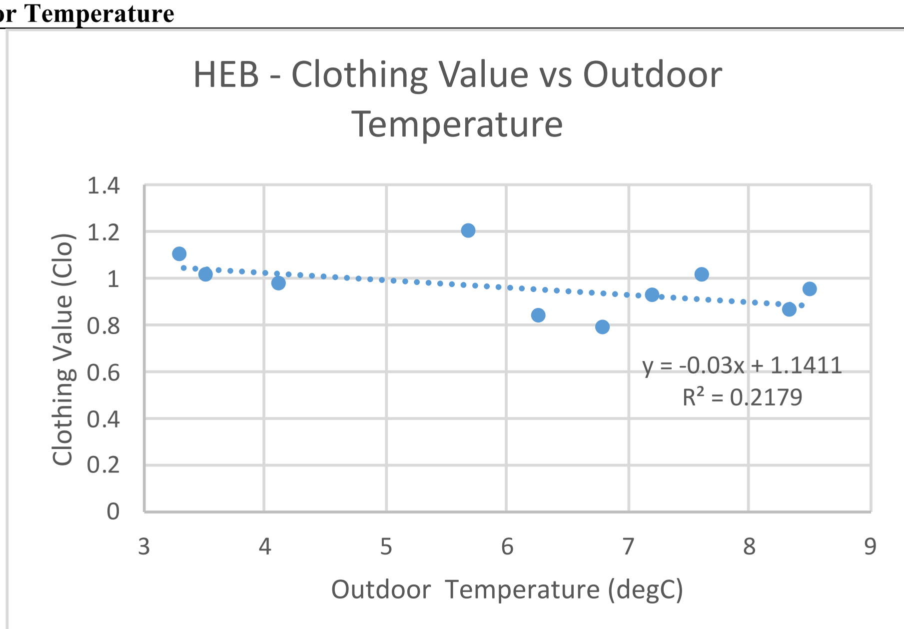
NAfW

Clothing Value

vs Indoor Operative Temperature



vs Outdoor Temperature



HEB

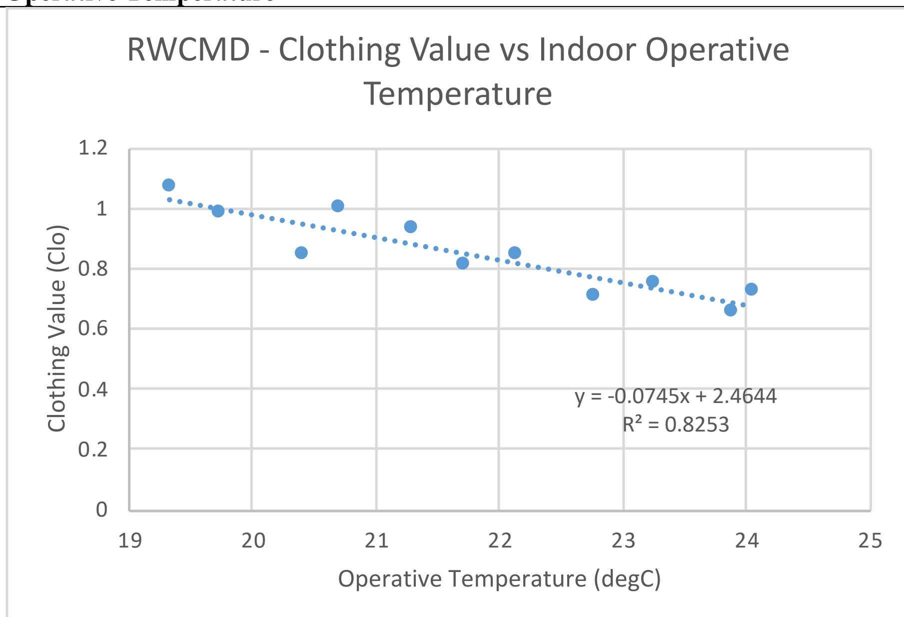
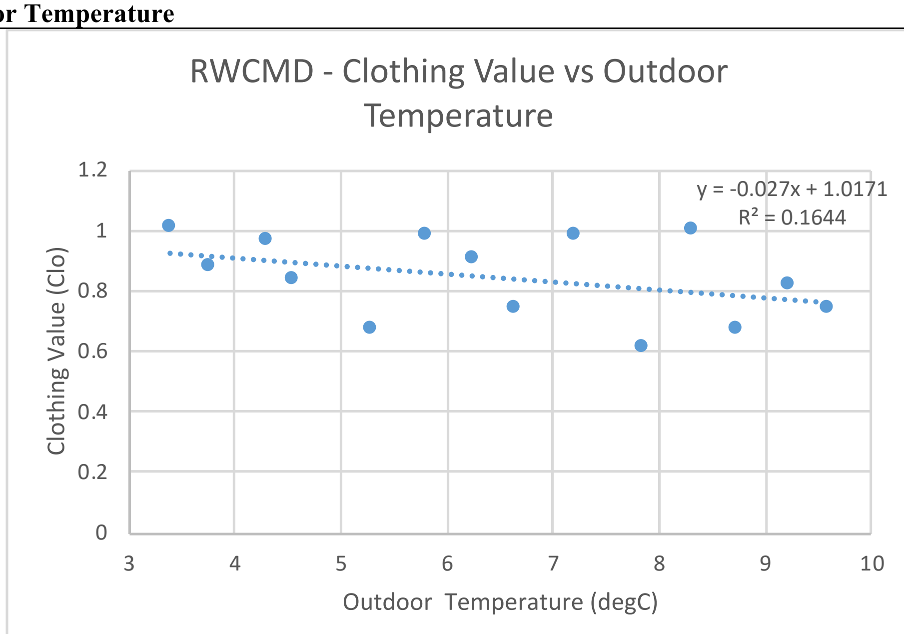
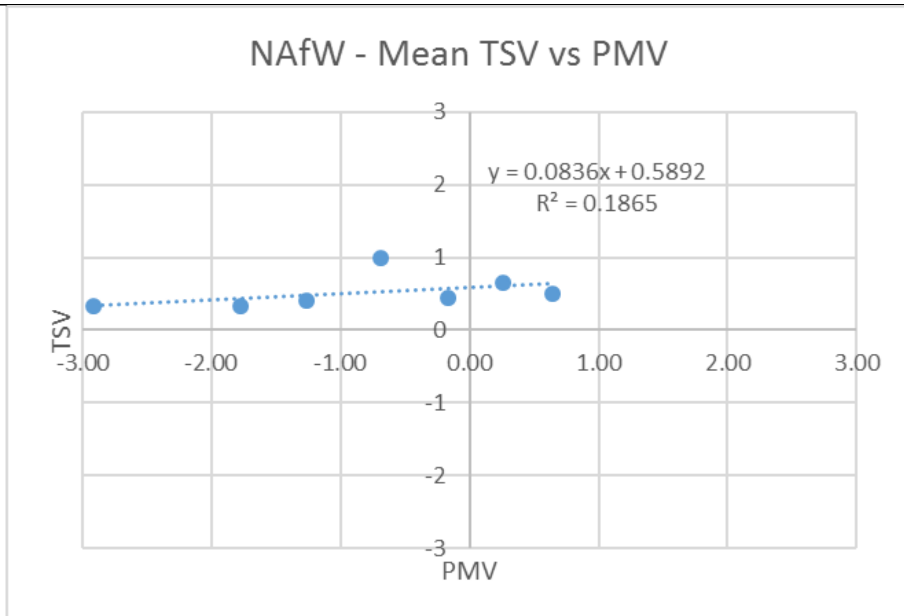
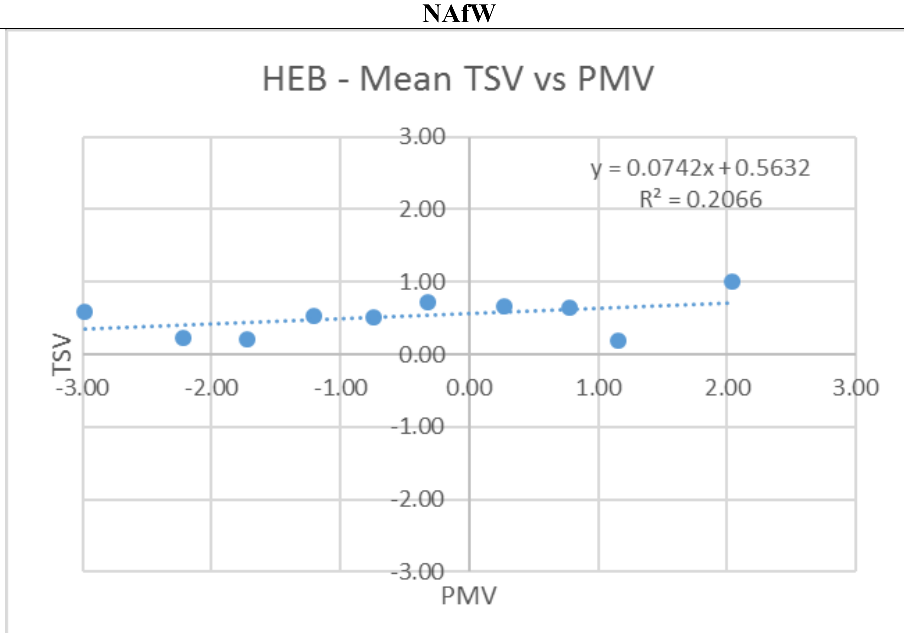
Clothing Value
vs Indoor Operative Temperature

vs Outdoor Temperature

RWCMD

Figure 4-9 Influence of indoor operative temperature and outdoor temperature on clothing value (winter period)

4.3.4 Evaluation of Prediction Accuracy of Thermal Comfort Level in Transitional Spaces using PMV Model

PMV, the widely-adopted thermal comfort prediction model for indoor environments (Humphreys et al. 2004), was applied to the field studies in this research in order to evaluate if it is an appropriate model for indoor transitional spaces. Based on the monitored and surveyed results, PMV was calculated and plotted against the actual thermal sensation vote (TSV) to test the relationship between these two values for each of the surveyed buildings. The results are illustrated in Figure 3. The correlations between the PMV and the mean TSV were not strong, which were ranged from 0.0402 to 0.2066 and the gradients varied from case to case. In short, PMV is not an appropriate model that can accurately predict thermal sensation in transitional spaces. Taking NAfW as an instance, for the PMV ranged between -3, the actual TSV reported was around 0.35, where the difference between the actual TSV and the predicted one was 3.35. From the other point of view, the average PMV calculated for the NAfW, HEB and RWCMD were -1.35, -0.62 and -0.58 respectively, while the average actual TSV for these buildings were 0.45, 0.51 and 0.69 respectively. The deficiency between the average values of PMV and TSV ranged from 1.13 to 1.80.

PMV vs TSV

NAfW

HEB

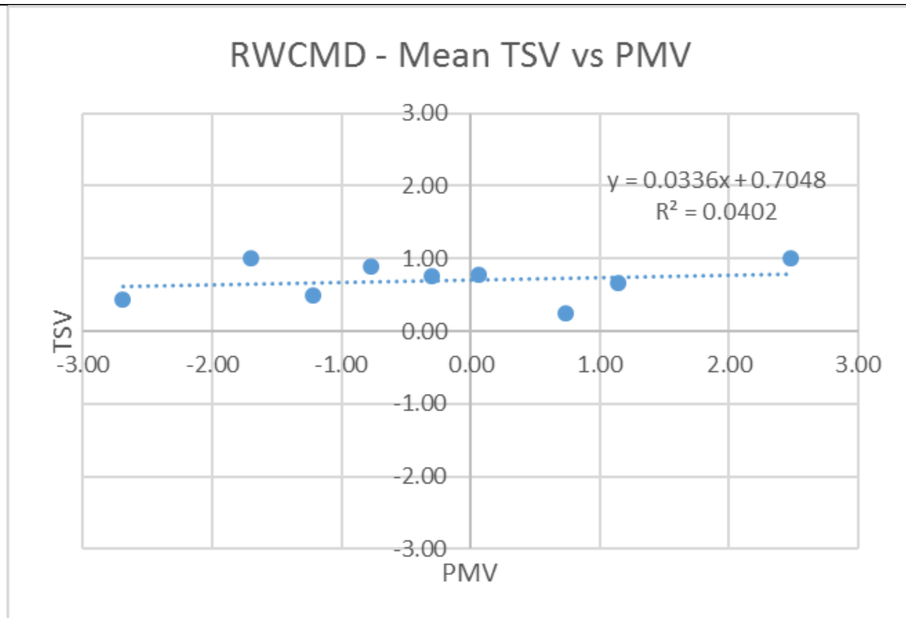
PMV vs TSV

RWCMD

Figure 4-10 Evaluation of Thermal Comfort Prediction using PMV

4.3.5 Investigation of Actions that People Would Take to Overcome Uncomfortable Situations

An open question was asked in the questionnaire about how the respondents would act to overcome uncomfortable situations. For the summer period, out of the 736 surveyed questionnaires in total for the three surveyed buildings, the response rate for this question was 320, or 43.5%. For the winter period, the response rate for the question was 259, or 44.7% for the 580 collected surveyed questionnaires. As some of the people gave more than one answer, the number of collected answers from the respondents were 339 and 298 for the summer period and winter period respectively. As it was an open question, the use of words was different from different answers but they can basically be grouped into nine categories, which are “adjust clothing”, “use mechanical means”, “drink/eat”, “move/leave from the uncomfortable location”, “report to building staff”, “do exercise”, “close the openings”, “improve the architectural design” and “other”. For example, answers such as “take off jackets”, “add a layer of clothing” and “put scarf / cardigan on” were classified as “adjust clothing”; answers such as “have a cup of coffee”, “eat a burger” and “drink water” were grouped into “drink/ eat”; and rare answers such as “talk my way through” and “more light” were classified as “other”. Table 4-5 summarises the details about the actions that respondents would take to overcome uncomfortable situations.

Table 4-5. Summary of respondents' actions to overcome uncomfortable situations

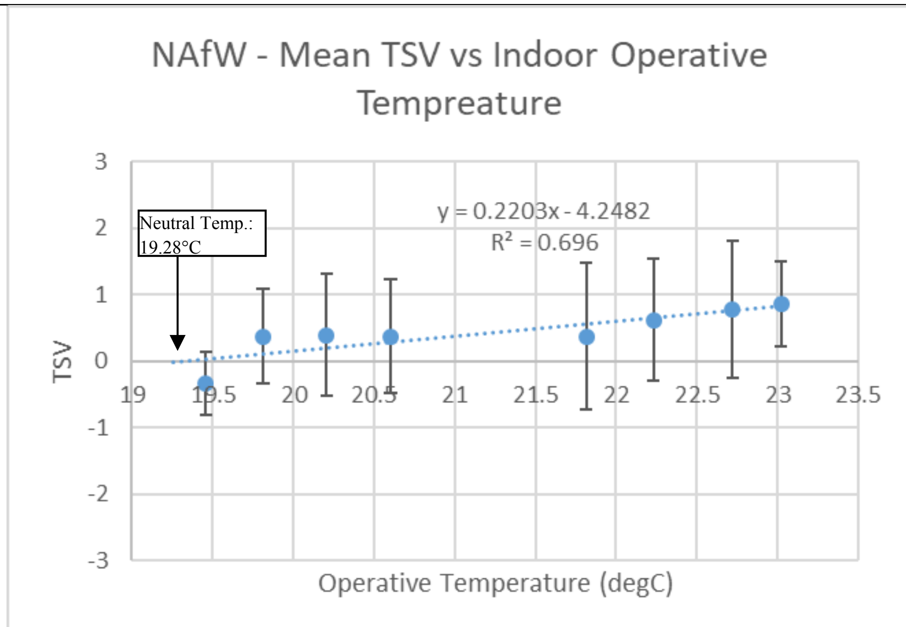
Categorised actions to overcome uncomfortable situations	**NAfW**		**HEB**		**RWCMD**		**Total**	
	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
Adjust clothing	55 (54%)	50 (46%)	43 (44%)	37 (59%)	71 (50%)	71 (56%)	**169 (50%)**	**158 (53%)**
Move / Leave from the uncomfortable location	23 (23%)	14 (13%)	14 (14%)	12 (19%)	35 (25%)	22 (17%)	**72 (21%)**	**48 (16%)**
Use mechanical means	11 (11%)	19 (17%)	12 (12%)	5 (8%)	11 (8%)	12 (10%)	**34 (10%)**	**36 (12%)**
Close the openings	1 (1%)	0 (0%)	16 (16%)	0 (0%)	6 (4%)	7 (6%)	**23 (7%)**	**7 (2%)**
Drink / Eat	4 (4%)	13 (12%)	4 (4%)	4 (6%)	10 (7%)	2 (2%)	**18 (5%)**	**19 (6%)**
Other	2 (2%)	2 (2%)	4 (4%)	2 (3%)	6 (4%)	4 (3%)	**12 (4%)**	**8 (3%)**
Report to building staff	2 (2%)	1 (1%)	3 (3%)	3 (5%)	1 (0%)	2 (2%)	**6 (2%)**	**6 (2%)**
Do exercise	3 (3%)	6 (6%)	2 (2%)	0 (0%)	0 (0%)	2 (2%)	**5 (2%)**	**8 (3%)**
Improve the architectural design	0 (0%)	4 (4%)	0 (0%)	0 (0%)	0 (0%)	4 (3%)	**8 (3%)**	**8 (3%)**
Total response rate	**101 (30%)**	**109 (37%)**	**98 (29%)**	**63 (21%)**	**140 (41%)**	**126 (42%)**	**339**	**298**

Out of these categories, "adjust clothing", "drink / eat", "move / leave from uncomfortable location" and "do exercise" can be treated as self-adaptive actions. Nearly 80% of the respondents opted for self-adaptive actions to overcome uncomfortable situation. In other words, a vast majority of people tended to adapt themselves to the thermal environment in order to make themselves feel more thermally comfortable, rather than attempting to change the building operations such as openings and air conditioning systems. Among these self-adaptive measures, “adjust clothing” was the most selected action by the respondents for all the three surveyed buildings. It constituted about half of the categorised actions. Similar distribution of the categorised actions that respondents would take to overcome the uncomfortable situations was also observed from the questionnaire surveys.

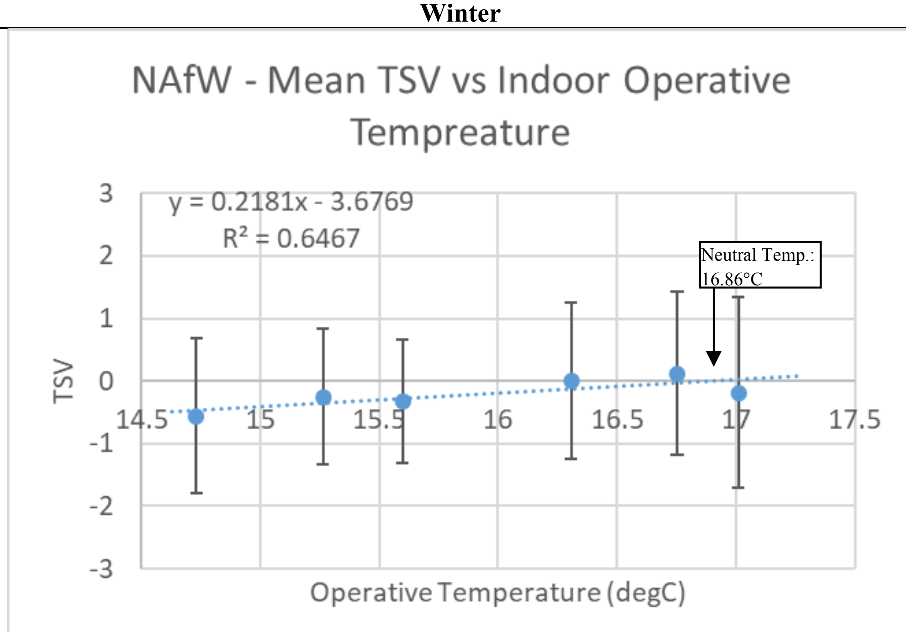
4.3.6 Investigation of Neutral Temperatures

Neutral temperature is defined as the temperature at which people reach their thermal neutrality, and they feel neither cool nor warm (Fabbri 2015). When neutral temperature can be achieved, most of the people would feel thermally comfortable and accept the thermal environmental condition (ASHRAE 2013). In order to identify the neutral temperature for the three selected case buildings, weighted linear regressions were performed. A binned method was adopted by setting the increments of indoor operative temperature at half-degree-Celsius in order to eliminate the outliers (Palme et al. 2016; Khalid et al. 2019; Luo et al. 2019; Wu et al. 2019) The mean TSV of each bin was determined. Linear regression, which has been used to investigate thermal comfort datasets since 1930s (Nicol et al. 2012; Zaki et al. 2017), was adopted to evaluate the neutral temperatures in this research. Figure 4-11 shows the regression results of the mean TSV against indoor operative temperature with standard deviation shown for each bin. The neutral temperatures were then identified by solving the regression equipment for TSV = 0.

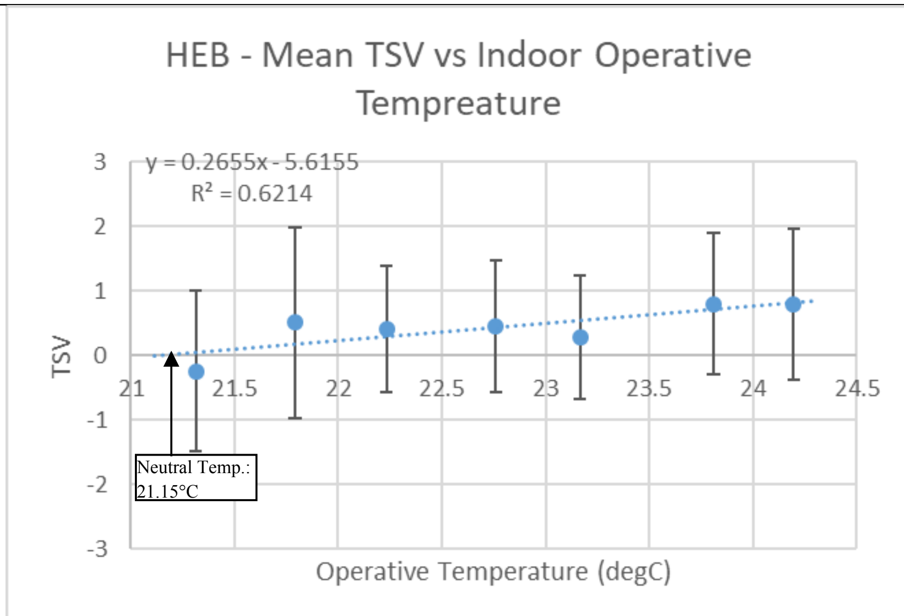
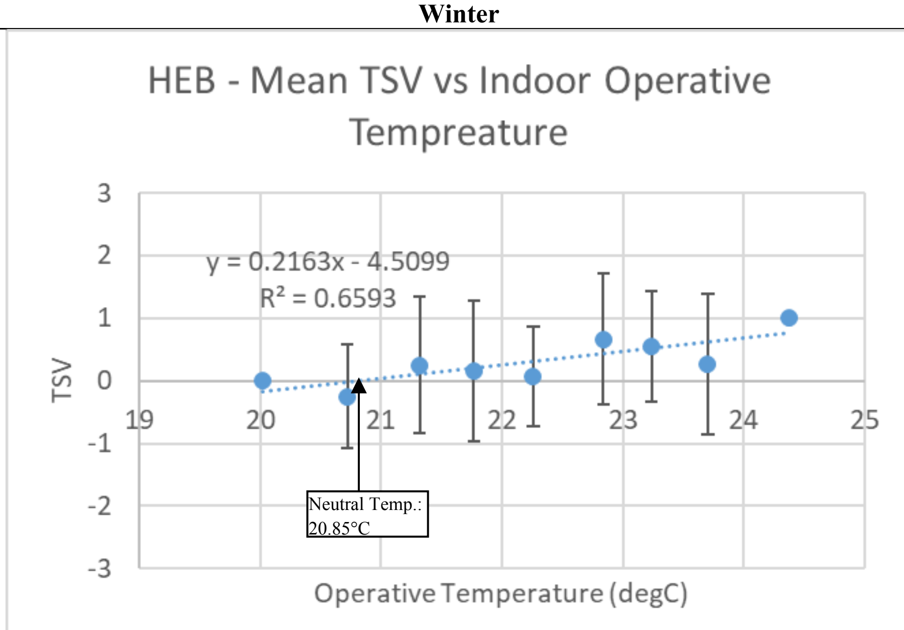
Summer



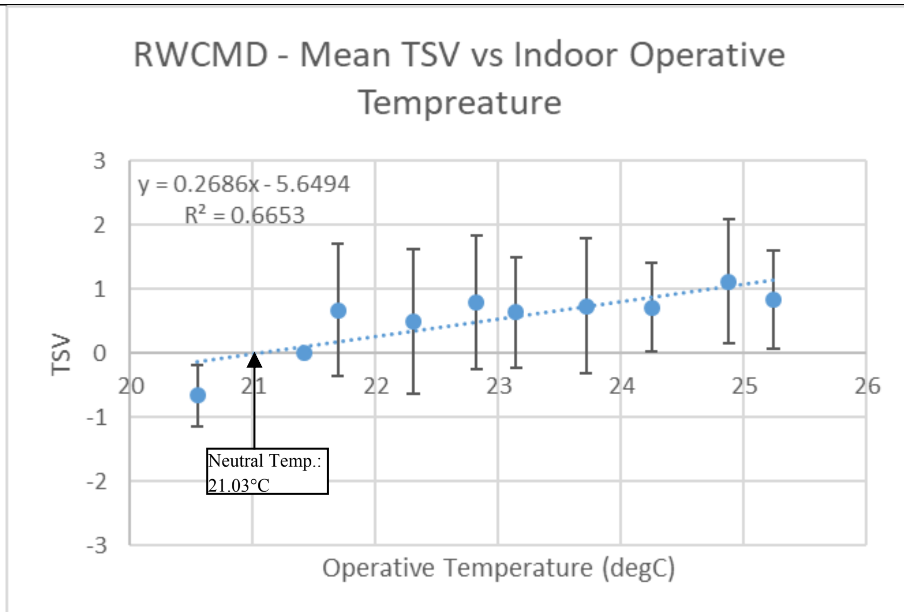
Winter



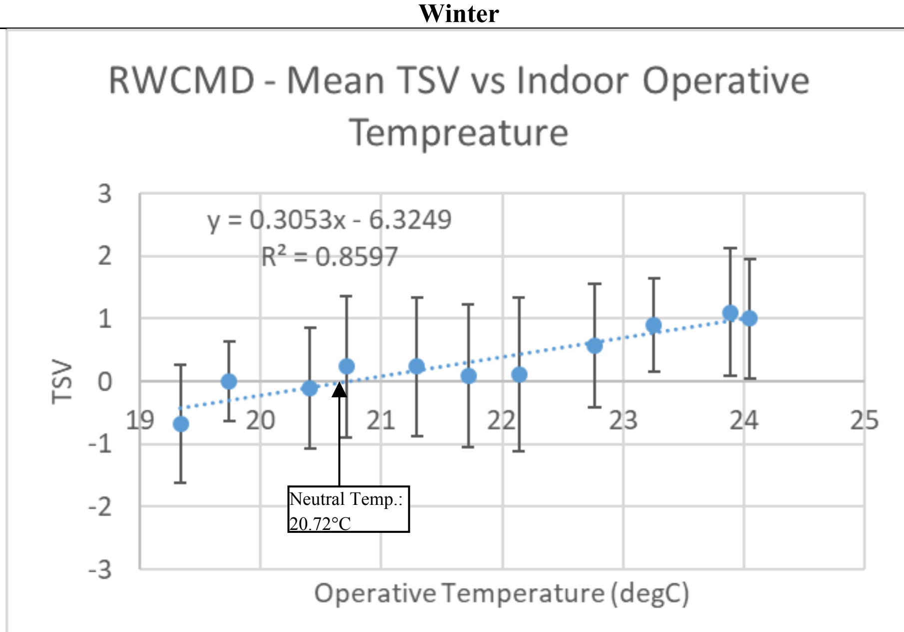
NAfW

Summer

Winter

HEB

Summer



Winter



RWCMD

Figure 4-11 Relationship between thermal sensation vote (TSV) and indoor operative temperature

For the summer period, a strong linear relationship between the mean TSV and the indoor operative temperature was identified, where the coefficient of determination (r2) ranged from 0.62 to 0.70. As the gradients were all positive, it implied that the higher the indoor operative temperature, the higher was the TSV. In other words, the building occupants felt warmer when the indoor operative temperature rose. The summer period neutral temperatures evaluated for the NAfW, HEB and RWCMD were 19.3°C, 21.2°C and 21.0°C respectively.

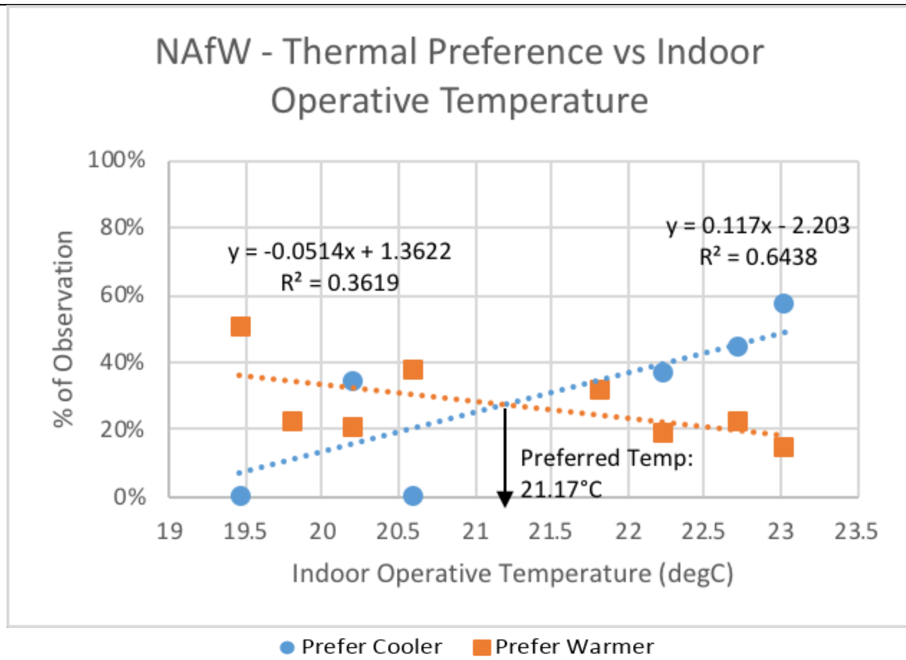
The linear relationship between the mean TSV and the indoor operative temperature that was identified for the winter period was wider, where the coefficient of determination (r2) ranged from 0.65 to 0.86. Similar to the case in the summer period, the gradients were all positive, implying that the higher the indoor operative temperature, the higher was the TSV. For the HEB and RWCMD, the correlations and the resulted neutral temperatures were similar when compared to the summer period. However, as the measured indoor operative temperature in the NAfW was lower during the field study, the resulted neutral temperature was found lower than that for the summer period. In summary, the neutral temperatures evaluated for the NAfW, HEB and RWCMD were 16.9°C, 20.9°C and 20.7°C respectively..

4.3.7 Investigation of Preferred Temperatures

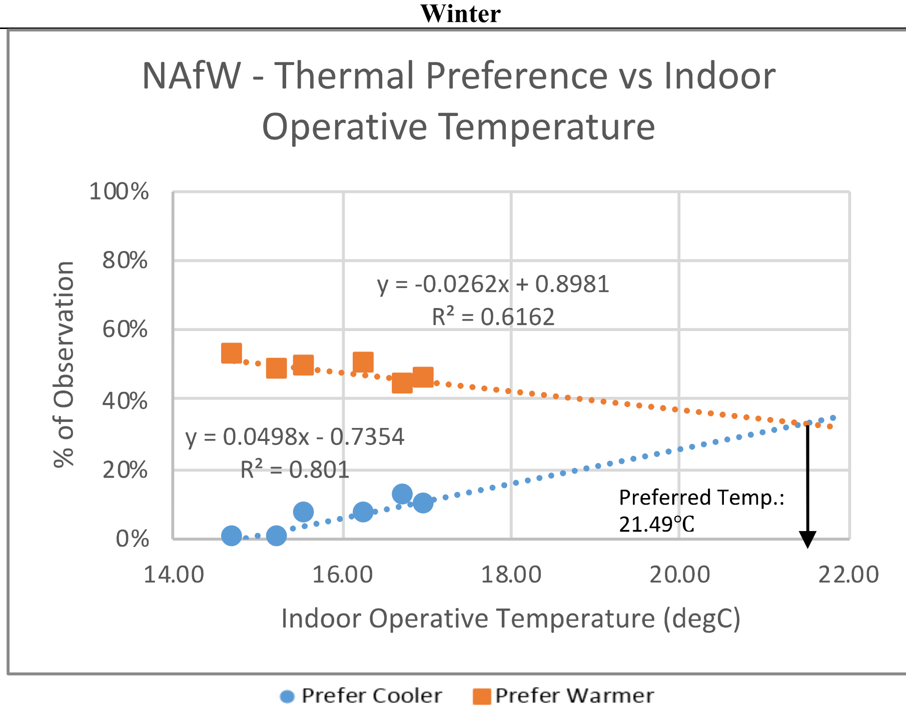
Preferred temperature represents the point at which people do not prefer either cooler or warmer. It is a subjective feeling about people's pleasantness or unpleasantness about their thermal environment, which may change with seasonality and climate. This can be explained by a concept called 'alliesthesia' (Spagnolo and de Dear 2003). The neutral temperature might not be the same as preferred temperature (Wang et al. 2018). People tend to have higher preferred temperature than neutral temperature in cold climate; and lower preferred temperature than neutral temperature in hot climate (Villadiego and Velay-Dabat 2014).

Weighted linear regression models and binned methods at half-degree-Celsius were adopted to identify the preferred temperatures for the surveyed buildings (Han et al. 2007; Humphreys et al. 2010; Liu et al. 2018a). A 5-point scale method was used to identify the respondents' thermal preference votes (TPV) on the thermal environment of the surveyed locations. The responses collected were classified into two groups. They were "prefer cooler" and "prefer warmer", which were defined as TPV<0 and TPV>0 respectively. After binning the TPV at each half-degree-Celsius increment, the sample size of TPV (in % of observation) for different groups was regressed against the indoor operative temperature separately. Figure 4-12 shows the results for the preferred temperatures for the surveyed buildings. The preferred temperature determined for the NAfW, HEB and RWCMD were 21.2°C, 21.6°C and 22.7°C respectively for the summer period. For the winter period, there was not any intersection between the "prefer cooler" and "prefer warmer" trends for NAfW as the indoor operative temperature was low. Therefore, the trend lines were extrapolated to identify the preferred temperature. In summary, the preferred temperatures for the NAfW, HEB and RWCMD were 21.5°C, 22.9°C and 22.5°C respectively.

Summer

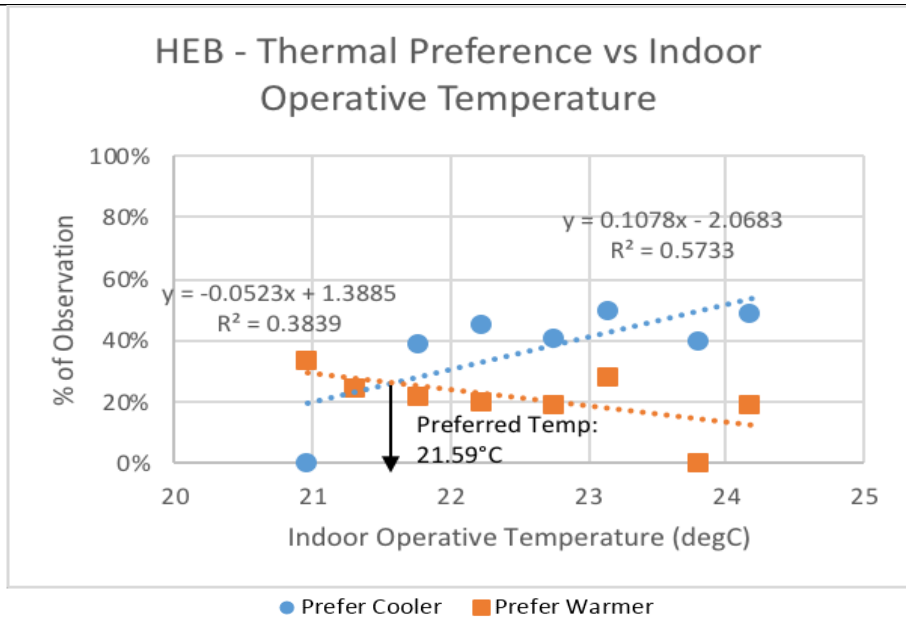


Winter

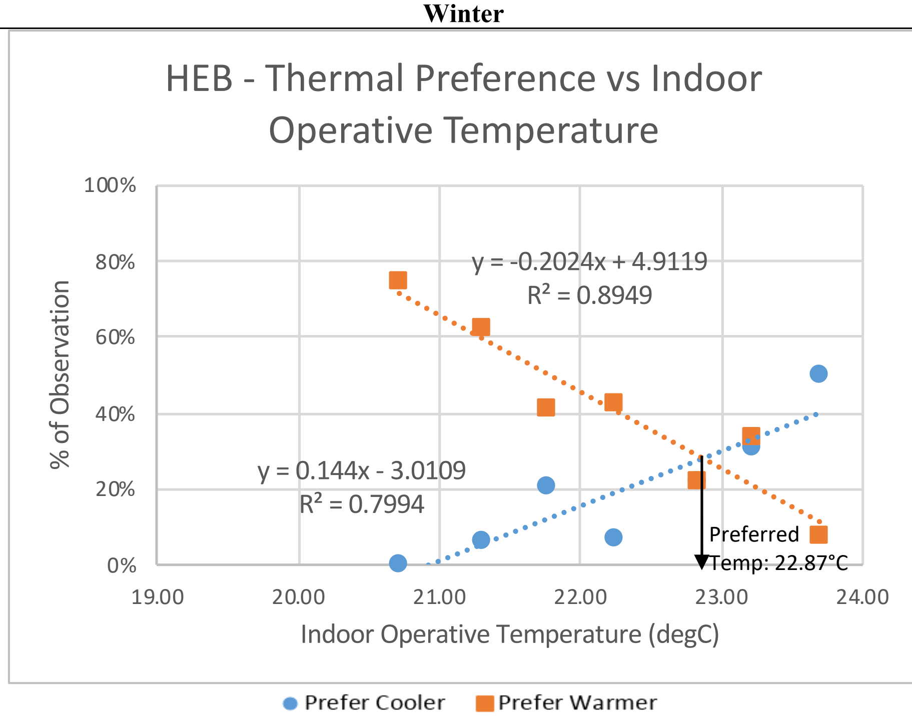


NAfW

Summer

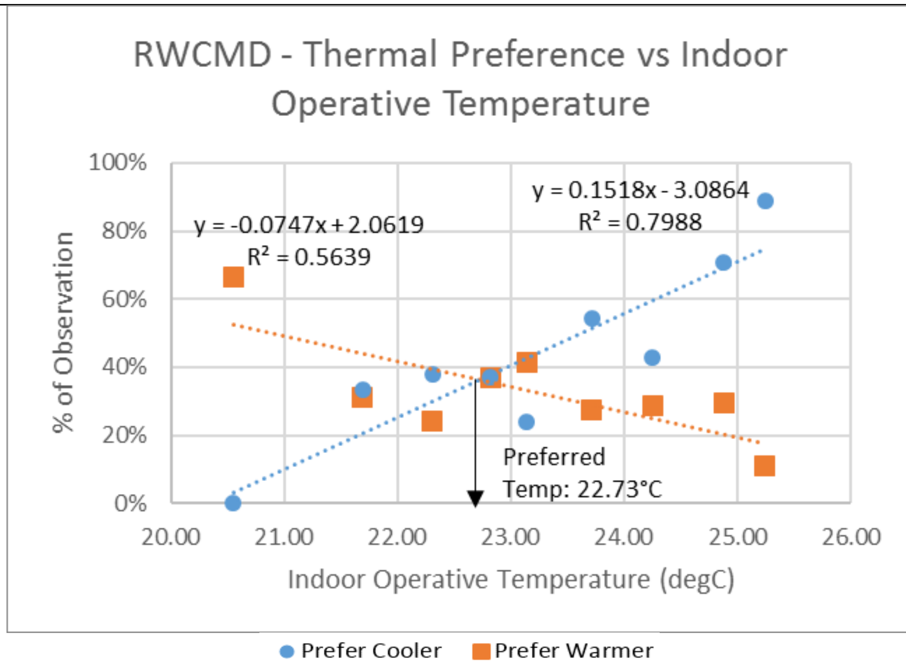


Winter

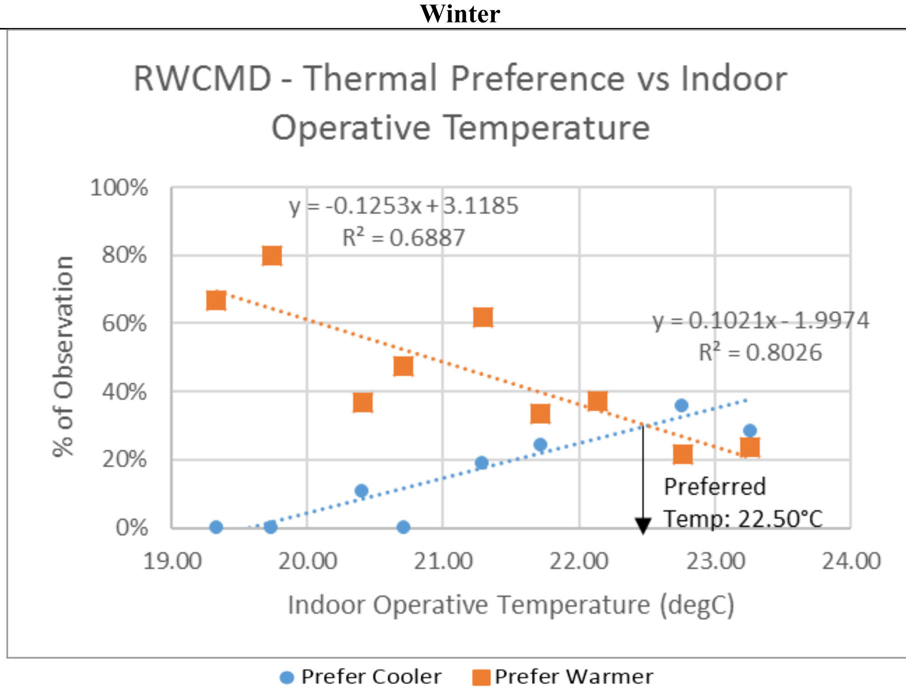


HEB

Summer



Winter



RWCMD

Figure 4-12 Preferred indoor operative temperatures of the building occupants

4.3.8 Investigation of Acceptable Temperature Ranges

The regression models developed in Figure 4-11 were used to identify the building occupants' thermal acceptability at the surveyed locations. The 80% and 90% acceptability comfort bands represent respectively that 80% and 90% of occupants declare a thermal environment as comfortable and they are defined as $-1<TSV<+1$ and $-0.5<TSV<+0.5$ respectively (ISO 2005). Table 4-6 summarises the evaluated results for the acceptable temperature ranges and the preferred and neutral temperature that were identified in previous sections.

For the summer period, the average preferred temperature and the average neutral temperature of the three surveyed buildings were 21.8°C and 20.5°C respectively. The NAfW had the lowest preferred and neutral temperature while the RWCMD had the highest preferred and neutral temperature. The average range for the 80% acceptable temperature range of the surveyed buildings was 8.0°C wide, which was brought down to 4.0°C wide for the 90% acceptable temperature range.

For the winter period, the preferred temperature for the NAfW cannot be identified as the linear trends for the thermal preferences (prefer cooler and prefer warmer) did not cross with each other. For the other buildings, the preferred temperatures were higher than that for the summer period, which were 22.9°C and 22.5°C for the HEB and the RWCMD respectively. In terms of natural temperature, except for the NAfW where the neutral temperature was lower than that for the summer period, the neutral temperatures identified for the HEB and the RWCMD were similar to that for the summer period. The average range for the 80% acceptable temperature range of the surveyed buildings was 8.3°C wide, while it was down to 4.2°C wide for the 90% acceptable temperature range.

Table 4-6 Summary of preferred temperature, neutral temperature and acceptable temperature ranges

	NAfW		**HEB**		**RWCMD**	
	Summer	Winter	Summer	Winter	Summer	Winter
Preferred Temperature (°C)	21.2	21.5	21.6	22.9	22.7	22.5
Neutral Temperature (°C)	19.3	16.9	21.2	20.9	21.0	20.7
80% Acceptable Temperature Range (°C)	14.7–23.8	12.3–21.4	17.4–24.9	16.2–25.5	17.3–24.8	17.4–24.0
90% Acceptable Temperature Range (°C)	17.0–21.6	14.6–19.2	19.3-23.0	18.5–23.2	19.2–22.9	19.1–22.4

4.4 Discussions

A large portion of the respondents (>82% for both the summer and the winter periods) voted the overall thermal feeling as "pleasant" (>+1 vote) in all the three surveyed buildings. Moreover, more than 80% of the respondents voted the TSV within the 80% comfort acceptability band (-1≤TSV≤+1). It implied that the thermal environment is acceptable for all the three buildings, as more than 80% of the respondents reflected thermal acceptability (ASHRAE 2013). Even though variations of the indoor temperature were greater than 4.5°C, the comfort level of these buildings did not vary too much.

Correlations between the clothing value, and the indoor operative temperature and outdoor air temperature respectively, were also investigated for both the summer and the winter periods. Similar trends were identified from both correlations, where the correlation between the clothing value and indoor operative temperature was stronger. This research confirmed that people in all three transitional spaces have a similar reaction to different temperatures, i.e. reducing the clothing values as the operative temperature increases, which aligned with research on thermal comfort in other building types (Wang et al. 2019a; Wu et al. 2019). It can be explained that people would choose the appropriate clothing according to the outdoor air temperature before they went out. After they entered the space, if they felt thermally uncomfortable, they would adjust their clothing to adapt themselves to the thermal environment in order to make them feel more comfortable. Morgan et al. (Morgan et al. 2002) explained why temperature affects clothing insulation by stating that "it is not difficult to understand how the temperature of the indoor microclimate surrounding the human body exerts an influence on clothing levels. Indoor temperature directly impacts the body's heat balance, skin temperatures and skin wettedness, which are, in turn, the main thermo-physiological drivers for thermal discomfort.”. The research carried out by Albatayneh et al. also had similar findings that people can achieve thermal comfort by adaptive behaviours such as changing clothes, instead of using mechanical heating or cooling systems (Albatayneh et al. 2017).

The correlation between PMV and actual TSV showed that PMV model was not an appropriate one to predict the thermal sensation in transitional spaces. This is not a surprising finding because it was known that PMV model was originally intended for application in spaces that are air-conditioned and well climatically-controlled (Van Hoof 2008). For the transitional spaces under study, they were not thermally well-controlled environments and people had a variety of activity levels in the spaces. This finding is in line with the research conducted by Chun et al., which verified that PMV model cannot be applied in transitional spaces due to its unstable and dynamic physical and activity level (Chun et al. 2004).

This statement was supported by the investigations of the open question, which asked about the actions that people would opt to overcome uncomfortable situations. The distributions of the voted actions were similar for the summer and winter periods. Almost 80% of the respondents would take self-adaptive actions, including “adjust clothing” (50% for summer;

53% for winter), “Move / Leave from the uncomfortable location” (21% for summer; 16% for winter), “Drink / Eat” (5% for summer; 6% for winter), and “Do exercise” (2% for summer; 3% for winter), to make themselves warmer or cooler when they felt cool or warm. Therefore, it can be concluded, that in order to maintain an acceptable thermal comfort level in indoor transitional spaces, people would take adaptive actions to make themselves feel comfortable. Similar adaptive actions can also be found in other researches for different indoor environments (Coley et al. 2017; Zaki et al. 2017; Carlucci et al. 2018; Xu et al. 2018).

A further analysis was carried out to quantify the acceptable temperatures, in terms of neutral temperature and preferred temperature in the surveyed buildings. Strong correlations were identified for the influences of the indoor operative temperature on people’s thermal sensations. Similar trends were identified for the three surveyed buildings where the gradients were all positive. In other words, the higher the indoor operative temperature, the warmer thermal sensation the building occupants would have, which is aligned with the findings from other researchers including Zaki et al., Khalid et al., and Kumar et al. (Zaki et al. 2017; Khalid et al. 2019; Kumar et al. 2019). The average neutral temperatures for all the three surveyed buildings were 20.5°C and 19.5°C, for the summer period and the winter period respectively. This gave an insight of how the thermal environment of a building with transitional spaces should be designed in order to maintain an acceptable thermal comfort level.

Moreover, in order to evaluate the preferred temperatures in the individual surveyed buildings, the intersection point of the "prefer warmer" and "prefer cooler" trends were used to identify the preferred temperatures. The average preferred temperatures identified for all the three surveyed buildings were 21.8°C and 22.3°C, for the summer period and the winter period respectively. It should be noted that the preferred temperature for the NAfW was identified by extrapolation for the winter period, as there was no intersection between the "prefer warmer" and "prefer cooler" trend lines. The average preferred temperatures were 1.3°C and 2.8°C higher than the average neutral temperature for the summer period and the winter period respectively. It reflected that people generally preferred a warmer thermal environment even when they felt thermally comfortable. This may be explained by that people surveyed were situated in a cool climate (Villadiego and Velay-Dabat 2014), as the average measured outdoor temperature was lower than 20°C for all surveyed buildings. This probably made people prefer a warmer thermal condition. People may have different preferred temperature than neutral temperature (Spagnolo and de Dear 2003; Villadiego and Velay-Dabat 2014; Wang et al. 2018).

The 80% and 90% acceptable temperature ranges for all the three surveyed buildings were relatively large for both summer and winter periods, with average ranges of 9.6°C and 4.0°C respectively. For the winter period, the average range for the 80% acceptable temperature range of all the three surveyed buildings was 8.3°C, which was brought down to 4.2°C for the 90% acceptable temperature range. This may be explained by the adaptability of the building occupants in the building transitional spaces. In other words, people inside the transitional spaces can still feel thermally comfortable without requiring a fine control of indoor air temperature as they can adapt to the thermal environment by different means such as adjusting clothing and drinking / eating. It met the expectation where adaptive behaviours such as changing clothing conditions and consumptions of drinks have an important role in improving occupants' acceptance of their thermal environments beyond the comfort zone (Gou et al. 2018).

The surveyed buildings served different purposes where the people's activity inside the buildings was different. For instance, people visited NAfW for public event such as building tour and exhibition. This led to a relatively higher respondent's activity level when compared to the other two buildings because of a greater number of people were walking or standing before taking the questionnaire surveys. On the other hand, HEB and RWCMD were academic / cultural buildings where more people used the transitional spaces for resting, dining and discussion. This may explain why NAfW had a lower neutral temperature and a wider acceptable temperature range when compared to the other two buildings. From other perspective, different architectural designs of transitional spaces could influence thermal comfort (Dili et al. 2011; Bodach et al. 2014; Chandel et al. 2016). In this study, it explained that this may be due to the different people's usage and activity level within the spaces as a result of architectural designs.

4.5 Conclusion

The field studies carried out in the transitional spaces of the three surveyed buildings produced an evaluation of the thermal environmental performance and people's adaptability. The majority of the respondents expressed that they experienced a pleasant overall thermal sensation in all the surveyed buildings, in both summer and winter periods. Indoor operative temperature, due to its strong correlation with the thermal sensation vote, was confirmed to be an important factor in determining thermal comfort.

Poor correlation was identified between PMV and actual TSV that were obtained from the questionnaire surveys. PMV model was therefore proven to be an inappropriate thermal model for predicting thermal sensation in transitional spaces. It could be explained that the transitional spaces under study were not air-conditioned and the people using such spaces had a variety of activity levels.

The identified neutral temperatures from the surveyed buildings imply that, in order to maintain an acceptable thermal environment within transitional spaces, the indoor temperature should be 20.5°C and 19.5°C, for the summer period and the winter period respectively. However, a fine temperature control is not necessary because of the fact that the 80% ($-1<TSV<+1$) and 90% ($-0.5<TSV<+0.5$) have a relatively wide range of acceptable temperatures. A temperature range of 4°C is considered good enough to maintain an acceptable thermal comfort level within building transitional spaces. The statement is strengthened by the strong correlation between clothing values and indoor operative temperature. Also, by the evaluation of the actions that people would take to overcome uncomfortable situations, where a majority of the people (>80%) would adopt self-adaptive actions such as adjusting clothing, drinking / eating, and moving position to deal with thermal discomfort. In short, people are more prepared to adapt to the environment in preference to attempting to alter the building systems, such as adjusting control of ventilation systems and windows opening.

People surveyed in all the three surveyed buildings tended to have a higher preferred temperature than neutral temperature, in both summer and winter time. This implies, that under Cardiff's weather condition, when the outdoor air temperature is relatively cool, people would prefer a warmer indoor thermal environment. Therefore, the neutral temperature may be considered as a measure of 'lack of discomfort', whilst the preferred temperature is a more positive measure of people's desired comfort level.

Chapter 5. COMPUTATIONAL SIMULATION

5.1 Introduction

From the field studies conducted in the three selected surveyed buildings, i.e. the National Assembly for Wales Senedd (NAfW), the Hadyn Ellis Building (HEB) and the Royal Welsh College of Music and Drama (RWCMD), the followings were identified: (1) basic site information such as site conditions, geometry, meteorology, building properties and building services system; (2) outdoor and indoor environmental conditions measurement data during field studies; (3) and the findings from the research of previous chapters, i.e. the adaptability and thermal comfort criteria within building transitional spaces. On this basis, this Chapter is aimed to investigate the improvement strategies of the thermal comfort environment of transitional spaces by evaluating the impacts of the architectural form and active system design on the thermal environment. Computational fluid dynamics (CFD) technique was adopted in the study to quantify the impacts. The indoor environmental performance of the three surveyed buildings was simulated under two weather scenarios, which were the Average Scenario and Extreme Scenario. Different improvement strategies such as natural ventilation and application of underfloor radiant system and underfloor air distribution system were simulated and compared. Thermal comfort solution on the environmental condition of transitional spaces was suggested from this research work.

5.2 Methodology

5.2.1 Research Methodology

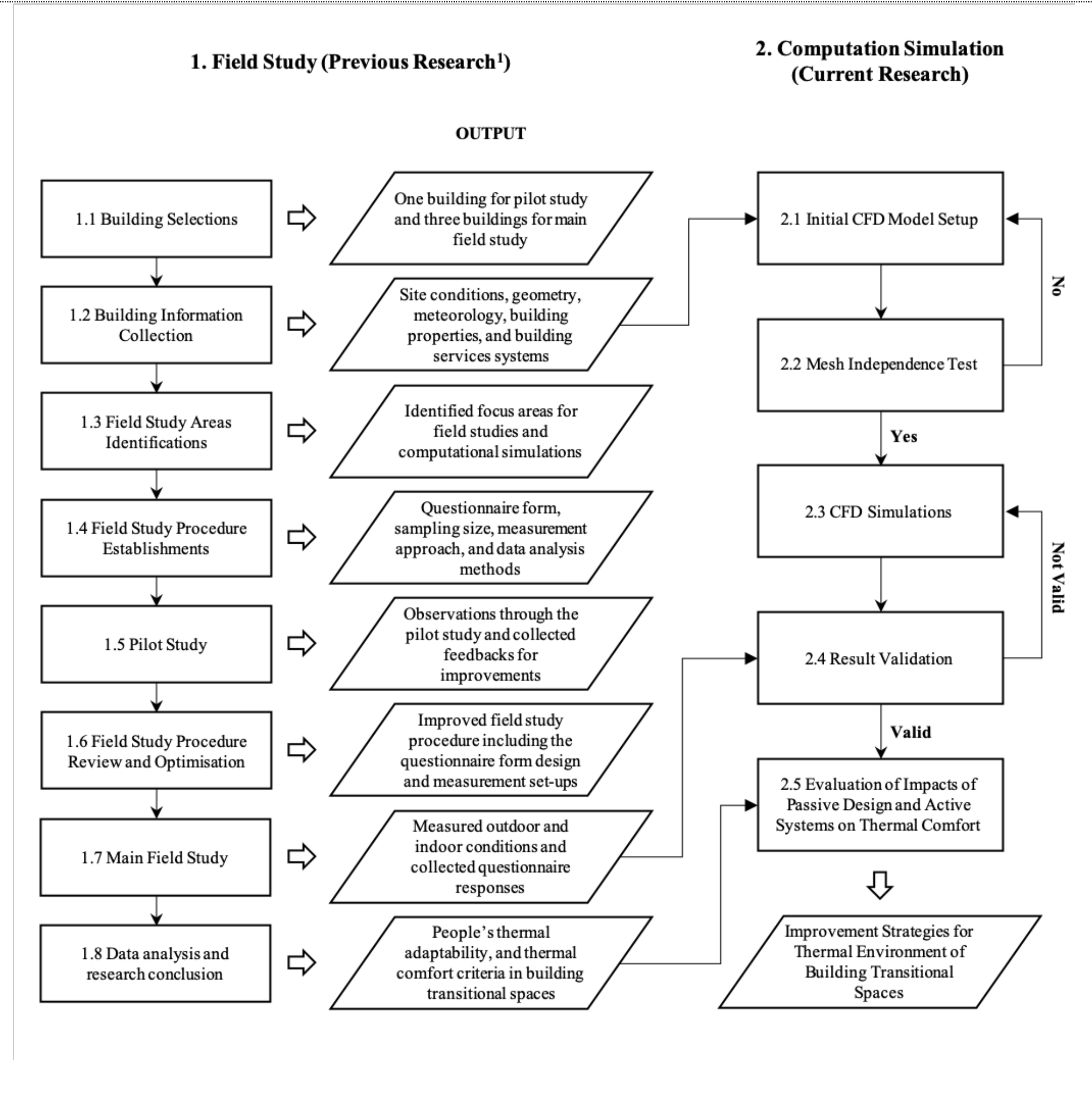


Figure 5-1 Research Methodology

Carrying on from the previous research, a methodology, as illustrated in Figure 5-1, was developed. Computational fluid dynamics (CFD) was used as a tool to facilitate the research process. With the collected building information, including building geometry, internal architectural designs and building services systems provisions and openings locations, initial models were built for the three selected buildings – the NAfW, HEB and RWCMD.

Due to the problems in defining the actual boundary conditions and different possible adaptation and acclimatisation of occupants to the thermal environments, there are always some discrepancies between the CFD model and experimental results (Kwong et al. 2014). Therefore, there is a strong need for model validation by comparing the simulated data from CFD with the experimental data in order to reduce the error introduced by numerical approximations, choice of turbulence models and boundary condition set-up (Yao 2016). In this research, after the mesh settings were identified by conducting mesh independence tests, the CFD models were, therefore, validated against the physical measurement results before carrying out detailed investigations of difference scenarios. For each case building, an external model and an internal model were built separately and were compared with the physical measurement results of the outdoor and indoor environmental conditions respectively. One surveyed date in the summer period was selected randomly for model validation. The model was considered as valid when the difference between the simulated results and the physical measurement results was less than 5%. The validation was conducted by comparing the physical measurement results and the simulation results in terms of indoor operative temperature and outdoor wind direction and velocity, for the internal model and external model respectively. The external model was used to simulate the external condition of the selected surveyed date. The wind pressure on the façade openings was extracted as inputs to the internal model. HEB and NAfW adopted natural ventilation during the field studies. The wind pressure was set in these internal models to simulate the natural ventilation effects on the indoor environment.

The validated models were then used to study the thermal performance of the building transitional spaces under an average condition and an extreme condition. Summer and winter conditions were investigated for each condition. Under the average condition, the average monthly maximum outdoor dry-bulb temperature, 21.7°C, and average monthly maximum outdoor dry-bulb temperature, 2.1°C, were input to the models for summer and winter conditions respectively. The average temperatures were extracted from the met office, where the database was generated for the climate period of 1981 -2010 (Met Office 2019). Under the extreme condition, the temperature settings were based on the future weather files developed by Liu et al. (Liu et al. 2016). The pHSY-2 weather file, which was developed upon the Physiologically Equivalent Temperature (PET) and highlighted the weather years that will have a significant impact on human thermal comfort, was used for this research.

The highest and lower temperatures of the weather file, which were 31.6°C and 1.6°C, were extracted for the investigations for the summer period and winter period respectively.

The identified comfort criteria from the previous research (Tse and Jones 2019) were used to justify whether the building transitional spaces of the selected buildings could still be able to maintain an acceptable thermal environment under the average and extreme conditions. To generate further ideas about the impacts on the thermal conditions, the impacts of different passive design and mechanical ventilation strategies on the thermal environment were evaluated.

5.2.2 Model Geometries

For each of the surveyed buildings, an external model and an internal model were built separately. The purpose of building the external model was to evaluate the wind pressure on the building openings which facilitated the investigations of natural ventilation of the indoor environment. The internal model was developed to evaluate the impacts of passive designs and active systems on the thermal environmental performance respectively.

External Model

In order to prevent interference on the numerical simulation results, Franke et al. (Franke et al. 2007) and Tominaga et al. (Tominaga et al. 2008) suggested that the minimum distance between the study objects and the domain boundary shall be maintained at 5 times the building height. On such basis, in this research, taking the surveyed building height as H, the surrounding buildings within a circular radius of 2H were built and the domain boundary was set at a distance of 10H from the surveyed building. By correlating against the measured data from the weather station, the boundary conditions were identified. With the validated models, the inlet pressure for the operable windows for the individual buildings was evaluated. The simulated pressure data were then used in the internal models for the model validation against the indoor physical measurement data for those buildings that operated under natural ventilation during the field studies.

Internal Model

For the buildings which adopted natural ventilation during the selected surveyed date for model validation, the inlet pressures at windows, generated from the validated external models, were imported to the internal models. The heat sources including the occupants, equipment and lighting were then correlated against the environmental data collected during the field studies.

The validated models were selected to conduct further studies under the average and extreme conditions. Under both conditions, the baseline models (CO), where all the windows were closed and no active systems were operated, were simulated. The comfort conditions were then evaluated. Further investigations were conducted on the impacts of passive design strategies and hybrid strategy. The adopted passive strategies included natural ventilation

(NV) and underfloor radiant systems (UF); while the hybrid strategy was the combination of radiant floor heating / cooling systems and underfloor air distribution system (UFAD) where the conditioned air was supplied to the occupied space through a trench system which was located along the perimeters of the building transitional spaces under study. For the NV system, it was assumed that the external wind pressure at the openings was 0 Pa. In order to test the appropriate temperature settings for the UF, different temperatures were tested in the research, e.g. 16°C, 20°C, and 24°C for the summer time; 24°C, 28°C, and 32°C for the winter time. The lowest UF temperature setting for the summer time were referenced to the research by Ning et al. which tested the radiant floor cooling system with temperature settings ranged from 16°C – 18°C (Ning et al. 2015). It also made sense that the temperature shall not be set too low as to prevent condensation on the floor surface. For the highest UF temperature settings for the winter time, it was referenced to the research conducted by Ding et al., where the average temperature of the radiant floor heating system ranged from 31°C - 33°C (Ding et al. 2020). The rationale of having different radiant floor surface temperature settings was to evaluate the impacts of floor surface temperatures on its thermal environment. The supply air temperatures for the UFAD system were set at a constant 18°C and 35°C for the summer and winter conditions respectively. As the air would be supplied via a trench grille for the UFAD, the annotation used in this paper for the cooling mode and heating mode were TC and TH respectively. With the consideration of occupants comfort, the supply air velocity was limited to 0.8m/s (Gon Kima; Laura Schaefer; Tae Sub Lim; Jeong Tai Kim

2013). It was aimed to generate a preliminary concept of how these systems may improve the indoor thermal comfort level.

In order to take into the account of the impacts of internal surface temperature on the environmental situation, a coupling method was adopted between a dynamic simulation code using HTB2 and a CFD model using Star-CCM+. HTB2 is a software that was developed by the Welsh School of Architecture of Cardiff University (Alexander 1997). Taking into account the building location, building materials and construction, spatial attributes, and occupancy profiles, dynamic thermal simulation can be performed by using HTB2. With the application of HTB2, simulation was conducted with the use of the exported internal air temperatures from CFD. Building façade surface temperatures calculated by HTB2 were used as the boundary settings for the CFD models.

Figure 5-2 below illustrates the meshed model for the external model and internal model for NAfW as an example of how the CFD models were built up for the surveyed buildings.

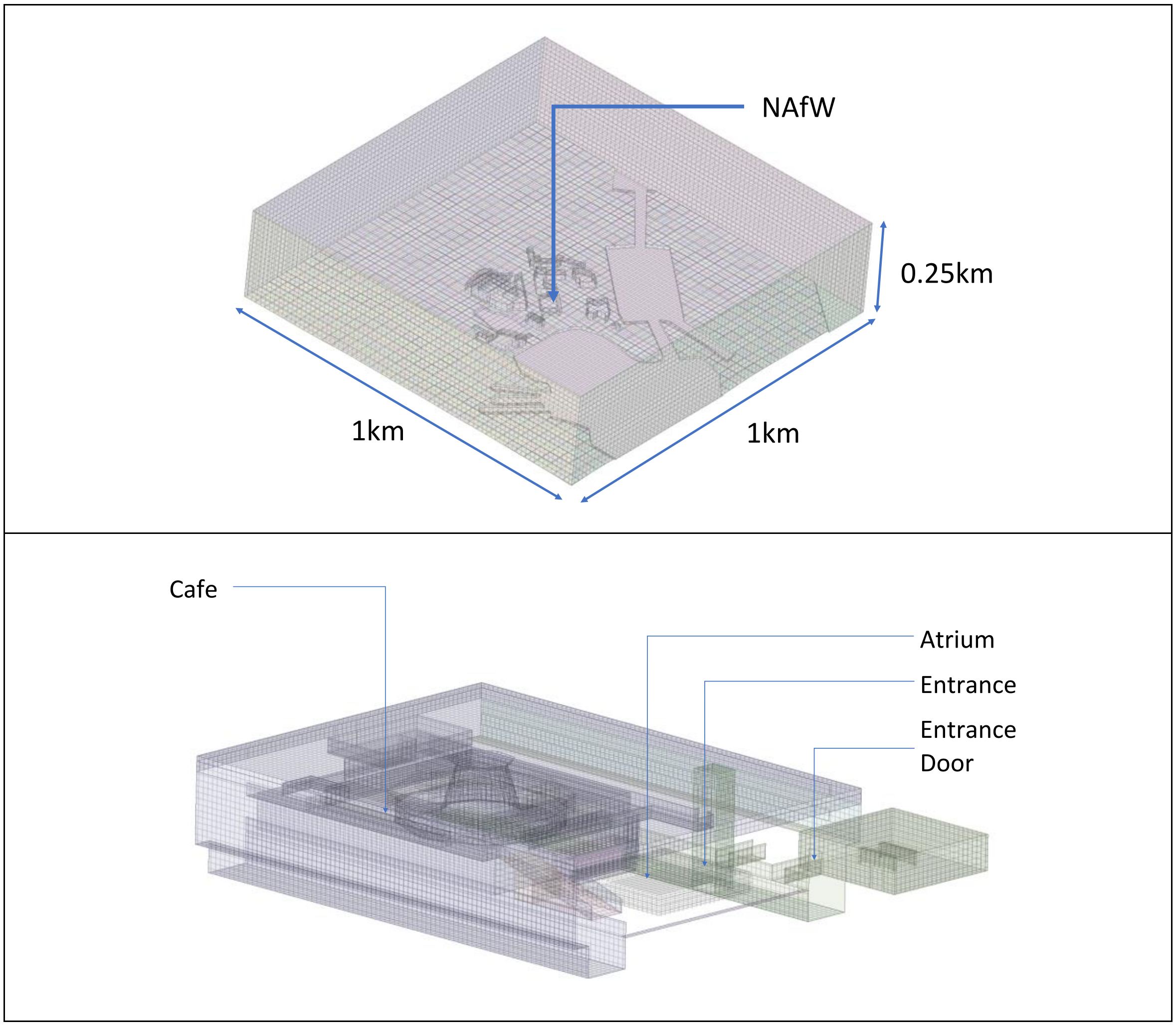


Figure 5-2Meshed External Model (Upper) and Internal Model (Lower) for NAfW

5.2.3 Model Validation

In order to ensure the accuracy of the CFD models that can give credible and verifiable results, it is suggested that model validation shall be conducted by creating the models with verified software and measured data (Oberkampf and Trucano 2008). Air temperature is a parameter that researchers would use for model validation (Mouriki et al. 2008; Mouriki

2009; Rundle et al. 2011; Karava et al. 2012; Hajdukiewicz et al. 2013). In this research, CFD models were built according to the three surveyed buildings respectively. The measurement dates randomly picked for the model validation process for the summer period were 26 August 2017, 4 August 2017 and 20 September 2017 respectively for NAfW, HEB and RWCMD; and that for the winter period were 7 January 2018, 2 February 2018 and 20 January 2018 respectively for NAfW, HEB and RWCMD. Table 5-1 summarises the validation results for the CFD models for all the three surveyed buildings at the summer and winter time. The validation results showed a good agreement between simulation modelling and the field measurement data by having the largest deviation of less than 5% or less than 1.0°C. Muhsin et al. suggested that ranges less than 20% are good validations (Muhsin et al. 2017). Warey et al. validated their CFD model by matching the CFD model with the experimental measurements within ±1°C (Warey et al. 2020). This is also in line with other studies in which validation of CFD model was performed against mean air temperature (Tominaga et al. 2015; Athamena et al. 2018).

	Physical Measurement Results (°C)			Validated Model Results (°C)		
	Atrium	**Café**	**Entrance**	**Atrium**	**Café**	**Entrance**
NAfW						
Summer	22.99	22.5	22.77	22.69 (-1.29%)	21.91 (-2.61%)	22.55 (-0.95%)
Winter	16.99	16.32	16.55	16.40 (-3.44%)	16.41 (+0.55%)	16.30 (-1.50%)
HEB						
Summer	22.19	22.59	22.23	21.86 (-1.50%)	21.86 (-3.24%)	22.41 (+0.81%)
Winter	23.78	21.27	20.23	23.84 (+0.25%)	21.42 (+0.71%)	20.92 (+3.41%)
RWCMD						
Summer	22.33	25.02	22.33	21.85 (-2.15%)	24.56 (-1.84%)	21.41 (-4.12%)
Winter	21.41	22.88	20.43	20.57 (-3.92%)	23.98 (+4.81%)	20.07 (-1.76%)

Table 5-1 Models Validation Results

5.2.4 Mesh Independence Test

Detailed information on the distribution of air velocity, temperature, and pressure within a study area can be provided with the use of CFD. The result accuracy, however, depends upon the quality of the mesh adopted, the correctness of the boundary conditions settings, and the appropriateness of any assumptions applied to the model. When it is modelled correctly, CFD can provide reliable results in different cases (Jiang et al. 2003; Jiang and Chen 2003; Ramponi and Blocken 2012; James Lo et al. 2013; van Hooff et al. 2017). Mesh independence test, therefore, was conducted for the simulated models in this research. The meshes were generated through an automatic element mesh generator with an adaptive mesh refinement algorithm employed. As the thermal condition at the occupied zone was considered as the focus area, finer mesh settings were applied for the human height level, i.e. distance of 2m from the floor. In addition, mesh refinement was also applied at the air inlets and outlet regions and the surfaces of heat sources. For each simulated model, three basic numerical meshes, which were coarse, medium and fine mesh settings, were generated respectively to identify the most suitable mesh settings for the study. The selection criteria for the mesh settings were based on the consideration of simulation time required and simulation accuracy. Indoor operative temperature was chosen to be the judging parameters for the evaluation of model accuracy. The three mesh levels for NAfW contained 346 451, 907 905 and 3 046 339; that for HEB contained 254 926, 1 130 979 and 3 479 900; and that for RWCMD contained 444 720, 1 506 444, and 3 741 946. The largest meshes were used for all the calculations conducted in this study.

5.2.5 Governing Equations

The airflow of constant density and segregated flow was simulated under steady-state conditions. The flow field of fluid was based upon the conservation of mass, momentum and energy. Simulations were considered as converged when the sum of normalised residuals for each flow equation was less than 10^{-4}.

For this research, the air was assumed to be turbulent flow in the CFD simulations. With the considerations of modelling accuracy in flow field estimations using acceptable computational time (Cheng et al. 2003; Liu et al. 2018b), a standard k-ε model was chosen as the turbulent model for the simulations. It has been widely used in academic studies in ventilation design and airflow analysis (Lam and Chan 2001; Mirade and Picgirard 2006). Particular to natural ventilation applications, the standard k-ε model is found to be the most widely used turbulence model (Mousa et al. 2017). This turbulence model has also been proven that a good results' accuracy with acceptable robustness of the solution can be achieved (Srebric et al. 2008; Hajdukiewicz et al. 2013). A number of researches have been conducted to validate the accuracy of this turbulence model. With the use of standard k-ε model, Kindangen et al. and Nishizawa et al. evaluated the influences of external conditions on indoor airflow (Kindangen et al. 1997; Nishizawa et al. 2016); Mak et al. studied the impacts of wing walls on air change rates and indoor air speed (Mak et al. 2007); Horan & Fin analysed the air change rates of an atrium space under natural ventilation mode (Horan and Finn 2008); Elmualim & Awbi and Li & Mak evaluated the effects of external wind on natural ventilation performance via the applications of wind catchers (Li and Mak 2007; Elmualim and Awbi 2016).

To take into account the radiation heat transfer from the building walls and radiant floors, a surface-to-surface radiation model was used in the CFD simulation models. The timeaveraged equations that considered the mean and fluctuating terms for incompressible flow can be expressed as following main governing equations:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial}{\partial x_j}\left(u_i u_j\right) = -\frac{1}{\rho}\frac{\partial p_{rgh}}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\nu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \overline{u_i' u_j'}\right] - \rho_o g_i \beta\left(T - T_{ref}\right) \tag{2}$$

$$u_j \frac{\partial T}{\partial x_j} = \frac{\partial}{\partial x_i}\left(\alpha \frac{\partial T}{\partial x_j} - \rho c \overline{v' T'}\right) \tag{3}$$

5.3 Result

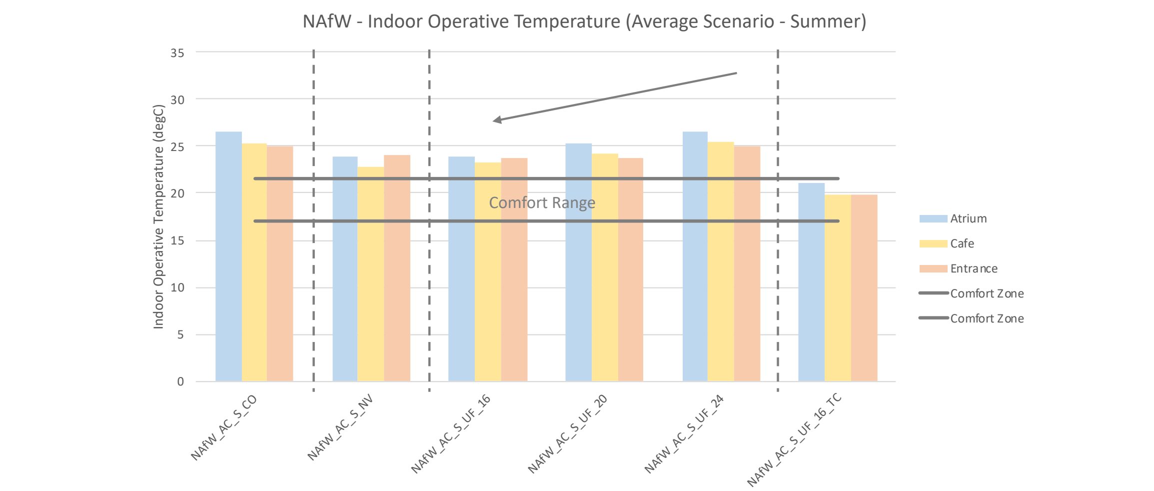
5.3.1 Computational Analysis

The results conducted by the CFD application were analysed in two different conditions, which were the average condition and extreme condition. Under each condition, the indoor operative temperature was simulated under different building and system setups, which included all building openings being closed (CO), natural ventilation (NV), underfloor radiant system (UF), UFAD cooling system via trench grilles (TC) and UFAD heating system via trench grilles (TH). In each selected building, three different locations within the indoor transitional space, including the main entrance area, atrium and café, were investigated in terms of indoor operative temperature.

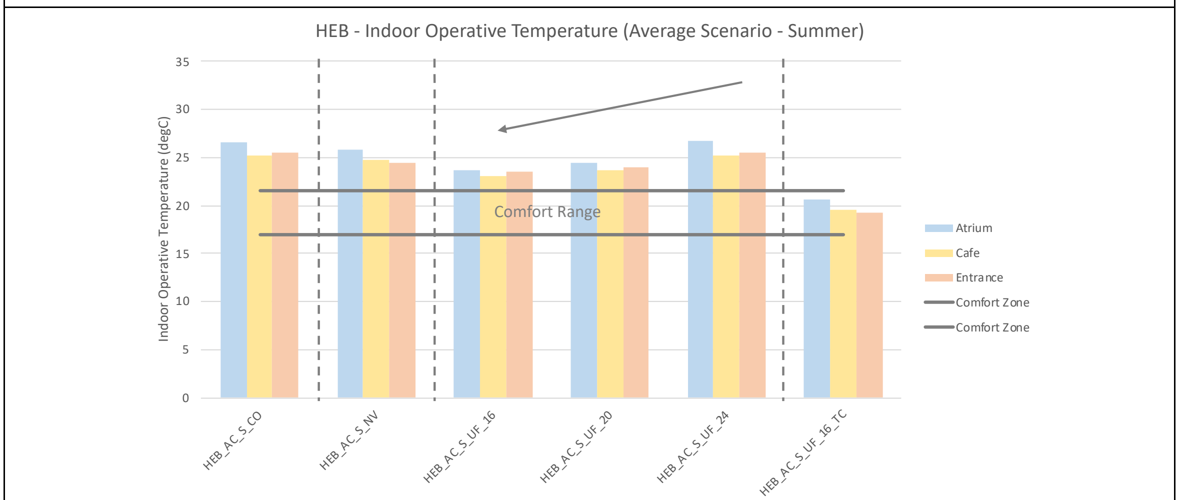
Average Condition (AC) - Summer

Figure 5-3 summarises the results of the computational analysis of different system operation of the transitional spaces under average condition in the summer period for the selected buildings. With the high outdoor air temperature and internal gains such as solar radiant heat gain, people load, lighting and equipment load, the indoor operative temperature of all of the three selected cases did not fall into the comfort range. With the operable windows opened to allow natural ventilation, the indoor operative temperature was reduced but still out of the comfort range. For the situation where only underfloor radiant system was operated, it could be found that the lower the surface temperature of the radiant system is, the more is the reduction of the indoor operative temperature. However, because openings were assumed to be closed for this situation, none of the temperature settings could help achieve thermal comfort. Only the hybrid system, i.e. UFAD and underfloor radiant system at 16°C, could help maintain the indoor transitional spaces at acceptable thermal comfort.

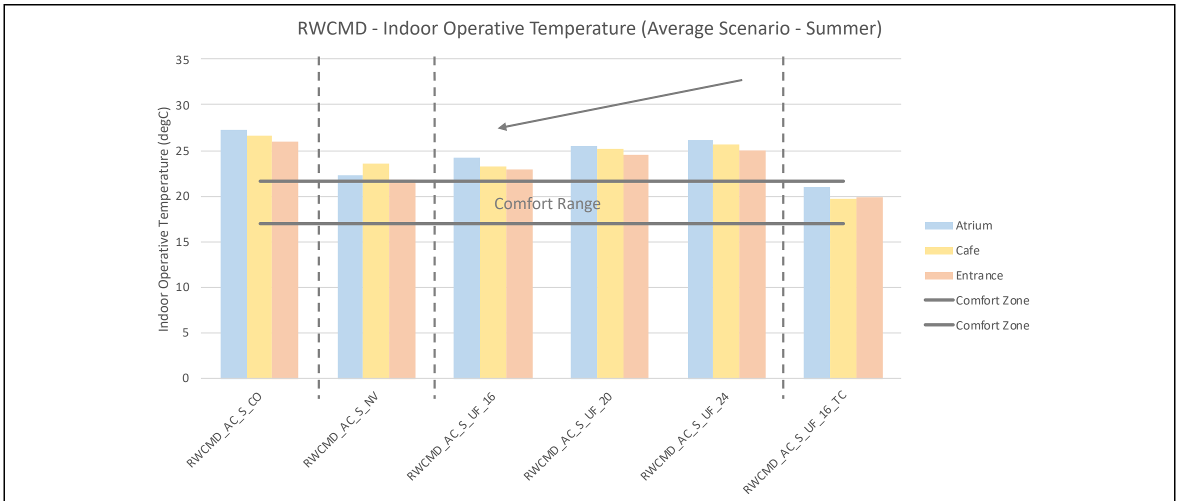
Out of the three selected buildings, HEB, in general, had a lower indoor operative temperature. It was mainly because the glazed area of the transitional spaces was smaller leading to smaller solar radiant heat gain.


NAfW - Indoor Operative Temperature (Average Scenario - Summer)
Indoor Operative Temperature (degC)
35
30
25
20
15
10
5
0
Comfort Range
NAfW_AC_S_CO
NAfW_AC_S_NV
NAfW_AC_S_UF_16
NAfW_AC_S_UF_20
NAfW_AC_S_UF_24
NAfW_AC_S_UF_16_TC
Atrium
Cafe
Entrance
Comfort Zone
Comfort Zone

NAfW


HEB - Indoor Operative Temperature (Average Scenario - Summer)
Indoor Operative Temperature (degC)
35
30
25
20
15
10
5
0
Comfort Range
HEB_AC_S_CO
HEB_AC_S_NV
HEB_AC_S_UF_16
HEB_AC_S_UF_20
HEB_AC_S_UF_24
HEB_AC_S_UF_16_TC
Atrium
Cafe
Entrance
Comfort Zone
Comfort Zone

HEB

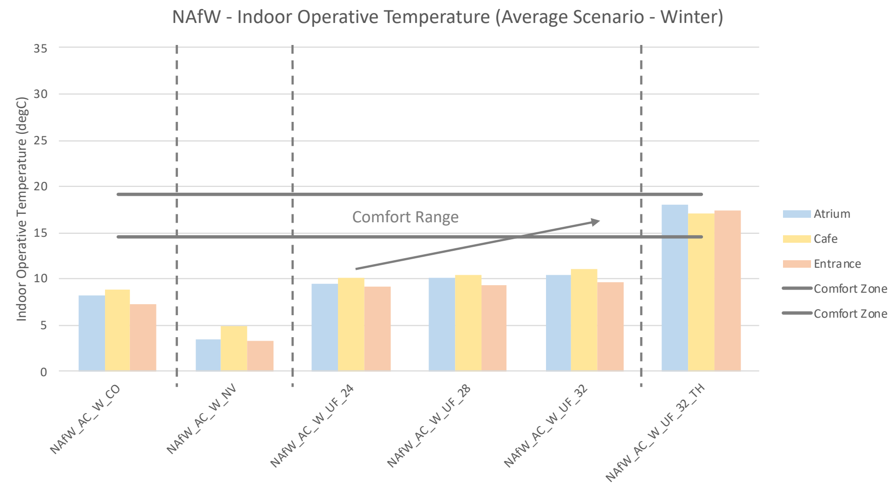


RWCMD

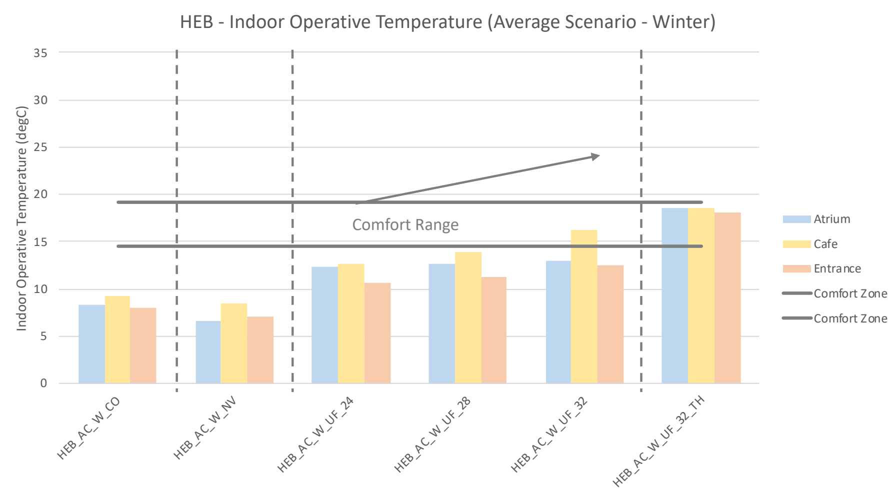
Figure 5-3 Simulation Results under Average Condition - Summer

<u>Average Condition (AC) - Winter</u>

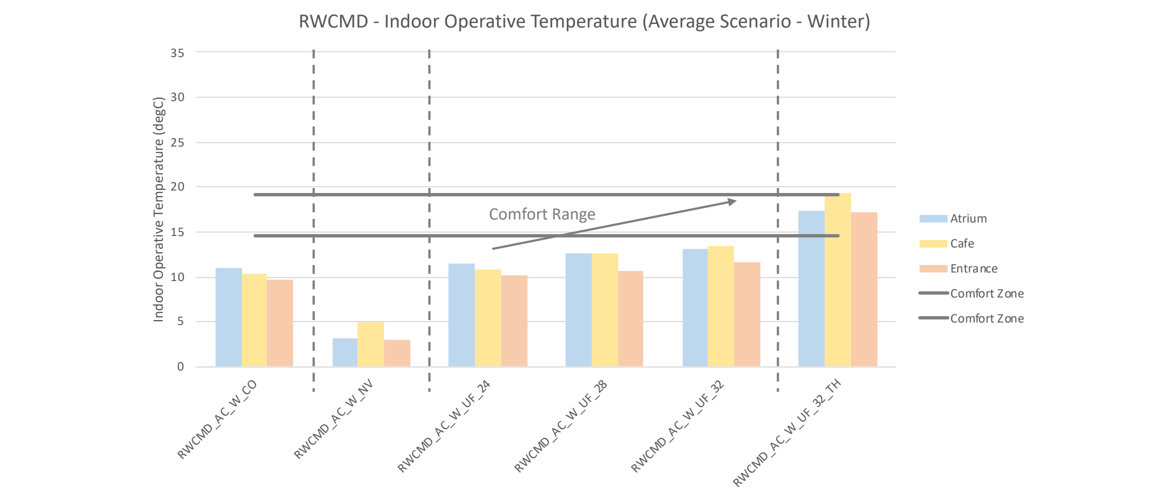
Under the average condition in the winter period, the indoor operative temperature was well below the comfort range. Figure 5-4 summarises the simulation results. It could be found that closing all the openings of the transitional spaces could keep the spaces warmer as it trapped the heat inside. However, due to the heat losses through the building envelope, the indoor operative temperature by just closing all the openings was not high enough to provide a thermally comfortable space for the occupants. By just applying underfloor radiant heating system could help further increase the indoor operative temperature but the spaces were not warm enough to hit the comfort range, except for the café space of HEB when the radiant floor temperature was set at 32°C. When the UFAD heating system was also operated, all the selected buildings could provide acceptable thermal comfort for the occupants.


NAfW - Indoor Operative Temperature (Average Scenario - Winter)
Indoor Operative Temperature (degC)
35
30
25
20
15
10
5
0
Comfort Range
NAfW_AC_W_CO
NAfW_AC_W_NV
NAfW_AC_W_UF_24
NAfW_AC_W_UF_28
NAfW_AC_W_UF_32
NAfW_AC_W_UF_32_TH
Atrium
Cafe
Entrance
Comfort Zone
Comfort Zone

NAfW


HEB - Indoor Operative Temperature (Average Scenario - Winter)
Indoor Operative Temperature (degC)
35
30
25
20
15
10
5
0
Comfort Range
HEB_AC_W_CO
HEB_AC_W_NV
HEB_AC_W_UF_24
HEB_AC_W_UF_28
HEB_AC_W_UF_32
HEB_AC_W_UF_32_TH
Atrium
Cafe
Entrance
Comfort Zone
Comfort Zone

HEB

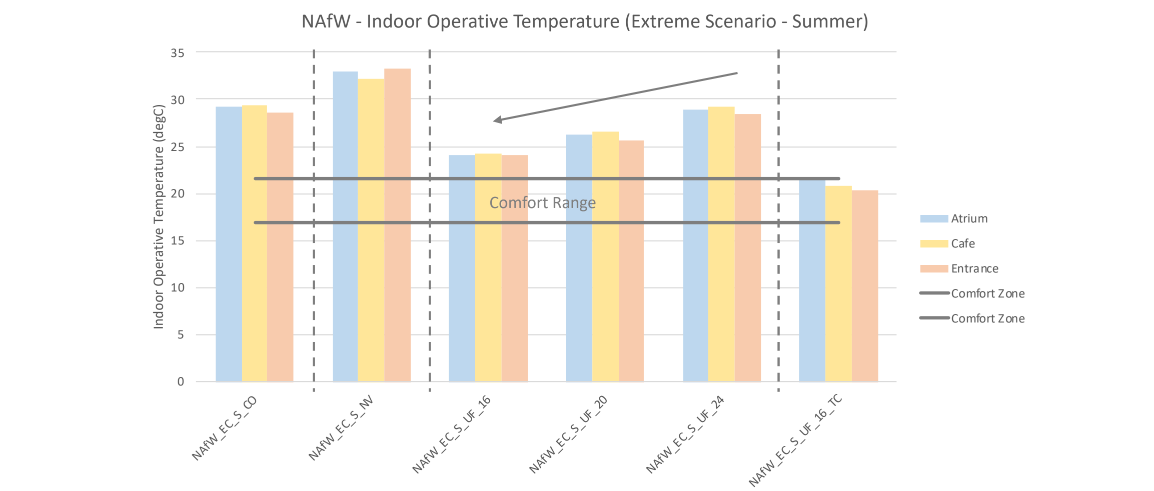


RWCMD

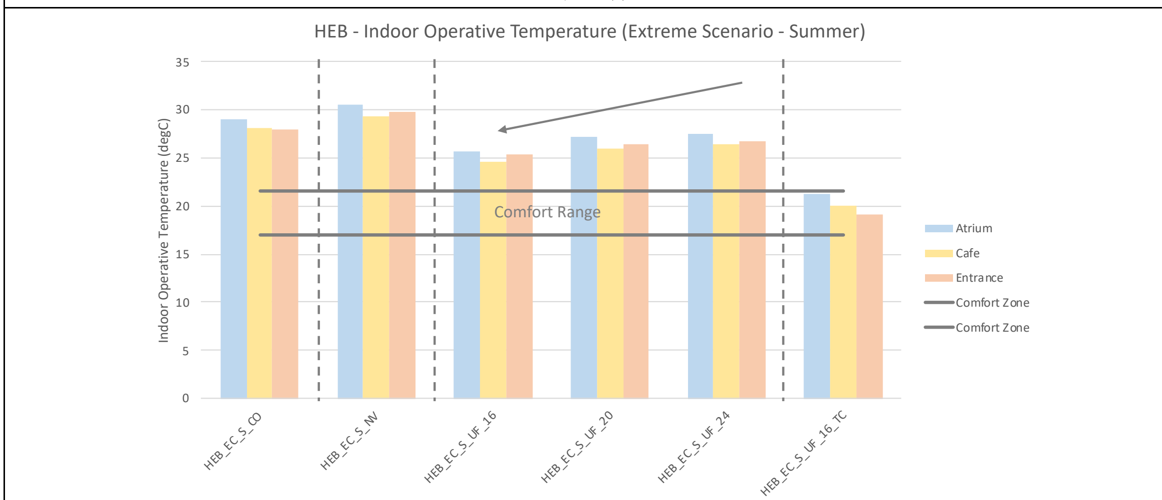
Figure 5-4. Simulation Results under Average Condition - Winter

Extreme Condition (EC) – Summer

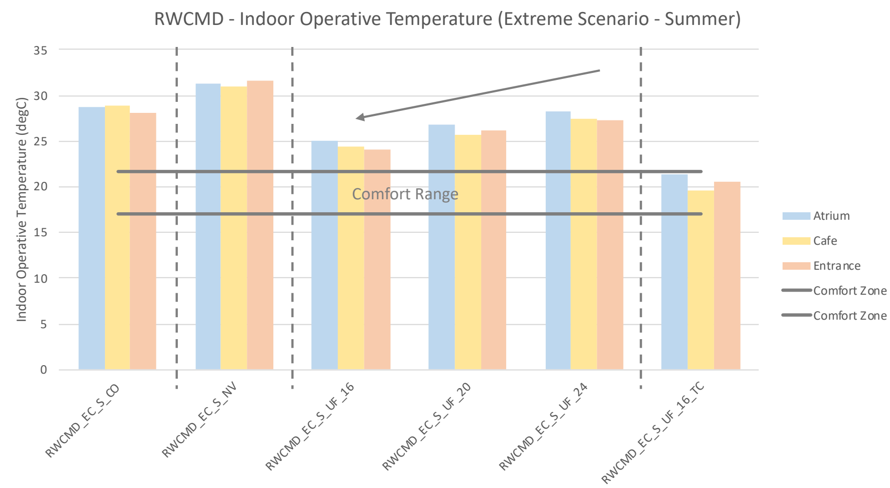
Figure 5-5 illustrates the simulation results for the surveyed buildings under the extreme condition in the summer period. As the outdoor temperature was high, the application of natural ventilation made the indoor transitional spaces even hotter than having all the openings closed. It could be explained that the incoming outdoor air of higher temperature through the building openings made the indoor environment even hotter. By adopting the underfloor radiant cooling system could help reduce the indoor operative temperature effectively but it was yet to maintain a comfortable indoor space. Only the operation of both the underfloor radiant cooling system at 16°C and UFAD through trench grilles could lower the indoor operative temperature to a thermally comfortable temperature.


NAfW - Indoor Operative Temperature (Extreme Scenario - Summer)
Indoor Operative Temperature (degC)
35
30
25
20
15
10
5
0
Comfort Range
NAfW_EC_S_CO
NAfW_EC_S_NV
NAfW_EC_S_UF_16
NAfW_EC_S_UF_20
NAfW_EC_S_UF_24
NAfW_EC_S_UF_16_TC
Atrium
Cafe
Entrance
Comfort Zone
Comfort Zone

NAfW


HEB - Indoor Operative Temperature (Extreme Scenario - Summer)
Indoor Operative Temperature (degC)
35
30
25
20
15
10
5
0
Comfort Range
HEB_EC_S_CO
HEB_EC_S_NV
HEB_EC_S_UF_16
HEB_EC_S_UF_20
HEB_EC_S_UF_24
HEB_EC_S_UF_16_TC
Atrium
Cafe
Entrance
Comfort Zone
Comfort Zone

HEB

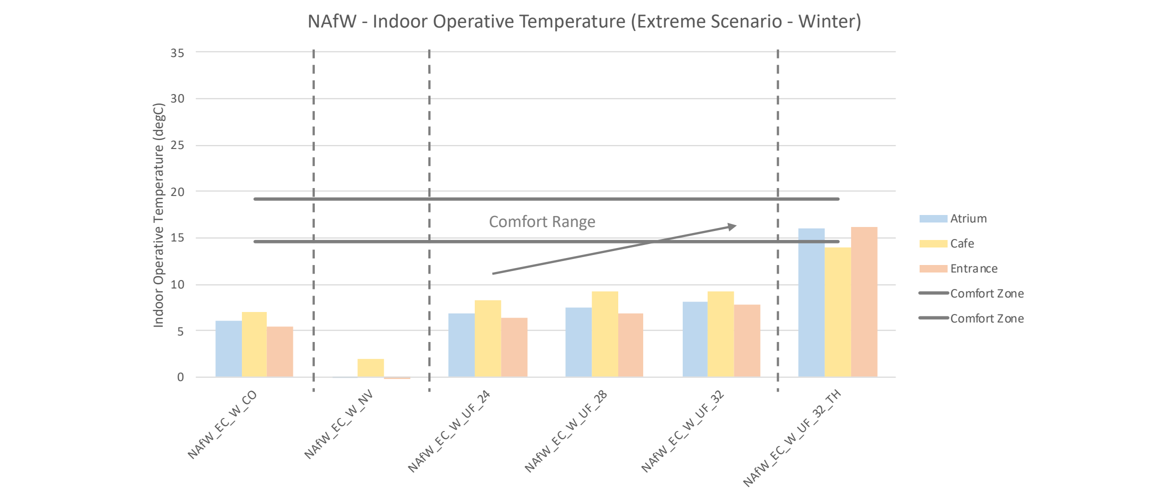


RWCMD

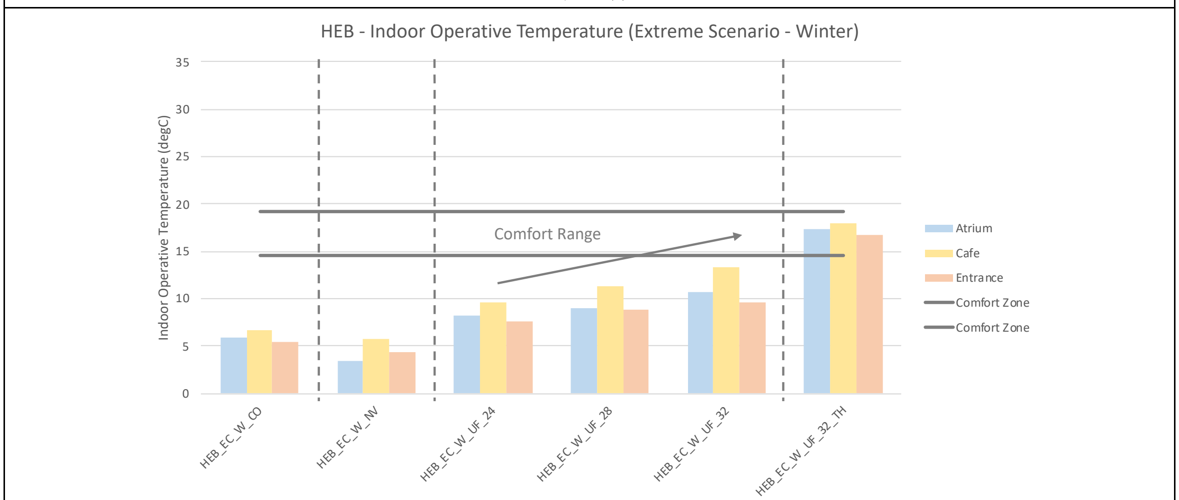
Figure 5-5. Simulation Results under Extreme Condition - Summer

<u>Extreme Condition (EC) – Winter</u>

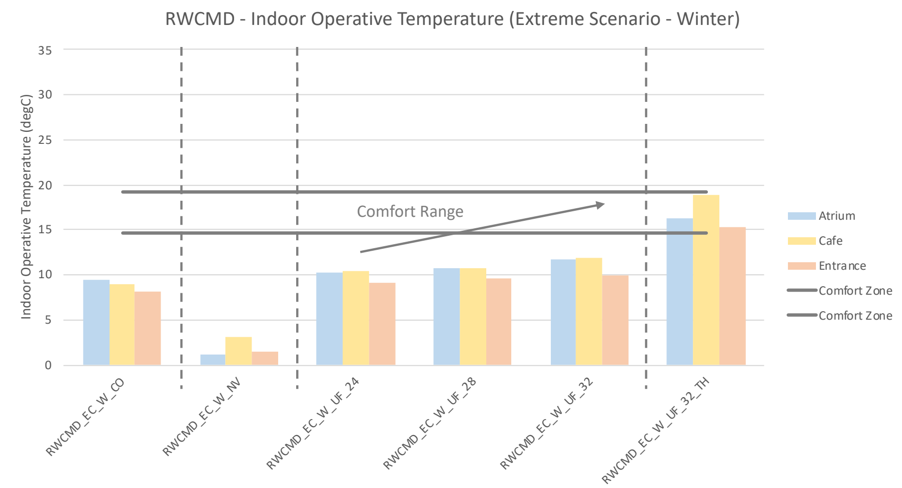
During the extreme condition in the winder period, as illustrated in Figure 5-6, the low ambient temperature led to a cold environment within the transitional spaces for all the three surveyed buildings. Heat could be trapped within the transitional spaces by closing all the openings. In addition, when the underfloor radiant heating system was operated, the indoor operative temperature could even be increased. Due to the significant heat loss as a result of big temperature difference between the ambient temperature and indoor temperature, none of the cases could provide the occupants with the thermally comfortable indoor transitional spaces by closing the openings and using underfloor radiant system alone. The indoor operative temperature could hit the comfort range only when the UFAD system also operated in addition to these measures.


NAfW - Indoor Operative Temperature (Extreme Scenario - Winter)
Indoor Operative Temperature (degC)
0
5
10
15
20
25
30
35
Comfort Range
NAfW_EC_W_CO
NAfW_EC_W_NV
NAfW_EC_W_UF_24
NAfW_EC_W_UF_28
NAfW_EC_W_UF_32
NAfW_EC_W_UF_32_TH
Atrium
Cafe
Entrance
Comfort Zone
Comfort Zone

NAfW


HEB - Indoor Operative Temperature (Extreme Scenario - Winter)
Indoor Operative Temperature (degC)
0
5
10
15
20
25
30
35
Comfort Range
HEB_EC_W_CO
HEB_EC_W_NV
HEB_EC_W_UF_24
HEB_EC_W_UF_28
HEB_EC_W_UF_32
HEB_EC_W_UF_32_TH
Atrium
Cafe
Entrance
Comfort Zone
Comfort Zone

HEB



RWCMD

Figure 5-6. Simulation Results under Extreme Condition - Winter

5.4 Discussion

From the research, it is found that the thermal comfort criteria of all the three surveyed buildings could not be met for both summer and winter periods when no air conditioning system operated. In the summer period where the ambient temperature was lower than the indoor temperature, i.e. Average Condition – Summer, there was a positive impact of natural ventilation on the indoor comfort environment by bringing down the indoor operative temperature closer to the comfort range. It aligns with the suggestion by Hussain and Oosthuizen that an optimum atrium design shall adopt natural ventilation for providing comfortable indoor environment while reducing energy consumption (Hussain and Oosthuizen 2012). However, if the ambient temperature was higher than the indoor temperature, i.e. Extreme Condition – Summer, natural ventilation would even make the environment even warmer. It met the expectation that natural ventilation could lead to discomfort during high outdoor temperatures as it cannot cool the incoming air (Jomehzadeh et al. 2017; Monghasemi and Vadiee 2018). During the winter period, the opened windows and doors made the indoor environment colder as the cold ambient air was introduced into the occupied area. In other words, it suggested that keeping doors and windows closed during cold weather could prevent the environment from being too cold. It is in line with Rijal that closing doors and windows in winter could avoid cold air coming inside and to prevent excessive heat loss (Rijal 2021).

The studies further investigated the impacts of underfloor radiant system on the indoor comfort environment. By operating the radiant system alone with all openings closed, an improvement on comfort situation was observed. During the summer time, the lower the surface temperature of the radiant floor, the cooler the indoor environment could be. A radiant floor operating at 16°C can bring the indoor operative temperature by about 2.5°C and 4.1°C on average for the average scenario and extreme scenario respectively. During the winter time, the indoor operative temperature could be averagely increased by 3.3°C with radiant floor operating at 32°C for both average scenario and extreme scenario. It matches the purpose of application of radiant floor system which acts as cool source at warm environment; and hot source at cool environment to provide better thermal comfort (Watson and Chapman 2002; Babiak and Olesen 2013). It is also aligned with the suggestion by Zhao et al. that floor surface temperature is critical in providing thermal comfort level in all applications (Zhao et al. 2016a). Although the application of radiant system could bring the thermal condition of the indoor transitional spaces closer to the comfort range, by its operation alone with all openings closed was not sufficient to provide a comfortable environment under the scenarios tested in the research.

Further investigation of the research found out that in order to provide a thermally comfortable space within interior transitional spaces, an acceptable thermal comfort could be achieved by operating both the underfloor air distribution system (UFAD) and underfloor radiant system. The supply air of the UFAD system along the perimeter of transitional spaces reduced the heat transfer between the interior and exterior environments. As a result, it could effectively prevent excessive heat from entering into the occupied space during the summer time; it prevent internal heat loss through the façade during the winter time. It has a similar agreement from other research that convective air conditioning systems can rapidly adjust the thermal environment of a space as a means to provide thermal comfort (Sun et al. 2020).

There are also a number of researches that suggested that a combined operation of radiation system such as radiant floor cooling / heating system, and convective air conditioning system is effective in maintaining thermal comfort within an occupied space (Lin et al. 2016; Hu et al. 2019; Peng et al. 2019; Wang et al. 2019b; Li et al. 2020).

5.5 Conclusion

Investigations of the improvement strategies for the thermal comfort of building transitional spaces were carried out by this research work. With the thermal range identified in the previous research studies, this research work tested the thermal environment under two climate scenarios. For each scenario, four different system setups were evaluated. They were (1) baseline where all the openings of transitional spaces were closed and no air conditioning system operated; (2) natural ventilation mode, where only all windows were opened with no air conditioning system operated; (3) underfloor radiant system only; (4) underfloor radiant system and underfloor air distribution system operated at the same time.

Based on the identified 90% acceptable comfort range for the transitional spaces, CFD modelling techniques were adopted to evaluate whether the existing building designs of the surveyed buildings were able to provide a thermal comfortable transitional space the building occupants under the extreme summer and winter conditions. Using the predicted future weather data which take into account the future climate change, the temperatures used for the extreme summer and winter conditions were 31.6°C and -1.6°C respectively.

The CFD models, both the external and internal models, were correlated against the physical measurement results obtained during the field studies before carrying out the computational analysis. By just closing all the openings, natural ventilation or operating underfloor radiant system along, the thermal comfort criteria could not be met under both scenarios. It was because (1) the buildings were assumed to operate under extreme weather conditions; and (2) no active systems such as heating and cooling air conditioning systems were operated.

By comparing the baseline model, where all the windows were set to be closed and no active systems were operated, it could be identified from the simulations that natural ventilation could help to improve the thermal environment under summer conditions; and door opening could have adverse impact on the thermal environment during winter conditions due to the external cold air infiltration. By having the underfloor air distribution system to supply conditioned air, the indoor operative temperature could be maintained within comfort range because the air supplied along the façade effectively reduced the heat transfer.

In summary, passive design can help to improve thermal environment but under extreme weather conditions, passive designs alone were not able to maintain a comfortable indoor environment for transitional spaces. Therefore, in order to maintain a thermal comfortable building transitional spaces, both passive design and active system shall be operated at the same time.

Chapter 6. CONCLUSION

6.1 Introduction

This chapter makes the final conclusions of the thesis. By conducting the field studies and computational analysis for the three selected buildings in Cardiff, this chapter concludes that the research aim and objectives were successfully achieved. Considering the limitation of this research, further research recommendations were also made for generating even clearer picture for the thermal environmental designs of building transitional spaces.

6.2 Key Research Findings

The followings summarise the key findings as the research's conclusions where the hypotheses are addressed accordingly:

1. People have adaptability to its thermal environment.
2. Fine control of indoor temperature is not necessary.
3. PMV model is not appropriate in predicting the thermal environment of building transitional spaces;
4. Passive design can help improve thermal comfort situation.
5. To maintain a good thermal comfort in transitional spaces, passive design and active systems shall both be incorporated into the design.
6. Active systems by convective means are more effective in controlling indoor temperature.
7. Just operating the underfloor radiant system is good enough to maintain an acceptable thermal comfort within the building transitional spaces during warm season; but during cold season, ventilation by convective means shall also be operated together with the radiant system to maintain good thermal comfort within the building transitional spaces.

6.3 Concluded Statement

This research is aimed **to investigate environmental performance and adaptive comfort of transitional spaces in order to achieve acceptable thermal comfort level by identifying the thermal comfort ranges, people's adaptive behaviours and means to improve thermal comfort.** This research's aim and the associated objectives have been successfully accomplished by conducting field studies with the means of questionnaire surveys and on-site measurements during the summer and winter time and computational analysis by CFD/HTB2 coupled simulations for three selected case buildings in Cardiff.

Details of how each objective was achieved are elaborated below:

Objective 1. To establish the current knowledge about thermal comfort of transitional spaces in terms of modelling techniques and study scenarios;

Result: It was revealed from other research that a poor design of transitional spaces can lead to thermal comfort issues due to excessive solar gain, daylight penetration and ventilation. It was also concluded from several researchers that there are still lack of clear methods, guidelines, recommendations or acceptable temperature range for evaluation of thermal comfort in transitional spaces.

In order to evaluate the thermal comfort of building transitional spaces, a robust methodology was developed, which included three major phases, i.e. Pilot Study, Field Studies, and Computational Simulations.

A pilot study is aimed to ensure or improve the appropriateness of the field study, to test the reliability and limitations of the proposed methodology, to improve the major field study procedure and decision making, and to improve the quality of the field study to reduce the unnecessary needs of resources including time and cost by optimising the study procedure.

Three different building cases in Cardiff were selected for field studies, which included the on-site physical measurements and questionnaire survey. They were conducted at the same time. The questionnaire survey was developed to collect two major information – the personal parameters and the subjective responses of participants on the current environmental conditions. Both open and closed questions were designed in the questionnaire. Open questions can obtain participants' own answers, while closed questions provide a set of fixed options for participants to choose as the answer(s). Field studies were considered as one of the most effective methods for investigation of thermal comfort in a particular region is field studies, other than the chamber studies as they are more realistic than chamber experiments when it comes to human activities and their psychological expectations. More importantly, field studies are reliable for the observation and investigation of human thermal comfort, particularly when human responses to the thermal environment are studied.

CFD modelling, which is an effective tool for predicting the air ventilation and identifying indoor and outdoor environmental improvement, was adopted in the computational simulations. It is a useful tool in optimising building systems design and operation of indoor environment and enabling to perform comparative analyses based on different scenarios. It provides a good platform to investigate different variables in the entire computational domain, as field studies in general can only generate a limited set of databases.

Objective 2. To establish the methodologies to evaluate the environmental performance of transitional spaces;

Result: Robust methodologies were established for the field studies and computational analysis for the three selected case buildings. The field studies consisted of questionnaire surveys and on-site measurements. Prior to the main studies in the three selected buildings, pilot study was conducted to optimise the whole approach of field studies in another selected building called the Optometry Building of Cardiff University. The pilot study of the research successfully demonstrated how the main study approach can be reviewed and optimised in a timely and effective manner. This research established a good reference for future researcher on related thermal comfort studies in terms of field studies including questionnaire surveys and on-site physical measurements. It included how a questionnaire survey form shall be developed in order to obtain the important parameters to facilitate research; and how to correlate the on-site physical measurements with the questionnaire survey responses. The computational analysis using CFD modelling and HTB2 was further adopted to evaluate the impacts of different improvement strategies on thermal environment under extended scenarios. The role of modelling in this research was to test the influence of different improvement strategies on the thermal environment under different outdoor conditions using the three selected buildings as example buildings. This generates insights for the future building transitional spaces designers of what systems they shall consider improving the thermal environment. More importantly, this research illustrated a structured approach to validate the computational model by the use of the data collected from the field studies.

Objective 3. To select three representative existing buildings with transitional spaces for detailed study;

Result: Three buildings in different locations in Cardiff were selected as case buildings for the research. They were the National Assembly for Wales Senedd (NAfW), the Hadyn Ellis Building (HEB) and the Royal Welsh College of Music and Drama (RWCMD). These buildings were located in different locations in Cardiff. A single outdoor weather station was used in the study, and the distance from the outdoor weather station to the selected buildings ranged from 0.1km to 2.8km. The function of these buildings was quite different but they were all open to the public during their opening hours. In each of the selected buildings, field studies were carried out over a three-day period, in summer and winter. This included questionnaire surveys and physical measurements. These buildings are classified as multi-functional building transitional spaces that provide longer-term occupancy zones. They have different functional provisions such as cafeteria, atrium and entrance zones, where people would tend to stay longer than the other types of transitional spaces. The selected transitional spaces for this research could represent a majority of modern design of building transitional spaces which have been evolved from single purpose to the ones which serve multiple purposes for people to enjoy the sense of space, the surroundings, and the social activities such as resting, working, and gathering within a sheltered environment, and to experience the dynamic effects of the external climatic changes. The findings from this research shall benefit the design thinking of similar kind of transitional spaces.

Objective 4. To develop structured questionnaire surveys to collect subjective responses from the occupants of the selected case buildings;

Result: A standardised questionnaire was developed to collect subjective data from the building occupants for comfort evaluation in the specified locations of the surveyed buildings. 24 questions were included in the questionnaire, which adopted a combination of open-ended, partially closed-ended and predominantly closed-ended questioning approaches. 7-point scale and 5-point scale methods were adopted for the thermal sensation questions and thermal and sunlight preference questions respectively. In order to understand people's adaptability to their thermal environment, an open question "how would you overcome uncomfortable situations, if any" was added to the questionnaire. Additional data collected from the questionnaire included the demographic data, activity level, clothing insulation, time spent at the interviewed location, previous space locations and time spent in previous space, and feedbacks and previous thermal experience in the interviewed location. Building users were randomly selected within the transitional spaces of the surveyed buildings to carry out the questionnaire survey. Each survey was carried out by means of a structured interview which took approximately 10 minutes to complete.

Objective 5. To carry out field studies which include questionnaire surveys and physical measurements in the selected case buildings;

Result: The total number of responses collected from the questionnaire surveys were 736 and 580, during the summer period and the winter period respectively. Throughout the summer period, 282, 207 and 247 surveys were collected from the NAfW, HEB and RWCMD respectively; throughout the winter period, 198, 155 and 227 surveys were collected from the NAfW, HEB and RWCMD respectively.

The physical measurements were carried out at the same time when questionnaire surveys were conducted. The measured indoor environmental parameters included air temperature, relative humidity, air velocity and black globe temperature. The accuracy of the instrumentations used for the field studies complied with the requirements of ASHRAE 55-2013. Measurements were located across the indoor transitional spaces, including entrance lobby, atrium and café area. The measurement locations were set at 1.1m height from the floor. For the outdoor environmental parameters, data were recorded every five minutes by a weather station which was installed on the rooftop of the Bute Building, the Architectural School of Cardiff University. The weather station data was recorded on a Campbell Instruments CR10 data logger. The air temperature and relative humidity were measured by a Rotronic temperature and humidity probe with a radiation shield.

Objective 6. To identify the acceptable comfort ranges and adaptive comfort behaviours within building transitional spaces

Result: Strong correlation between thermal sensation and indoor operative temperature was identified, which was further elaborated into 80% and 90% acceptable temperature range. The 80% and 90% acceptable temperature ranges for all the three surveyed buildings were wide for both summer and winter periods, with average ranges of 9.6°C and 4.0°C respectively. This reflected that a fine temperature control is not necessary to maintain a thermally comfortable environment for occupants within the transitional spaces. In other words, it indicates that people within building transitional spaces have a higher tolerance to their thermal environment. The table below summarises the key findings from the research.

	NAfW		HEB		RWCMD	
	Summer	Winter	Summer	Winter	Summer	Winter
Preferred Temperature (°C)	21.2	21.5	21.6	22.9	22.7	22.5
Neutral Temperature (°C)	19.3	16.9	21.2	20.9	21.0	20.7
80% Acceptable Temperature Range (°C)	14.7–23.8	12.3–21.4	17.4–24.9	16.2–25.5	17.3–24.8	17.4–24.0
90% Acceptable Temperature Range (°C)	17.0–21.6	14.6–19.2	19.3-23.0	18.5–23.2	19.2–22.9	19.1–22.4

The statement of having a fine control of temperature is not necessary was strengthened by the people's adaptability to their thermal environment, as a result of the analysis of the relationship between clothing values and outdoor air temperature and indoor operative temperature. People were found to be prepared to adapt to the environment rather than attempting to alter the building systems such as ventilation systems and windows opening. In order to maintain the comfort level within a building transitional space, a majority of people would opt to adopt self-adaptive actions such as adjusting clothing, drinking / eating, and moving.

The actual thermal sensation is influenced by environmental parameters of the building transitional spaces, including air temperature, relative humidity, air speed, and globe temperature. As a result of detailed analysis of questionnaire surveys, the most important factor that affects people's thermal sensation is found to be the indoor operative temperature.

The findings from this research give an idea to the future designers of multi-functional transitional spaces of what temperature criteria they shall base on when selecting and sizing air conditioning provisions. Whether 80% or 90% acceptance band shall be adopted in the design shall depend on the particular function of the transitional spaces is designed for. For the area that people may stay longer such as seating areas, cafeteria and reception area, their requirement on the thermal comfort may be higher so 90% acceptance band is recommended; for the other areas, 80% acceptance band could be adopted.

The research findings also suggest that PMV, which is one of the most popular thermal prediction models, is not accurate in predicting the thermal environment in building transitional spaces. This is in line with the agreements of the research by Chun et al. (Chun et al. 2004).

Objective 7. To set up computational models and identify improvement strategies for transitional spaces to achieve acceptable environmental performance of building transitional spaces.

Result: Based on the identified 90% acceptable comfort range for the transitional spaces in the field studies, CFD and HTB2 modelling techniques were adopted to evaluate whether the existing building designs of the surveyed buildings were able to provide a thermal comfortable transitional space the building occupants under the extreme summer and winter conditions.

The CFD models, both the external and internal models, were correlated against the physical measurement results obtained during the field studies before carrying out the computational analysis. By just closing all the openings, natural ventilation or operating underfloor radiant system along, the thermal comfort criteria could not be met under two studied scenarios – average scenario and extreme scenario. It was because (1) the buildings were assumed to operate under extreme weather conditions; and (2) no active systems such as heating and cooling air conditioning systems were operated. The conclusion from the computation analysis is that passive design can help to improve thermal environment but under extreme weather conditions, passive designs alone were not able to maintain a comfortable indoor environment for transitional spaces. Therefore, in order to maintain a thermal comfortable building transitional spaces, both passive design and active system such as radiant floor system and underfloor air distribution system shall be operated at the same time.

From this research, coupling simulations CFD / HTB2 were found effective in thermal comfort evaluation and investigation of the impacts of different system settings and designs on the thermal environment. In other words, it suggested that computational simulation would take an important role in future building designs for architectural design, air conditioning system selection and design in order to achieve acceptable thermal comfort within an indoor building environment. It is because the thermal environment could be quantified and visualized in the computational simulation tool where the realistic conditions including air temperature, occupants, and other heat sources are modelled. Moreover, the power of modelling in an actual building design is that it allows a high degree of flexibility of changing the system settings and options in the early design stage in order to identify the optimised solution for better thermal comfort in a timely and cost-effective manner. Modelling could also help better coordination among the project team, including building owners, architects, system designers, contractors and facility management team.

6.4 Limitations of this Study

The followings list out the subject matters that are either beyond the scope of this research or are recognised as shortcomings characteristic of investigations on the thermal comfort of indoor transitional spaces.

- Since field studies were conducted at three selected buildings in Cardiff, the UK, where they are in Mediterranean climate region in which the weather is warm and temperate, the findings may not be applicable to some extreme climate zones where the temperature is much hotter in summer time or much cold in winter time. Therefore, the determination of thermal comfort range may not be as accurate for the buildings in similar climate zones of Cardiff, although the comfort range could be estimated with the correlation identified in the research;

- The majority of questionnaire respondents were British and European, where the thermal perception may be different from the people of different nationalities. In addition, the thermal adaptation methods to deal with thermal discomfort may also be different for people of different culture. Therefore, the outcomes from the field studies may only be indicative of how people would react to the thermal environment;

- The computational analysis was aimed to identify the impacts of different approaches on the thermal environment within indoor transitional spaces only. It did not investigate the energy performance. In other words, this research does not constitute a full picture of system optimisation from the aspects of thermal comfort and energy effectiveness;

- This research does not consider wind-driven natural ventilation, which means that analysis of external airflow in urban environments was not explored.

6.5 Further Recommendations

On the basis of the identified limitations of this research, several topics listed below may be of interest for further investigations into thermal environment in building transitional spaces:

- Investigation of adaptive thermal comfort of building transitional spaces in different climate zones, such as tropical and cold climates;
- Evaluation of thermal perception of different ethnics in building transitional spaces;
- Identification of an optimised solution for thermal comfort within building transitional spaces from the perspective of thermal comfort and energy performance;
- Investigation of wind-driven ventilation on thermal environment of building transitional spaces.

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