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INDIVIDUAL THERMAL CONTROL IN THE WORKPLACE:

CELLULAR VS. OPEN PLAN OFFICES:

NORWEGIAN AND BRITISH CASE STUDIES

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PhD in Architecture

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DECLARATION

I declare that this research has been composed by myself and the contained work is my own, except where stated otherwise. It has not been submitted for any other degree or professional qualification except as specified.

Salome Sally Shahzad

ABSTRACT

This research is based on the challenge in the field of thermal comfort between the steady state and adaptive comfort theories. It challenges the concept of standard 'comfort zone' and investigates the application of 'adaptive opportunity' in the workplace. The research question is: 'Does thermal control improve user satisfaction in cellular and open plan offices? Norwegian vs. British practices'.

Currently, centrally controlled thermal systems are replacing individual thermal control in the workplace (Bordass et al., 1993, Roaf et al., 2004) and modern open plan offices are replacing traditional cellular plan offices in Scandinavia (Axéll and Warnander, 2005). However, users complain about the lack of individual thermal control (Van der Voordt, 2003), which is predicted as an important asset to the workplace in the future (Leaman and Bordass, 2005). This research seeks users' opinion on improving their satisfaction, comfort and health in two environments with high and low levels of thermal control, respectively the Norwegian and British workplace contexts. Two air conditioned Norwegian cellular plan offices which provide every user with control over a window, blinds, door and the ability to adjust the temperature are compared against two naturally and mechanically ventilated British open plan offices with limited thermal control over the windows and blinds for occupants seated around the perimeter of the building. Complimentary quantitative and qualitative methodologies are applied, with a particular emphasis on grounded theory, on which basis the research plan is formulated through a process of pilot studies. Occupants' perception of their thermal environment within the building is recorded through a questionnaire and empirical building performance through thermal measurements. These traditional techniques are further reinforced with semi-structured interviews to investigate thermal control. A visual recording technique is introduced to analyse the collected information qualitatively regarding the context and meaning.

The ASHRAE Standard 55-2010 and its basis do not apply to the case study buildings in this research. This thesis suggests that thermal comfort is dynamic rather than fixed. Occupants are more likely to prefer different thermal settings at different times, which is in contrast with providing a steady thermal condition according to the standard 'comfort zone'. Furthermore, the occupants of the Norwegian cellular plan offices in this research report up to 30% higher satisfaction, comfort and health levels compared to the British open plan offices, suggesting the impact of the availability of individual thermal control. This research suggests that rather than providing a uniform thermal condition according to the standard 'comfort zone', office buildings are recommended to provide a degree of flexibility to allow users to find their own comfort by adjusting their thermal environment according to their immediate requirements.

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Instructions

When a gender-neutral singular pronoun is required or an unknown person is discussed instead of 'he/she', in the thesis 'they' and 'their' have been used with a singular antecedent. 'He' or 'she' is only used when a particular individual is discussed, such as in an interview. In addition, 'satisfied respondents' refers to either 'satisfied' or 'very satisfied' participants. The same instruction applies to 'comfortable respondents'.

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CHAPTER 1

INTRODUCTION

1. Introduction

This thesis is based on the challenge in the field of thermal comfort between steady state and adaptive comfort theories. It seeks to challenge the view that the ‘comfort zone’ is universally applicable, and explores users’ options on what would improve their satisfaction, comfort, health, and productivity. The key research question being examined is ‘Does thermal control improve user satisfaction in cellular and open plan offices? A comparison of Norwegian and British practices’.

This research questions the application of the ‘optimum temperature’ that satisfies everyone, and investigates the application of ‘individual thermal control’ in the workplace. These are the two distinct views of, respectively, steady state and adaptive comfort approaches. In this chapter, the research approach is outlined and summarised.

1.1. Research Significance

A constant characteristic in the history of the workplace is that users require access to a window, which allows an outside view, natural light and ventilation, as well as the ability to adjust the temperature (Van Meel, 2000). Based on contrasting views regarding these demands, Northern European and Anglo-Saxon countries followed two separate paths in designing office layouts (Van Meel, 2000). However, recent office designs are moving away from these demands as organisational goals tend to replace workers' rights (Van Meel and de Jonge, 2006) and centrally controlled thermal systems replace user control (Bordass et al., 1993, Roaf et al., 2004). Climate change, technological advances, economic challenges, organisational changes and goals are the main drivers of office design replacing users' demands and workers' rights. As a result, the Workers' Council in Northern Europe is losing its influence (Van Meel and de Jonge, 2006) and Scandinavian countries are moving away from the design of personal offices based on users' requirements (Axéll and Warnander, 2005, Gadsjö, 2006).. Duffy explains that office design is disconnected from the user, as it has 'little to do with what the man at his desk really needs' (Duffy, 1966a). The future of applying users' requirements in the workplace is under debate. Harris claims that in the future these demands will not be necessary as flexibility will replace fixed workstations (Harris, 2006). In contrast, Katsikakis suggests that attracting a talented workforce will be the main concern for organisations, therefore providing a pleasant work environment for the user will be essential (Katsikakis, 2006). This thesis attempts to make a contribution in improving user satisfaction, comfort, health, and productivity in the workplace through understanding users' needs and their application in the workplace.

1.2. Themes

This section discusses the two themes of the thesis:

- Norwegian cellular vs. British open plan workplace contexts
- Individual control over the thermal environment in the workplace

The Norwegian vs. British theme is inspired by the history of the workplace and the influence of users' demands on office design. In the 1970s and 1980s Norway and the UK followed separate paths regarding office design. In the UK, organisational goals are the main criteria in designing the workplace. Thus, an open office layout is preferred in order to increase communication, efficiency and flexibility. In contrast, the design of Norwegian offices is based on users' demands and workers' rights. Therefore every occupant is provided with the ability to adjust their personal environment.

In the second theme, which is individual thermal control, users' demands and comfort are investigated in more detail, particularly users' comfort regarding the thermal environment of the workplace. There is a challenge in this field between setting a uniform temperature in the office to satisfy everyone and passing the responsibility for adjusting the thermal environment to the occupant. This thesis investigates the merits of the latter in the form of 'individual thermal control'.

This research compares the Norwegian cellular plan offices with high levels of thermal control and the British open plan office layouts with low levels of thermal control in investigating occupants' health, comfort, satisfaction, and productivity.

1.3. Research Question and Objectives

The aim of the research is to contribute to the debate of improving occupants' satisfaction, comfort, health, and productivity in the workplace. Based on these two themes, which are discussed in Chapters Two, three and four, the research question is formulated as follows: 'Does thermal control improve user satisfaction, comfort, health, and productivity in open plan and cellular plan offices? A comparison between the British and Norwegian Practices'.

Pilot studies, which are set up in Chapter Six, allow the research objectives to be finalised. This thesis challenges the concept of 'comfort zone' and examines 'individual thermal control' in the workplace. The former concept tends to present comfort to everyone by providing an 'optimum temperature' according to comfort standards in an endeavour to satisfy everyone. In contrast, the latter view is based on allowing occupants to adjust their thermal environment through the building design and facilities so that they find their own comfort. The standard 'comfort zone' is examined through the followings:

- The applicability of the ASHRAE comfort zone, as the most widely used comfort standard
- The application of the 'neutral thermal sensation' as the basis of the thermal comfort standards
- The consistency of the overall thermal preference of every user throughout the day

The application of 'individual thermal control' is investigated through examining the following:

- The impact of thermal intention of the user on their satisfaction and comfort
- User satisfaction, comfort and health in comparison between two office layouts, the Norwegian cellular plan with high and the British open plan with low levels of thermal control

1.4. Research Approach

In order to research the thesis question, two office layouts with high and low levels of thermal control are compared. The Norwegian cellular plan offices provide every user with a high level of thermal control, including an openable window, blinds, a door, and a thermostat. In contrast, the British open plan layout provides limited thermal control, such as openable windows and blinds, only for users around the perimeter of the building. However, the majority of the occupants, who sit further from windows and closer to the centre of the open plan, have no control over the thermal environment.

Complimentary quantitative and qualitative methodologies are applied, with a particular emphasis on grounded theory as the qualitative methodology. In grounded theory, research objectives and plan are refined through a process of testing, analysing and planning. Therefore through an initial process of pilot studies, research methods and analysis are formulated as the research plan. Users' perception of their thermal environment is recorded through a questionnaire and empirical building performance through thermal measurements. These traditional techniques are further reinforced with semi-structured interviews to investigate thermal control.

The appropriate criteria for selecting case study buildings are framed based on the research question and objectives, literature and findings of the pilot study. Overall, four case studies are selected: two Norwegian cellular plan layouts and two British open plan office. The research plan was applied on the selected buildings successfully and valuable observations in support of the argument were made. The collected data is analysed through quantitative and qualitative methods. An innovative visual recording method is applied to qualitatively analyse the subject in its context.

1.5. Thesis Outline

The research method, which informs the layout of the thesis, is organised in four major sections. They present a review of the literature, followed by methodologies, data from the fieldwork and analysis, and finally thesis discussion.

1.5.1. Section I: Literature Review

Following the introduction to the thesis, the literature and established experience are reviewed:

- Chapter 1: Introduction
- Chapter 2: The Workplace
- Chapter 3: Thermal Comfort and Control
- Chapter 4: Cellular vs. Open Plan Offices

The first section of the thesis is laid out as the foundation, on which the thesis operates. It includes a literature review of the history of workplace design, and the previous research in the field of thermal comfort and thermal control. Chapter four combines these two bodies of knowledge with a focus on thermal control in Norwegian cellular and British open plan offices.

The first part is an introduction to the thesis, which includes the research question, objectives, approach, and outline. It also explains the significance of this research. This is followed by the history of the workplace from the ancient to modern periods and predictions for the future of the workplace in the next chapter. The focus of this section is the impact of users and organisations on office design. Based on these two distinct objectives, separate paths in Scandinavia and the UK, respectively cellular and open plan layouts are identified as exemplary. This development is continued by the role of the users, their requirement and influence. These are particularly important in finding criteria and office layouts that occupants consider ‘satisfactory’, such as allowing privacy and the ability to adjust the thermal environment.

In Chapter Three, the research and design practice is reviewed in the literature on thermal comfort and thermal control. The debate in the field between steady state and adaptive comfort theories is studied, which is followed by two separate approaches, respectively the standard ‘comfort zone’ and ‘adaptive opportunity’. The research focuses on the latter and its impact on users’ satisfaction, comfort, health, and productivity. The next chapter combines

the essential parts of the previous two chapters, including the Norwegian vs. British workplace layouts as well as individual thermal control. Norwegian cellular plan offices with high levels of thermal control and British open plan offices with limited thermal control are compared, in terms of design, culture and regulations. Finally, the debates on the future of thermal control are discussed.

1.5.2. Section II: Research Approach

This section contains methodologies and research plan:

- Chapter 5: Research Methodologies
- Chapter 6: Pilot Studies and Research Plan

This section of the thesis presents the research approach. It includes the formulation of appropriate methodologies and methods. In Chapter Six, these methods are examined in pilot studies in order to formulate the research plan.

In Chapter Five, the research aim and question are clarified. Accordingly, the appropriate methodologies, methods and analysis techniques are selected through studying traditional and non-traditional approaches in the field. A combination of quantitative and qualitative methodologies is applied with a particular emphasis on grounded theory. Post Occupancy Evaluation and field studies of thermal comfort are studied and relevant methods are selected for examination in a series of pilot studies, presented in the next chapter. Finally, an innovative visual recording technique is presented. In the next chapter, based on grounded theory and through a process of pilot studies, the research objectives, methods and approach are refined and finalised in this chapter. A series of pilot studies, including a process of examining, analysis and retesting, are discussed. The research objectives are modified based on the findings of the pilot studies, which include challenging the concept of the ‘comfort zone’ and investigating ‘individual thermal control’ in the workplace. The final research plan is formulated accordingly. Users’ perception of their thermal environment is recorded through a questionnaire and empiric building performance through environmental measurements. These traditional techniques are further reinforced with semi-structured interviews to investigate user behaviour and satisfaction. The chapter ends with a discussion on the criteria used to select the case study buildings.

1.5.3. Section III: Fieldwork Analysis

This section is the fieldwork analysis:

- Chapter 7: Building Performance
- Chapter 8: Stage I: Comfort Zone
- Chapter 9: Stage II: Individual Thermal Control

This section of the thesis includes an introduction to the selected Norwegian and British case study buildings and their building performances. It is followed by interpretation of the collected data at the site, which includes challenging the standard ‘comfort zone’ and investigating the application of ‘individual thermal control’ in the case study buildings.

Chapter Seven introduces the case study buildings and analyses their building performance. This research is based on good practice examples of workplaces with high and low thermal control. Two air conditioned cellular plan offices are selected in Oslo, in which every individual has access to an openable window, blinds and a control device to adjust the temperature. In contrast, two open plan offices with natural and displacement ventilation in Scotland are selected, in which only occupants sitting around the perimeter of the building have access to a window and blinds. The majority of the occupants are allocated to workstations at the centre of the open plan with no means of control. The building performance of these offices is compared against the benchmarks and standards.

Chapter Eight focuses on the research objective in regard challenging the notion of ‘comfort zone’. This is mainly the result of the steady state theory to provide comfort in an office building, which is applied through centrally controlled systems that are regulated based on the standard comfort zone. In order to challenge the view of ‘comfort zone’, this research examines the accuracy of predictions of ‘comfort zone’ defined by the ASHRAE Standard 55-2010, the application of ‘neutral thermal sensation’ as the basis of thermal comfort standards and the consistency of the users’ thermal preference throughout the day. Participants’ responses towards the measured thermal environment in all four case study buildings are compared with the ASHRAE comfort zone. Qualitative and quantitative analysis methods are applied in this section, with the emphasis on an innovative qualitative method as visual recording technique. Chapter Nine interprets the collected data in the field in order to investigate the application of ‘individual thermal control’ in the workplace. Adaptive opportunity is the solution of adaptive comfort theory to provide user comfort. This research examines the impact of users’ desire to apply thermal control on their satisfaction and

comfort. In addition, two office layouts with high and low levels of thermal control are compared. User satisfaction, comfort, health, and productivity of the two Norwegian cellular plan offices with high levels of thermal control are compared against the two British open plan layouts with limited thermal control. Quantitative analysis is applied for this comparison and it is combined with qualitative interviews for further clarification.

1.5.4. Section IV: Discussion

This section contains the discussion and conclusion of the thesis:

- Chapter 10: Discussion
- Chapter 11: Conclusion

This section of the thesis includes the main discussion on the challenge between ‘comfort zone’ and ‘individual thermal control’ as identified in the survey and analysis of the case studies. It also presents an innovative analysis method based on a comparison between quantitative and qualitative analysis techniques. Finally, the thesis conclusion is presented.

Chapter Ten is the main thesis discussion regarding the application of ‘individual thermal control’ in the workplace. It links the findings of the research to the previous research in the field and the challenge between steady state and adaptive comfort theories. The main findings suggest the inconsistency of occupants’ desire for a thermal condition throughout the day and comparison between the Norwegian and British workplace contexts regarding the application of individual thermal control. The new qualitative analysis method is compared with traditional quantitative analysis. Finally, the limits of the study and the wider context are discussed. Chapter Eleven is the summation of the project that ties together the field research and the strategies that are derived from its findings. The thesis investigates how to improve thermal comfort conditions for occupants in the workplace. It suggests that rather than searching for a ‘comfort zone’ that satisfies all, it recommends buildings to provide a degree of flexibility to allow users to adjust their thermal environment to their needs. Further research is encouraged through the application of qualitative methodologies such as ethnographic survey to research users’ behaviour in context.



Figure 1: Diagram of the thesis, the complete diagram is presented in Figure 298

CHAPTER 2

THE WORKPLACE

2. The Workplace

This research seeks to improve comfort conditions for occupants in the workplace. Therefore the history of the workplace design is studied in this chapter in order to understand users' demands and to find office layouts that provide them with high levels of comfort and satisfaction. The Anglo-Saxon and Northern European countries have played an important role among developed countries in improving office buildings to meet technological, economical and organisational changes in every period of modern workplace history. The Anglo-Saxon and Northern European countries followed two separate paths according to their distinct objectives in designing office layouts, including organisation and user demands. Therefore in this chapter, office designs which were introduced by the UK, North America and Scandinavia are studied. The chapter ends with predictions for the future of the workplace.

2.1. Definition of the Office Building

Different cultures define the office in different ways. In the UK, emphasis is on the business aspect of an office, while in Northern Europe, individual employees influence the workplace and its definition. In the UK, Harris explains that ‘the principal role of the workplace is to provide a physical environment, in which organisations configure themselves efficiently and effectively to support operational imperatives’ (Harris, 2006). Worthington explains that the new workplace environment is where the culture of the organisation is shaped. It is an environment for training, relaxing, meeting, and discussing ideas (Worthington, 2006). Duffy states that ‘the average office building has been designed from structural, technical and economic considerations that have little to do with what the man at his desk really needs; or, for that matter, what the company needs’ (Duffy, 1966a). Becker mentions that ‘rather than thinking of the office as a place primarily for solitary activity from which one occasionally breaks out in time and space to settings intended for social setting, the office is designed primarily as a social setting, from which one occasionally seeks out more private places for contemplation, concentration and confidentiality’ (Becker and Sims, 2001). Van Meel indicates that ‘office buildings are the materialisation of norms and values about issues such as hierarchy, interaction and privacy. They reflect ideas about the meaning of work and opinions about how work should be performed. As these ideas change over time, so does the office’ (Van Meel, 2000).

2.2. History of the Workplace

This section includes key transformations in the history of the workplace, such as industrial and digital revolutions, since they had a major influence on office development.

In ancient times, work was not done in an office. Only during the past century was the ‘office building’ introduced as a place dedicated to work (Harrison et al., 2004). The use and design of office buildings developed to an extent that work and workplace became united (Harrison et al., 2004). Duffy states that ‘you cannot get good work out of bad offices’. It is easy to point out a ‘bad’ office, though difficult to define a ‘good’ one (Duffy, 1966a). Based on distinct qualities and advances in technologies, different office layouts were introduced, including the cellular plan, Bürolandschaft, Combi office, open plan, Hive, Den and Club layouts. Some of these concepts are based on organisations’ requirements and advantages, whereas the others are designed according to individual users’ rights and benefits. There is an argument in regard to the future of the workplace. Marmot seeks the solution in the ‘open plan’ layout (Marmot and Eley, 2000), while Van Meel suggests a combination of cellular and open plan layouts according to the nature of the organisation (Van Meel et al., 2010). Duffy explains ‘no one building, no single form of layout can possibly accommodate all users. There is no such thing as the ideal office building’ (Duffy, 1992). Advances in information technology provide an opportunity to work anywhere at anytime (Duffy, 1992). Currently a nomadic work style is booming, including working anywhere in the office as well as at home, a café, hotel lobby, train, and airport lounge (Breure and Van Meel, 2003). So now once again work is separated from the workplace.

2.2.1. Agricultural Revolution: Home & Public Offices

Klein describes how ‘the earliest “offices” can be dated to the moment one person crouched down and bartered with another for goods or services and some kind of record was made of the exchange, like at home, a shelf in the kitchen, a desk in the front room’ (Klein, 1982). In the Roman Empire, people worked in public forums and basilicas (Uffelen, 2007). In 1560s, the Uffizi building in Florence was designed by Giorgio Vasari for Medici governmental administrative work (Klein, 1982). In the 14th century in the UK, Inns of Court in London were used for barristers to train and practise. Generally over a century ago, office buildings as experienced today did not exist, so office work took place mainly in palaces and industrial buildings (Harrison et al., 2004).

2.2.2. Industrial Revolution: Factories & Insurance Offices

In the late 18th and 19th centuries, work was separated from home. After the industrial revolution, factories accommodated workers. New materials, energy systems, machines, communication, and management systems greatly influenced the workplace and it became equipped with new machinery and technology (Klein, 1982). Trade systems expanded globally through the new developments, such as telegraphs, posts and train, which influenced the expansion of the new workplace (Mumford, 1938, Klein, 1982). Paperwork and clerical professions were introduced (Leffingwell, 1925). Finally in the late 19th century, the invention of the telephone made it possible for the office to be separated from the factory. In insurance office buildings, such as the Sun Fire Insurance Office designed by Cockerell in London in 1842, administrative and paperwork were the main activities (Klein, 1982).

2.2.3. Administrative Revolution: Open Floor Offices

Harrison indicates that ‘only in the late nineteenth century, with the increasing bureaucracy associated with governing nation states, or running large corporations, did office buildings emerge as a specialised type’ (Harrison et al., 2004). Although ‘office’ work has been done since olden times, the association of work and office building is relatively new (Harrison et al., 2004). New economy, high-rise buildings, new technologies and managerial concepts changed the way work was done and the shape of office buildings in the early 20th century in America. New construction techniques, such as the steel skeleton frame, made it possible for Chicago to boom with high rise office buildings (Klein, 1982, Harrison et al., 2004). Technological advances, such as the typewriter and the telephone, provided the opportunity to ‘work together’ (Marmot and Eley, 2000). Financial developments caused the administrative revolution (Van Meel, 2000). The number of people working in offices processing information, the ‘white-collar factory’, was greater than the number of people working in factories producing goods (Klein, 1982). Women also started working as knowledge workers (Van Meel, 2000). Ford (Myerson, 2008) and Taylor’s mass production concepts were introduced in America (Taylor, 1915, Klein, 1982, Myerson, 2008) and offices with large open floors with rows of desks were designed (Van Meel, 2000). Le Corbusier described office furniture and equipment as objects of ‘our modern life’ (Corbusier, 1927, Hart, 1993). Harrison explains that ‘the dominant ideology of the time was based on a mechanistic view of office workers as units of production, to be housed in a unified and controlling space’ (Harrison et al., 2004). Mies Van der Rohe describes workers as ‘machines for working’ (Myerson, 2008).

2.2.3.1. Larkin Building

In this period, since windows were the main source of light and fresh air, buildings were quite narrow. The Larkin Building designed by Frank Lloyd Wright is an example of the workplace in 1904 (Klein, 1982), presented in Figure 2. It shows the ‘unity of the organisation and the power of the owner’. As Myerson says, ‘the corporate’s slogan ‘Intelligence, Enthusiasm, Control’ ‘was emphasised on the atrium walls’ (Myerson, 2008). Forty explains that ‘the clerk no longer worked in a private space: the chief clerk or supervisor was able to see whether he or she was working at maximum efficiency (Forty, 1986, Myerson, 2008). Wolfe describes this kind of office as ‘worker housing, developed by handful of architects’ (Wolfe, 1981, Myerson, 2008).



Figure 2: Larkin Building, Frank Lloyd Wright, 1907 (Van Meel, 2000)

2.2.3.2. Seagram Building

After the Second World War, offices were mainly used to process paperwork information. Their function as well as their layout was similar to factories (Klein, 1982, Laing, 2006). In North America, shallow plan towers became deeper open plan offices with personal offices at the perimeter of the plan (Laing, 2006). Figure 2 presents the Seagram Building, as an example of office buildings in this period.

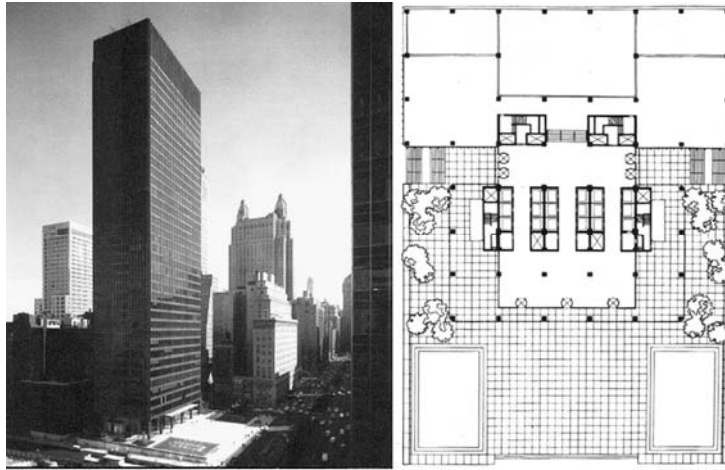


Figure 3: Seagram Building designed by Mies Van Der Rohe in 1954 (image source: <http://lebbeuswoods.wordpress.com/>)

Duffy explains that although the Seagram Building in 1954 seemed revolutionary, Mies van der Rohe was ‘more interested in the formal possibilities of reflective glass than any real organisational requirements or actual developmental possibilities’ (Duffy and Tanis, 1993).

2.2.4. Workplace Transformation: Landscape, Open & Cellular Plan Offices

This section is a general history of office design according to the technological revolution after the Second World War. More details on the open and cellular office layouts are presented in Chapter Four.

2.2.4.1. The Bürolandschaft or Landscape Office

The concept of the landscape office or Bürolandschaft was introduced by the Quickborner team after the World War Two in Germany in 1959 (Myerson, 2008). This concept was based on a research project on communication and paper flow in the office (Harrison et al., 2004, Laing, 2006). It was mainly influenced by post war American managerial concepts (Hookway, 2009), like Ford's mass production and Taylor's ideas about industrial efficiency (Taylor, 1915, Klein, 1982) (Van Meel, 2000). Quickborner's research resulted in a very open layout with no interior walls. This new office layout was described thus: 'they arranged office workers in the optimal relationship to one another and free, well-served space was assumed rather than a 'normal' office floor' (Duffy, 1966a). In 1960, the landscape office was put into practice in Germany (Laing, 2006) and it accommodated flexible communication and teamwork (Harrison et al., 2004). In 1963, Banham referred to this new design under the title 'Office Cluster' in *Architectural Review* (Banham, 1963). Duffy was motivated by this article, which included a drawing of Bürolandschaft or office landscaping, explained in section 2.2.4.3. The office layout and work groups were shaped by communication through the use of plants, organic geometry and furniture. Klein describes that in the landscape office, 'six people sitting together in one partitioned space was the maximum, anything above that was quite alien to the European' (Klein, 1982).

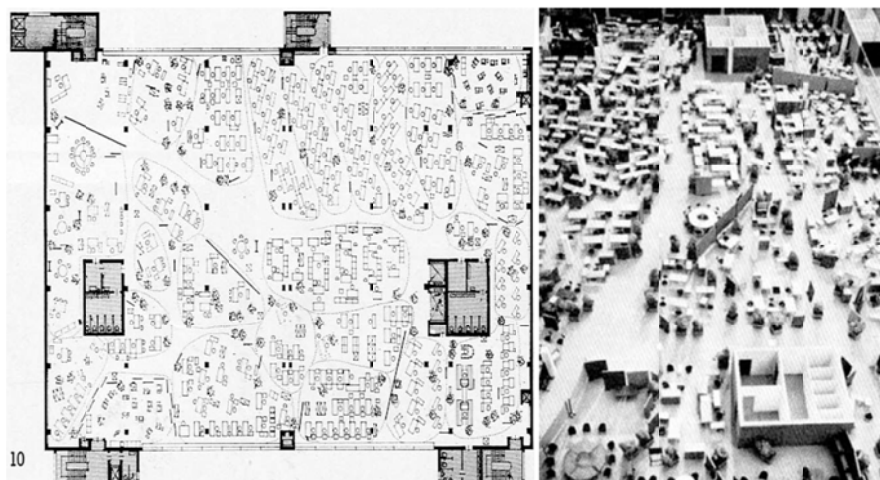


Figure 4: Quickborner's project for Buch und Ton in Germany in 1961 (Hookway, 2009)



Figure 5: Office Landscape (Van Meel, 2000).

The ease of paper flow and communication in the landscape office encouraged a deeper layout with no walls, such as Bertelsmann Publishing Company (Van Meel, 2000). Occupants' ability to open the windows and light switches were eliminated (Knobel, 1987).

2.2.4.2. The Workers' Council

The Workers' Council in Germany protested and ruled out the landscape office because of workers' rights in 1968 (Hookway, 2009). Employees complaints included the 'unpleasant temperature variations, draughts, low humidity, unpleasant noise levels, poor natural lighting, lack of visual contact with the outside, and lack of natural ventilation' (Van Meel, 2000). Myerson explains that landscape office allowed the 'Big Brother to watch over' (Myerson, 2008). In Scandinavia in particular, the landscape office was unsuccessful due to cultural differences, including the close contact between occupants and the openness of the landscape office (Van Meel, 2000). Duffy explains that in Northern Europe, 'when users have power the provision of windows and close proximity to windows for everyone becomes tremendously important' (Duffy, 1992). Although British employees had similar complaints, employers' power and their unity in opposition overruled the workers in the 1970s. Therefore general and vague work regulations of the 1960s were followed in the UK, and organisational goals took over workers' rights (Van Meel, 2000). Although the landscape office was abandoned in the UK, this was not for the sake of employees. It was mainly due to insufficient communication and lack of a hierarchical organisational system, which was not beneficial for organisational goals (Laing, 2006).

2.2.4.3. Francis Duffy

Duffy has played an essential role in promoting the design of the Bürolandschaft and open plan office layouts as well as ‘the changing workplace’ and new ways of working. He has introduced and developed these ideas in the Anglo-Saxon world. In the 1960s, Duffy visited several Bürolandschaft offices in Germany. In 1964 he wrote an article on teamwork, free communication and the flow of work in the Bürolandschaft office (Duffy, 1964). Duffy was amazed by the large non-hierarchical office floor with ‘the screens and the random disposition of desks’ (Duffy, 1992). The social area at the centre of the landscape office encouraged staff to have an informal break in a less hierarchical manner (Hookway, 2009). Every workstation had a different set up, which showed ‘individuality’ and there was a high level of visual comfort. Duffy concludes that ‘landscaped’ offices not only protect the individual and allow him more comfort and the freedom to work in the way that he wants, but they are also designed for the good of the organization, ensuring that work flow is an easy manner and that formal and informal communications are uncomplicated and unobstructed’ (Duffy, 1992).

In 1966, Duffy published ‘Office Landscaping’ (Duffy, 1966b). He wrote his Masters and PhD theses (Duffy, 1974) on this subject (Hookway, 2009) Duffy applied the practical methodologies of social science to architecture in researching the office landscape, questioning the influence of buildings on users’ behaviour (Hookway, 2009). He researched the relationship between the nature of organisation and office layout (Duffy, 1974). Duffy expected the office to be a ‘framework for a changing variety of behaviour’ (Handy, 1992). However, he discovered that layouts of landscape offices were very similar. So he questioned their application of following users’ communication and behaviour. He proposed that ‘no one building, no single form of layout can possibly accommodate all users. There is no such thing as the ideal office building’ (Duffy, 1992).

2.2.4.4. The Open Plan Office

The concept of landscape office was introduced in North America and it was developed into the open plan office layout. Although management preferred their personal offices, the majority of workplaces were designed with an open plan layout (Laing, 2006). Based on technological advances in earlier decades, such as air conditioning in the 1930s and florescent lights in the 1940s (Van Meel, 2000), there was no longer the requirement for natural ventilation and light. Therefore, deep open plan offices were designed in the 1960s in North America (Klein, 1982), which was considered to be a flexible solution in the 1970s. However,

practical difficulties of the deep open plan layout started to emerge, such as user dissatisfaction (Leaman, 2006).

In the 1970s, the North American open plan office was introduced in the UK. In this period, the majority of offices in the UK were rented (Van Meel, 2000). However, the custom designed offices led to new concepts, such as group spaces in the open plan layout to increase teamwork. Laing describes this as ‘a self-regulating structural grid within which working groups grow and change’ (Laing, 2006). In 1975, Norman Foster designed an office layout similar to the ‘controlling’ office layouts in the 1920s. Van Meel describes it as ‘a very ‘controlled’ and ‘clean’ work environment with very rigid arrangement’ of workstations. This workplace had raised floors, as it was driven by technological advances (Van Meel, 2000).

2.2.4.5. The Action Office

Robert Probst, who was working for Herman Miller in the 1960s, worked on the furniture design for open plan offices to balance communication and privacy. Users were able to move their furniture in their workstation to a setting that was suitable for them (Laing, 2006).

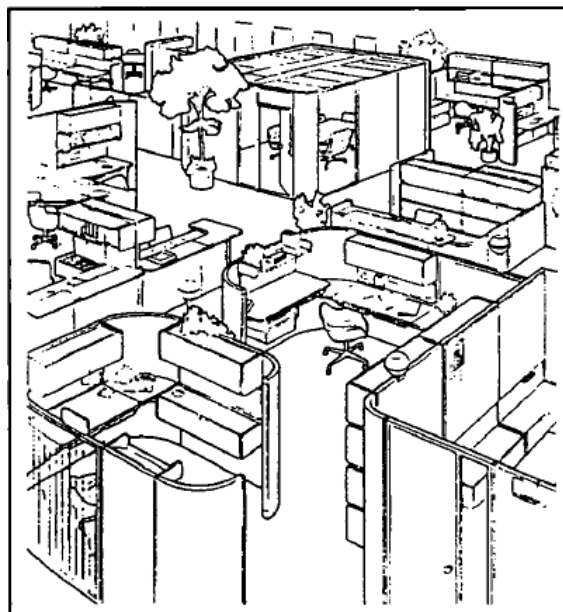


Figure 6: Herman Miller, action office (Laing, 2006)

2.2.4.6. The Cellular Plan Office

After World War Two, the majority of European offices had a cellular plan layout resisting the American managerial system. In the 1960s in Scandinavia traditional personal offices were re-designed (Van Meel, 2000). Although air conditioning and florescent lights were

costly, the main reason for keeping the traditional personal offices was the cultural difference between European countries and North America (Laing, 2006). The 'social democratic office' (Myerson, 2008) in Northern Europe and Scandinavia was more concerned about providing a pleasant environment rather than higher salaries and mass production concepts (Forty, 1986, Myerson, 2008). In the 1970s, the Workers' Council in Scandinavia gained power to influence the design of the workplace based on users' demands (Hookway, 2009). According to these new regulations, cellular plan offices were designed with much higher standards of indoor environment, such as access to an outside view, natural ventilation and light, which occupants found satisfactory (Van Meel, 2000).

2.2.4.7. The Combi Office

In 1978, the Combi office was introduced in Sweden by Åke Beijne to design Canon's headquarters in Stockholm (Van Meel, 2000). This office layout is a combination of cellular and open plan layouts (Axéll and Warnander, 2005), mixing the private personal rooms with an open area as the 'living room' in the middle to encourage communication (Van Meel, 2000). In this layout, every occupant has a personal room, as privacy is highly valued (Laing, 2006). Harrison describes a Combi office as 'private cells group around a common space' (Harrison et al., 2004). The personal rooms are located around the perimeter of the building in order to access a window, while the social and facilities area are located in the centre, including copy rooms and archives (Laing, 2006). The personal office is connected to the shared area by a glass wall (Axéll and Warnander, 2005).

2.2.4.8. Centraal Beheer

In order to avoid the difficulties of the landscape office, such as lack of privacy and identity, other office layouts were introduced in Northern Europe. The Centraal Beheer office building designed by Herman Hertzberger in 1972 is a successful example (Laing, 2006), presented in Figure 7. This office design had a balance of communication and privacy, called 'work islands' (Myerson, 2008). Although it included open spaces to increase the communication, it had local group working areas that gave a sense of identity to occupants (Myerson, 2008, Laing, 2006). This was a user-driven design, in which occupants could decorate and furnish their own workstation to promote a sense of ownership and autonomy. Myerson calls it 'intellectual modernism with a human face' (Myerson, 2008).

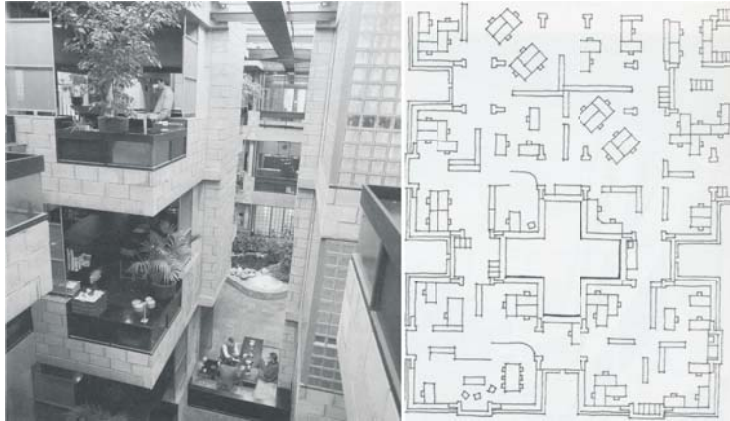


Figure 7: Herman Hetzberger's Centraal Beheer Building in 1972 (Van Meel, 2000)

Centraal Beheer was a successful office with high user satisfaction (Van Meel, 2000). Nevertheless, it was considered expensive as it lacked efficiency in use of space, which is the advantage of the open plan layout (Laing, 2006). Duffy explains 'Centraal Beheer was built when money was cheap and people dear. By the end of the decade when Centraal Beheer needed more space, money had become dear and people cheap because of changes in the world economy' (Duffy, 1975).

2.2.4.9. Concept of a Mobile Office

The initiative idea of a mobile office was introduced when technological advances required to support it did not exist. In 1969 in Europe, Hans Hollein suggested the idea of a 'mobile office' that allows work to take place in various locations. He demonstrated this concept with an art exhibition in an airport (Van Meel, 2010), presented in Figure 8.



Figure 8: Hans Hollein's prediction of the mobile office in 1969 (image source: <http://www.hollein.com>)

2.2.4.10. Non-Territorial Office

In 1970 in North America, IBM introduced the new concept of a 'non-territorial office', which was a very flexible office layout with different functional spaces (Van Meel, 2010). Although this layout improved the communication level, at that time researchers explained that such an advanced idea 'can provoke a good deal of fear among those who have not yet experienced it' (Allen and Gerstberger, 1971).

2.2.5. Digital Revolution: New Ways of Working

In the 1980s, two factors influenced the design of the workplace, including economic challenges and advances in information technology (IT) (Harrison et al., 2004). In 1980, IBM introduced personal computers to the world and revolutionised the workplace. Individual computers appeared on desks in offices and changed the way work was done. This was followed by a change in the nature of the workplace from a 'data processing factory to a centre for the creative application of ideas and information' (Laing, 2006). Information technology, globalisation and organisational changes required new offices (Harrison, 2006). Space, building use and design of offices were questioned (Duffy, 1992, Laing, 2006). For the first time, the idea that people could work out of the office with a computer and communicate with other colleagues was considered (Duffy, 1992).

2.2.5.1. The ORBIT & HVAC

In the 1980s, a Swedish furniture company called DEGW started to design furniture based on computer use (Laing, 2006). As the founder of the DEGW in early 1980s, Duffy applied a study called ORBIT (Organisations, Buildings and Information Technology) to research the impact of information technology on the design of offices in the UK (Duffy and Chandor, 1983). In North America, Becker et al researched a similar subject (Becker, 1985, Duffy, 1996, Harrison et al., 2004). They researched the relationship between information technology, user and office layout, so called 'intelligent buildings'. Harrison explains that 'an 'intelligent building' was defined as that which contained a collection of technologies able to respond to organisational change over time' (Harrison et al., 2004). They discovered that electronic equipment, such as computers and cables, produce extra heat that created difficulty of overheating in offices. Therefore a new requirement for heating, ventilation and air conditioning (HVAC) was introduced (Becker et al., 1996).

2.2.5.2. Skyscrapers

As the primary city in Europe, London was quickly transformed by the design of new offices and skyscrapers in the 1980s. London offices, particularly skyscrapers in Canary Wharf, were greatly influenced by the American style of offices (Van Meel, 2000). They had open plan layouts and were designed to maximise flexibility and efficiency (Laing, 2006), as they were based on occupancy of multiple or unknown users (Harrison et al., 2004). In the mid 1980s, Sick Building Syndrome studies in the US and the UK influenced public's opinion in regard to the open plan office (Van Meel, 2000).

2.2.5.3. Lloyd's of London

Lloyd's of London, which was designed by Richard Rogers in the 1980s, had an open plan layout and a large atrium in the middle (Van Meel, 2000), presented in Figure 9. The raised floors in this building with the purpose of accommodating cables show the impact of information technology on architecture (Powell, 1994).

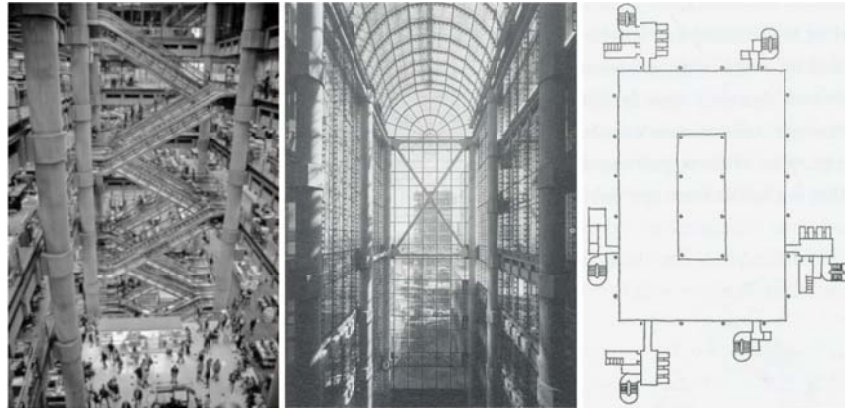


Figure 9: Lloyds of London in 1986 (Image source: <http://www.archdaily.com/> and (Van Meel, 2000))

2.2.5.4. The 'Small City'

In the 1980s in Northern Europe, user satisfaction was the main criterion for office design, rather than the influence of information technology or skyscrapers. According to Van Meel, there was an emphasis on 'privacy, individual climate control, daylight, openable windows and an outside view' (Van Meel, 2000). Cellular plan offices were designed in a new way with a combination of private and social spaces, such as the NMB Headquarters in Germany, presented in Figure 10.

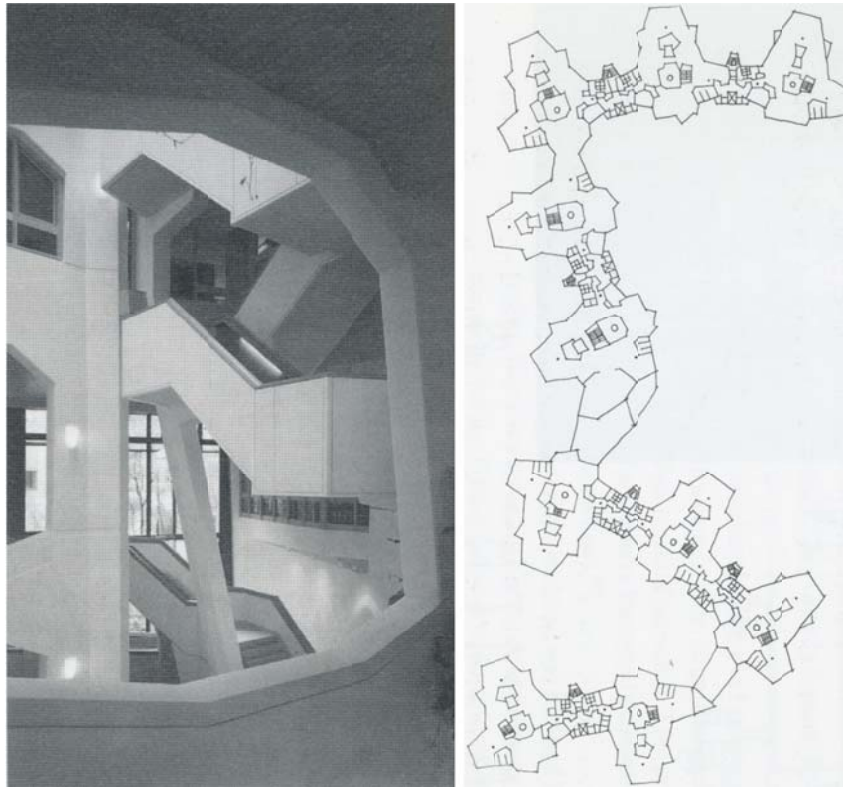


Figure 10: The NMB Headquarters in Germany in the 1980s (Van Meel, 2000)

Scandinavian Airline Systems (SAS) Headquarters, designed by Niel Torp in Sweden in 1980s, is another example of this model, presented in Figure 11. It had a ‘social community, complete with park benches and tree lined boulevards’ (Myerson, 2008). It had shops, gyms, medical centres, restaurants, and cafés to inspire social activities as well as personal offices (Laing, 2006, Myerson, 2008). It was designed based on sustainable criteria (Beatley, 2000) and role of the end user, which is a different design purpose compared to Northern American office designs (Van Meel and de Jonge, 2006). Van Meel describes this new design as ‘a small “city”, but on a human scale. The buildings were cut into separate ‘houses’ that were united by internal ‘streets’ or ‘squares’. The main purpose of these atria was not to bring daylight into the building, as in Lloyd’s London, but to function as a “social heart”’ (Van Meel, 2000).

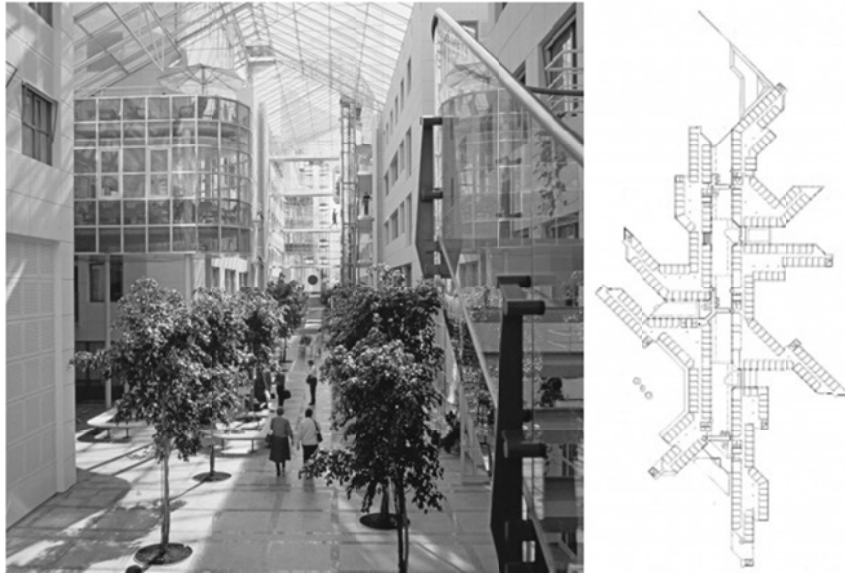


Figure 11: The SAS Headquarters in Sweden in the 1980s (Image source: <http://www.nielstorp.no/>)

The architecture of the SAS Headquarters influenced the British office design to encourage informal meetings (Myerson, 2008), such as the business park, presented in section 2.2.5.6 and 2.2.6.6. However, the ‘small city’ office layout was criticised to be inefficient, inflexible, expensive, and not suited for challenges in the 21st century (Myerson, 2008).

2.2.5.5. The Combi Office with Desk Sharing.

In the 1990s in Northern Europe, the cellular office layout could not keep up with the globalisation criteria. Thus, new office layouts were introduced. Modern Scandinavian offices, the Combi office with desk sharing facilities, became popular in Northern Europe. As Van Meel describes, ‘Scandinavia is regarded as the place where the workplace of the future has already been implemented’ (Van Meel, 2000).

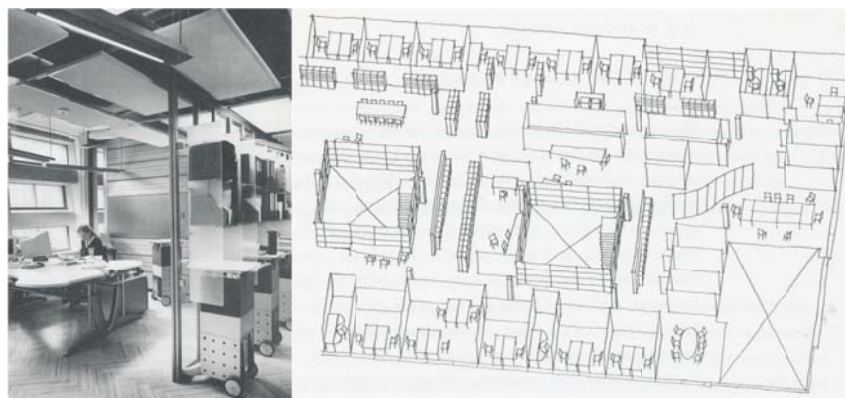


Figure 12: Dynamic office in Netherlands, combination of Combi office and desk sharing (Van Meel, 2000)

2.2.5.6. The Business Park

In the 1990s in the UK, open plan offices continued to bloom. However, cost-driven concepts, such as desk sharing, were introduced. The British Telecom, designed by Norman Foster, was considered the ‘Workstyle 2000’, which was an efficient ‘business park’ (McGregor and Then, 1999, Van Meel, 2000).

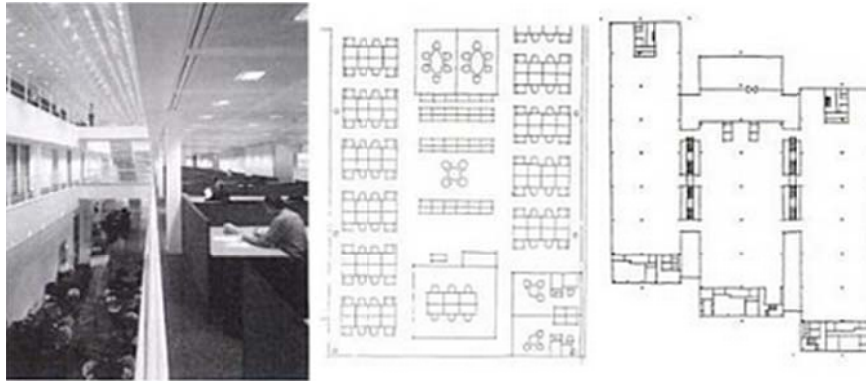


Figure 13: British Telecom in the 1990s (Van Meel, 2000)

2.2.5.7. Virtual Communication

The economic pressure at the end of the 1980s and beginning of the 1990s influenced the design of the workplace (Laing, 2006) and underlined the importance of productivity and performance (Harris, 2006). The idea of a multi-tenant skyscraper office with an open plan layout or an expensive ‘tailor-made’ Scandinavian layout had to change. Offices had to become much more efficient in order to survive, and this called for a different way of thinking about how to work. An emphasis was given to the ‘end user’, in regard to their cost, productivity and personal requirements (Laing, 2006). Wireless LAN technology was introduced in 1997 (Gillen, 2006). Technology and communication became essential for productivity in offices (Turner and Myerson, 1998) so that service providers led the ‘momentum’ rather than management (Myerson, 2008). Effectiveness replaced efficiency and knowledge work replaced process work in the networked office (Myerson, 2008). Communication through the wireless system connects individuals to other people and locations. Different virtual tools, such as messaging, were introduced for instant communication. Some tools were considered as effective as personal meetings (Gillen, 2006), so that the need for face-to-face communication declined (Harrison et al., 2004). Thus, the idea of working out of the office started to grow in practice, as Stone and Luchetti state: ‘Your office is where you are’ (Becker et al., 1996, Duffy, 1992).

2.2.5.8. New Ways of Working

In the 1990s, advances in information technology and communication provided the possibility for a nomadic work style (Gillen, 2006). These ‘new ways of working’ transformed ‘cultural, social, technological and construction processes’ (Harrison et al., 2004). Occupation of the workstations in an office decreased to 50% to 80% (Kern et al., 1999). Several terminologies were introduced to the workplace, such as job sharing, nomads and team workers (Worthington, 2006). Virtual communication was efficient, sustainable, with less travelling and time wasting (Gillen, 2006). Offices became flexible as they were connected to other places around the world (Laing, 2006), making global competition between organisations possible (Klein, 1998).

2.2.5.9. Communication vs. Autonomy: Hive, Den, Cell & Club

In 1997, the DEGW researched the building typologies that are suitable for modern organisations and transformations (Harrison et al., 2004, Laing, 2006), which led to a new typology for the workplace called ‘design logic in the new office’ (Harrison et al., 2004). This is based on the nature of organisations, which is diverse (Klein, 1998) so that a particular office layout does not suit this diversity (Laing et al., 1998). The office layout is subject to change as the business transforms over time (Harrison et al., 2004). Figure 14 shows the transformation in the nature of the organisations.

They have changed how they work	
From	To
Routine processes	Creative knowledge work
Individual tasks	Group, teams and projects
Alone	Interactive
They have changed where they work	
From	To
Places	Networks
Central	Dispersed
Transport	Communication
Office	Multiple locations including the home
They have changed their use of information technologies	
From	To
Data	Knowledge
Central	Distributed
Mainframe	PC, video, telecomms, e-mail, Internet
One place	Mobile, personal, nomadic, virtual
Big	Palmtop, pocket, laptop
They are using space over time in new ways	
From	To

One desk per person	Shared group and individual settings
Hierarchical space standards	Diverse task based space
9 to 5 at one place under-occupancy	Anywhere, anytime, varied patterns of high density use
Owned	Shared

Figure 14: DEGW: Changes in the nature of office organisations (Laing et al., 1998)

In addition, users ‘will want more and more control over their own comfort’. Hence centrally controlled thermal systems faced a challenge (Laing et al., 1998). Laing and Duffy produced models for office layouts, including den, club, hive, and cell (Laing et al., 1998). Communication and autonomy were the main criteria in creating these models.

- The hive has low levels of both communication and autonomy, which is suitable for administrative and information operations. This is an open plan layout, which is deep, highly screened and impersonal, designed for full time occupancy. The hive is suitable for call centres and financial operations.
- The den has high communication and low autonomy, which is suitable for team working. It is designed for ‘owned workstations’ close to team members with shared facilities to apply short term tasks and group process functions. The den is suitable for design, research and media organisations.
- The cell has low communication and high autonomy. This is the same as the Scandinavian cellular plan offices and it is designed for irregular occupancy hours. The cell is suitable for lawyers, academic and consultancy occupations.
- The club has high levels of both communication and autonomy, which is suitable for knowledge work in a team as well as applying individual tasks. It includes various spaces offering different facilities for a short term use. The space occupation is based on instant requirements of an individual or a team. It is flexible to facilitate out of office work styles, such as home and tele-working. The club is suitable for management, advertising and IT companies.

The cost of environmental systems for these models from low to high demand is as follows: hive, den, club, and cell.

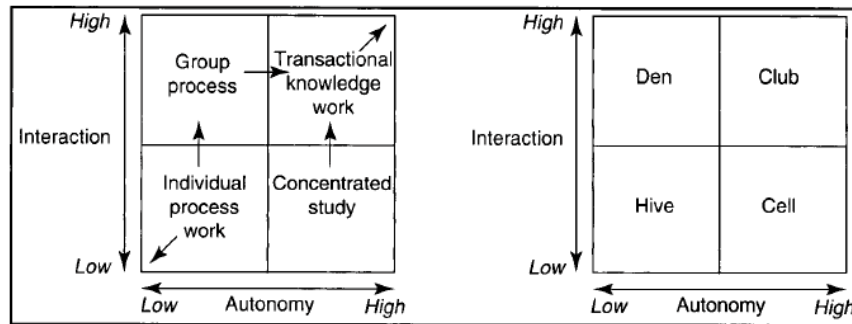


Figure 15: The DEGW's patterns of work: four major types (Laing, 2006)

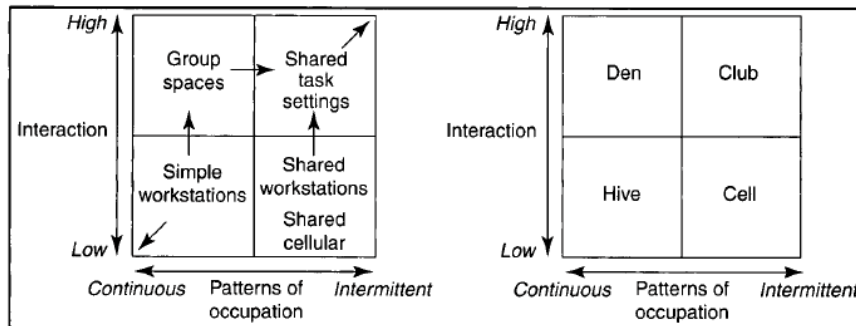


Figure 16: The DEGW's patterns of space occupancy (Laing, 2006)

2.2.5.10. The Club

Laing and Duffy predict that in the 21st century most of the organisations will move towards the club model, in which communication and individual autonomy are highly valued (Laing, 2006). The 'Club' is an efficient and effective office that is flexible enough to hold variety of settings for different individual and social tasks like the traditional 'Gentleman's Club' (Laing, 2006). Turner clarifies that employees need to play by the rules of the club, which depends on 'individual behaviour rather than corporate procedures or structures. Club is informal and unhierarchical, because it is not based on precedent or territory' (Turner and Myerson, 1998). The club is a concept with the qualities of both the expensive customer-based Northern European cellular plan and the efficiency of the Anglo-Saxon open plan offices (Duffy, 1997, Laing, 2006). It contains the best characteristics of both models, including interaction and autonomy (Duffy, 1997). The design of a club is based on the nature of the organisation that occupies the building. Open plan offices with medium depth and an atrium are flexible, able to accommodate this transformation to functioning as a club layout. However, deep open plan and shallow layouts are not flexible enough to accommodate organisational changes (Laing et al., 1998).

2.2.6. Current Offices: Task Oriented, Flexi & Virtual Offices

In the early 21st century, information technology, such as mobile systems, computing and the Internet, is already well established and has revolutionised the way of working (Harrison, 2006). It provides a new opportunity for people to choose the location of their work, such as home, hotels, trains, airports, cafes, and clients' offices (Worthington, 2006). However, it also creates some difficulties, such as work-life balance (Kurland and Bailey, 1999). Currently, knowledge workers are the dominant 97% of the workforce (Katsikakis, 2006) and most of them spend only 45% of the office hours working at their workstations (Nathan and Doyle, 2002). The tradition of office workers at their desks no longer applies, as they are no longer bound to their desks in the office (Duffy, 1996). Working full time (i.e. five days a week nine to five) is questioned (Harris, 2006), which inspires flexible and new office designs in addition to new work pattern opportunities (Laing, 2006). Although flexibility seems necessary (Gillen, 2006, Harris, 2006), today most organisations are still committed to fixed tenancy (Gillen, 2006) and buildings are not occupied efficiently. In 2004, the vacancy rate of the office buildings in London increased by up to 15%. Workstations were occupied up to 45% and the whole building up to 70% of the time (Harris, 2006). This was not a sign of economic downturn, as for three years the economy and employment were booming. Harris suggests that this change is structural and it demands flexible properties and services (Harris, 2006). Gillen suggests that the use of space per workstation could be more efficient leaving room for other useful services and spaces (Gillen, 2006). Mobile workers require high technologies rather than physical space at the office (Gillen, 2006). There is a challenge to accommodate the constant change in the workplace with new ways of working, and also to make physical and virtual environments work side by side. In order to respond to this challenge, architecture and technology must join in the creation of a new environment (Worthington, 2006).

	Pre-War	1950s	1980s	2000s
Workplace	Production line Labour intensive Task oriented Hierarchical	Data processing Departmental Corporate	High specification Extended hours Large, open floors Cellular space	Mobility Core/periphery Hotelling Flexitime/place
Systems	Simple lighting Simple heating Natural ventilation	Mainframe Data processing Typewriters	The workstation BMS PCs and networks Fax/teleconference	Individual control Integrated BMS Natural ventilation IT convergence
Culture	Small scale Uniformity Task oriented	Multi-layered Corporate identity Large scale	Delaying Outsourcing Individualistic Meeting space	Flexitime/place Group areas Employee welfare Networking
Finance	Owner occupiers Long leaseholds Large estates	25 year, FRI lease Mortgage finance Debentures	Non-recourse Off balance sheet Debt finance	REITS Management Flexibility

▲3.1 Long-term change in offices

Figure 17: Long term change in offices (Harris, 2006)

2.2.6.1. Organisational Changes

Organisations are becoming less hierarchical and more horizontal networks (Turner and Myerson, 1998, Harris, 2006). Turner explains that as a result of advances in information technology, ‘young people are much less obsessed with status and security than their parents’ generation, and much more focused on the interest of the work and its financial rewards’ (Turner and Myerson, 1998). In the past, workstations were based on employees’ status, now they are based on tasks and efficiency (Harris, 2006). There is a contradiction in the new organisational culture, as efficiency and effectiveness are sometimes two opposite incentives of the workplace that require a fine balance. Efficiency is in regard to costs, reducing the use of space and facilities. It is about quantity and ‘achieving more with less’ (Worthington, 2006). In contrast, effectiveness is about quality, through a support system and accommodating change to encourage motivation and productivity (Worthington, 2006). Flexible ways of working are expected to have higher levels of user satisfaction and productivity with lower costs (Van der Voordt, 2003). Hill reports that telework and virtual communication improves productivity (Hill and Weiner, 2003). Scandinavia, UK, Germany, and the Netherlands have higher numbers of teleworkers compared to the rest of Europe (Harrison et al., 2004), presented in Figure 18. Organisations require social, financial and environmental sustainability (Worthington, 2006). Leaman explains that there is a basic paradox between ‘economic development and the new agenda of sustainability’ (Leaman and

Bordass, 1996). In order to reduce costs and improve quality, they share facilities such as a gym, restaurant, library and meeting spaces. The cutting edge organisations seek flexibility, mobility, multiple and intensive use of space as well as providing individual control (Worthington, 2006). Van Der Voordt reports user complaints in new offices regarding the lack of privacy and individual thermal and lighting control (Van der Voordt, 2003, Gorgievski et al., 2010).

Table 5.2 Teleworkers (working at least one day from home) as a percentage of the total working population

Country	Teleworkers (%)
Netherlands	21
Denmark	18
United States	17
Finland	16
Sweden	15
United Kingdom	11
Germany	8
France	4
Italy	3
Spain	2
European Union (average)	7

Source: SIBIS, 2002.

Figure 18: Home working (Van Meel and de Jonge, 2006)

2.2.6.2. Open vs. Cellular Plan Solutions

Marmot focuses on the design of an open plan office. According to Marmot, an open plan office is no longer a modern idea. It has been accepted as a better and more flexible way of working. She mentions that this layout increases employees' communication and productivity (Marmot and Eley, 2000). Although she recognises that noise and concentration are difficulties in an open plan office, she strongly suggests the open plan as the layout for new workplaces. She even discourages management from having a personal office as they gain much more by sitting with their staff in the open plan office. They are more involved with their team, more aware of their decision making and they require fewer formal meetings. Even confidential phone calls and meetings can be predicted and arranged in advance to take place in a quiet room or meeting rooms (Marmot and Eley, 2000). In contrast, Van Meel has a more moderate and flexible solution to design current offices. He produces guidelines for different types of workplaces based on the nature of organisations on a European model. He combines cellular and open plan layouts based on the nature, culture and requirements of an

organisation (Van Meel et al., 2010). Harrison explains that no particular settings or solution suits everyone or every organisation (Harrison et al., 2004).

2.2.6.3. The Creative Workplace

Although it seems that in the future there will be less need for a physical workplace and more need for a virtual workspace, Worthington states that ‘organisations still require buildings but with a change in emphasis’ (Worthington, 2006). Although collaborative work is essential for companies, users still spend over 60% of their time on solitary tasks (Harrison et al., 2004). Creativity is an important issue for organisations and it should be considered in the office layout, such as particular spaces to encourage users to be more creative as a team as well as individually (Harrison et al., 2004). By providing various spaces and conditions to work, knowledge workers are more likely to be creative (Stegmeier, 2008). Gillen calls this kind of design ‘Piazza’ (Gillen, 2006). There are different approaches to improve creativity, for instance some organisations, such as Google and Pixar, provide an excellent environment that attracts the most talented people in the field so that they prefer to spend their whole day in the office.

2.2.6.4. The Task Oriented Space

The office is a combination of different spaces for different activities according to the requirements of the organisation (Harrison et al., 2004). Harrison’s categories of office spaces and activities are as follows:

- ‘Small rooms or booths for concentrated work, or confidential telephone calls
- Open areas for informal meetings
- Quiet open plan areas
- Touch-down desks for ad-hoc or short-term users’

The company’s location and how they treat their staff is becoming more important. Many offices move to the edge of cities because of rental costs and working hours (Gillen, 2006). The way a company treats the staff shows how the company handles the business (Gillen, 2006) so the image or design of the office is important for getting better contracts. This design directly influences these two aspects, location and community (Gillen, 2006). 30% of offices are given to service systems such as meeting rooms and the canteen (Gillen, 2006).

2.2.6.5. The Flexi-Office

In Northern Europe, more offices are moving away from cellular and open plan offices with fixed workstations towards the 'flexioffice' with shared desks (Van der Voordt, 2003). In Scandinavia, economy and rental prices drive offices away from cellular layout towards open plan offices (Axéll and Warnander, 2005). In Sweden, companies that are located in areas away from centre with lower prices may hold on to the cellular layout. In contrast, companies that are located closer to the city centre with higher prices prefer to have a combination of open and cellular layout (Axéll and Warnander, 2005). Users prefer cellular offices while working on individual tasks and shared spaces for meetings, teamwork and interaction (Van sprang et al., 2013).

2.2.6.6. The New Business Park

In the UK, government regulations to reduce energy use, pollution and traffic congestion encouraged new forms of offices (Becker et al., 1996). Some workplaces, such as Chiswick Park in London, are designed to provide the best work environments to attract the best staff to improve the productivity. The Park's slogan 'enjoy work' demonstrates this aim. The more people enjoy their work, the more productive they are and the more successful the business is (Katsikakis, 2006). These large companies, which are not located in the centre of the city, have a social street or a 'street cafes' in the middle of the building with activities such as cafes, restaurants, dry cleaners and groceries. On the one hand, in these streets staff meet informally and unexpectedly, which is beneficial for communication in the company (Gillen, 2006). On the other hand, this design provides a better work-life balance for the staff (Katsikakis, 2006). Employees have reported high levels of satisfaction regarding their work environment at Chiswick Park (Katsikakis, 2006).

2.2.6.7. The Virtual Office

Some organisations have gone so far as to be completely disconnected from place: they have no physical appearance as an office for staff (Harrison et al., 2004). This new kind of organisation is called 'virtual'. Although their requirement for individual workstations has been eliminated, virtual companies still require 'technology, support and usually a meeting place'. The virtual company is usually the expansion of the main company, while the parent organisation usually has a physical headquarters. Harris explains that such new virtual companies demand 'new management skills and working practices to manage an organisation, which is 'not there'' (Harris, 2006).

2.2.6.8. Face to Face Meetings

Still many current workplaces are designed as fixed settings for full time employees. This is due to rapid change and there is a need to adjust to this transition period from the predictable to the unknown territory of a variety of physical and virtual locations. The new office is important as a place to hold in-person meetings (Gillen, 2006). Although all sorts of voice and video meetings are possible, the main business contracts take place through personal meetings (Breure and Van Meel, 2003), called 'Workscape' (Gillen, 2006). An actual meeting is a more effective way to negotiate and read people's reactions. Therefore management prefer to take a flight to other cities to negotiate large business matters (Breure and Van Meel, 2003). As Breure explains 'None of them thought that technology could overtake the need for face to face contacts', 'personal meetings such as sharing a meal or a drink are highly important for creating a basis of trust and bonding. So, real-life contact, and not technology, is the main reason why these mobile workers are mobile' (Breure and Van Meel, 2003). In addition, virtual meetings need to be scheduled in advance rather than occurring spontaneously. They eliminate the possibility of informal meetings and casual face-to-face conversations, which are very beneficial for knowledge transfer within an organisation (Gillen, 2006). Woodling states that 'the more people communicate, the more they want to meet' (Woodling, 2006).

2.2.6.9. Working in the Office

As Davenport explains, knowledge workers 'like flexibility and they like to work at home occasionally. However, they know that to be constantly out of the office is to be 'out of the loop', unable to share gossip, exchange tacit knowledge, or build social capital' (Davenport, 2005). Marmot explains that working at home is beneficial for some people allowing a better life-work balance. However, for others the balance is in separating where they work from where they live. Many people look at their work as a place to hide from their real life, families and difficulties at home, such as a crying baby or a challenging teenager (Marmot and Eley, 2000). If they have to work at home they struggle to find a quiet place to concentrate, in the basement or under the stairs. Paying expensive bills such as electricity, heating and phone calls are additional difficulties. Working at home benefits a sustainable society mainly in reducing pressure on the transport system rather than benefiting the actual organisation (Marmot and Eley, 2000).

2.2.6.10. New Office Models

Most of the revolutionary workplaces with new working methods and technologies are built without professional assistance for their design, such as the Digital Office in Finland and Sweden. They were inspired by the relaxed environment of a 'home', efficiency and flexibility of 'hotels', and communication of a 'gentlemen's club' (Laing, 2006). Laing demonstrates the 'characteristics of new ways of working' as mobile and nomadic patterns, shared group spaces, task-based workspaces, long hours of work, shared spaces and fewer long term allocated spaces, teleworking and homeworking (Laing, 2006). Different models of offices are as follows:

- Work palace: a workplace with extra facilities to support the user's life such as entertainment, child and granny care units (Marmot and Eley, 2000). These environments encourage staff to spend as much time as possible in the building to improve their creativity and productivity. Google and Pixar offices are examples of the work palace.
- Project rooms or collaborative team office: an office to be used by a team for the period of their project (Becker et al., 1996). This is similar to the 'group address', which a term to specify staff in a particular group who work on a specific project (Becker et al., 1996).
- Non-territorial office: staff don't have a particular assigned workstation, instead they use the activity zones and workstations in a 'first-come, first-served' basis (Becker et al., 1996).
- Shared assigned: a desk to be used by two employees based on agreement or allocated by a computer software (Becker et al., 1996).
- Desk sharing: a particular workstation is used by different staff over a period of time (Becker et al., 1996).
- Hot desking: no one has a particular assigned desk, similar to non-territorial office (Becker et al., 1996). This term is originally used in the Navy, which means the bunk is still warm when the next sailor occupies it (Becker et al., 1996, Marmot and Eley, 2000).
- Drop-in: a workstation which is available for a very short period of time such as a few hours, usually used by visitors or visiting employees (Becker et al., 1996).

- Club: a relaxed lounge with refreshments that allows discussions between employees. Similar to the old Lloyds Coffee House in London (Marmot and Eley, 2000).
- Technoemporium: small offices with advanced and exotic equipment that is used in short periods when large and expensive equipment are required (Marmot and Eley, 2000).
- Call centres: they act like a help desk offering different services such as information, advertising and selling goods. Sometimes different groups use a call centre day and night (Marmot and Eley, 2000).
- Business centre: a desk or a team space is rented for a short or long period of time. These offices are mainly used for new businesses or expansion of a business.
- Client location: individual or groups are located at the client's office in order to compete to sell goods or services (Marmot and Eley, 2000).
- Home office or home-based telecommuting: employees work at home and communicate with the office and colleagues when necessary (Becker et al., 1996). The employees use a room or a corner of their house, which is equipped with mobile computers, phones and possibly other equipment. This corner may be the kitchen, under the stairs or study room (Marmot and Eley, 2000).
- Satellite office or telework centre: a work environment in occupant's local neighbourhood equipped with advanced technological equipment (Becker et al., 1996, Marmot and Eley, 2000). Organisations use a satellite office either close to employees' homes for their convenience or as an expansion of their business in a new location (Marmot and Eley, 2000).
- Cybercafé or Internet café: a café with an easy access to computer and Internet (Marmot and Eley, 2000).
- Airport lounge or hotel lobby: a peaceful space with a table and access to power, telephone and fax where travellers work on their mobile computers in between their activities (Marmot and Eley, 2000).
- Non-traditional work settings: any place that productive work and communication can take place, such as vans, cars and hotel rooms (Becker et al., 1996).

- Virtual office: a term used to disassociate the office from time and place, in other words 'your office is where you are' (Becker et al., 1996).

Marmot explains that most offices are a mixture of some of the above mentioned office forms, based on the nature and requirements of the organisation. Various combinations result in various outcomes (Marmot and Eley, 2000). These new offices are designed to accommodate more users over a longer period to apply tasks that cannot take place in other places (Marmot and Eley, 2000).

2.2.7. Future Offices: Flexible & Mobile

Although during the 1970s, 80s and 90s the demand for physical office space was increasing, many researchers predict that in the future this demand will decrease (Harris, 2006, Duffy, 2008). Duffy predicts that quality of the workplace will be more important than its quantity (Duffy, 2008). However, some researchers such as Gillen argue that in the future organisations will require different settings rather than less space (Gillen, 2006). The amount of space may remain the same, but a variety of spaces will be required for different tasks and services (Gillen, 2006). Buildings will be used at almost full capacity (Katsikakis, 2006). Gillen predicts that designers will be more involved with occupant organisations, users and space management (Gillen, 2006). Design of workplaces will become more important as they influence the ‘business strategy’, nature and culture of the organisations (Gillen, 2006). Woodling predicts a change in the nature of organisations so that hierarchy will be replaced by ‘flat organisational structures’ (Woodling, 2006). He argues that organisations should be adjusted to the process of work and collaboration between individuals. Katsikakis confirms this, as the design of workstations will be based on tasks and the work process rather than status and hierarchy (Katsikakis, 2006). The evidence shows that large headquarters are being replaced with small organisations and self-employed people (Woodling, 2006). New organisations prefer to rent rather than own the office building for more flexibility in organisational changes, such as the growth of their business (Klein, 1998). In contrast, in order to attract talented workforce, ‘the driving force for change in the provision of space’ will be more important than ever to increase user satisfaction (Woodling, 2006). Katsikakis questions the future of contrasting values, such as productivity versus best staff, competition versus sustainability, and central office versus distributed collaboration (Katsikakis, 2006). She argues that ‘increased demand for space to support collaborative activities that can typically be accommodated in deep plan space will be balanced against increasing demand for spaces that stimulate, and have access to views, and natural light and provide aesthetic and sensory variability’ (Katsikakis, 2006).

The workplace is moving in new directions ‘such as distributed work, shared space and new partnering arrangements’ (Worthington, 2006). Van Meel predicts that standardising uniform workplaces will end and a variety of innovative offices will be introduced (Van Meel and de Jonge, 2006). Harris explains that ‘the relationships between employers and their employees, between workers and their places of work, and between occupiers and suppliers will become increasingly important in determining the form and function of the emerging office environment’ (Harris, 2006). The management of people, technology and space becomes essential for organisations (Harris, 2006).

2.2.7.1. Flexible & Mobile

The workplace will be a flexible environment that can accommodate various tasks (Harris, 2006). Communication and cooperation will be even more essential for organisations (Katsikakis, 2006). Individual tasks will be replaced by teamwork tasks. Machines will take over routine jobs, such as documenting, monitoring, controlling, and following rules. In contrast, people will undertake tasks such as innovating, communicating, judging, and caring. Individually owned workstations will be replaced by mobile ways of working inside and outside the office (Katsikakis, 2006). Information technology will advance further than before (Katsikakis, 2006) leading to further mobility and flexibility (Harris, 2006) to provide mobile services for individuals as well as groups to work innovatively regardless of time and place (Katsikakis, 2006). Therefore location is no longer essential to maintain communication or work. There will be a greater demand for efficiency and 'low cost locations'. Replacing the 'fixed' systems with portable systems allows organisations to grow in a new way that was not possible before. Quality of private life combined with management's desire to reduce costs encourages more employees to work from home or away from the office (Harris, 2006).

2.2.7.2. Hotel Facilities

In the history of workplaces during the past century, this is the first time there has been a separation between the demand for space and business output. This new way of working requires 'hotel facilities' that allow employees to book a space, technology and required support services by a 'concierge' system. This kind of workplace is flexible, based on the nature and requirements of the organisation. It may be only partially hot desk for visiting staff or completely non-territorial in that no one claims to own a space. Time, location and space will no longer limit a business or organisation, as they can be easily distributed (Harris, 2006). Gillen explains that 'an organisation's accommodation needs may be met by a combination of four types of space (Gillen, 2006):

- 'Iconic', reflecting the long term values of the company
- 'Event', high quality space for hire
- 'Home base', flexible, pragmatic space for back office functions
- 'Serviced office' on short lease to match sudden change in demand'

	Location	Lease	Fit-out
Client Image Space	Central/Prestigious – major city	Long-term	Moderate- to High-level
Hub	Central/Transport – large city	Medium- to long-term – tiered options	Moderate
Satellite	Suburban/Residential	Short-term	Basic
Service Centre	Low cost	Long-term	Basic (some specialised)
Delivery Centres	Near shore/offshore	Medium- to long-term	Basic (some specialised)

Figure 19: Workplaces to support requirements of a variety of organisations (Katsikakis, 2006)

The new ways of working that are presented in this chapter do not apply all over the world. Gillen states that they only refer to a small part, which includes developed countries with high standards (Gillen, 2006). Many people in the world still struggle to cover the basics of life, such as food and shelter, and they do not have access to any technologies, such as the Internet. Even in Southern Europe, the virtual office is not as common as it is in Northern Europe and America, due to the quality of technical infrastructure (Van Meel and de Jonge, 2006).

2.3. Summary

The history of the workplace shows that Anglo-Saxon and Northern European countries followed separate paths for different reasons. Business and economy are the main initiatives in the former, while user satisfaction is important in the latter. Control over a window, thermal environment and light, which influences the office layout, is much more important in Scandinavia compared to the UK. In addition, workers in both places demand environmental control. Therefore, thermal comfort and environmental control are investigated in Chapter Three. Furthermore, environmental control in Scandinavian and British practices is studied in detail in Chapter Four.

Based on the technological advances after the World War Two and particularly after the 1960s, two distinct office layouts emerged. These layouts include North American open plan and Northern European cellular plan layouts. In the 1970s, the gap between Anglo-Saxon open plan office layout and Northern Europeans cellular plan office layout became clear. Workers' rights, regulations and organisational goals in Scandinavia and the UK followed two separate paths, which highly influenced their office design (Van Meel, 2000). For instance, landscape office was ruled out in the UK and Scandinavia, but for two very different reasons. In Scandinavia, the Workers' Council and workers' rights were the main reason (Hookway, 2009). In contrast, in the UK organisational goals, such as insufficient communication and hierarchical organisational system, were the main objectives (Laing, 2006). In the 1980s, this gap between Northern Europe and the UK became ever clearer, as they continued their separate paths in office design, which were respectively business and user oriented paths. However, in the 1990s, this gap started to narrow. Although the main driver of the British offices was still cost and efficiency, they became more user-friendly with shallow plan layouts, openable windows and natural light. In Northern Europe, the cellular office layout could not keep up with the globalisation criteria so that new office layouts were introduced (Van Meel, 2000).

CHAPTER 3

THERMAL COMFORT AND CONTROL

3. Thermal Comfort and Control

Chapter Two showed the history of office design and users' demand in applying control over the thermal environment (e.g. control over a window and thermostat) as well as privacy in Scandinavia and the UK and the two separate paths on this basis. This chapter investigates thermal comfort and thermal control in depth, including human thermal reception, thermal comfort, challenge in the field, thermal control and its impact. The main part of this chapter is based on occupants' ability to adjust the thermal environment.

3.1. Thermal Comfort

3.1.1. Human Thermal Reception

This section explores the physical relationship between the human body and the thermal environment. The human body receives feelings such as touch, pain and thermal sensation through the skin. This is the largest organ in the body, as its surface area is approximately 1.7 (Nicol et al., 2012) or 1.8 square metres (Karim et al., 1967, Bluysen, 2009). The skin has separate receptors for cool and warm feelings (Hensel, 1974). The former responds to temperatures between 15°C to 34°C, while the latter reacts to 38°C to 43°C (Bluysen, 2009). Human sensory organs constantly send reports to the brain through the nervous system to confirm health. When there is a difficulty with health related issues, the affected organ sends a report to the brain. The latter processes the report and sends back a message to the affected organ on how to react accordingly. The section of the brain that deals with temperature issues is called the hypothalamus, which has separate sections to analyse cool and warm sensations (Bluysen, 2009).

The overall thermal sensation, which is processed in the brain, (Nicol et al., 2012) is a combination of the temperatures of the inner organs and the skin (Bluysen, 2009). Thermal sensation depends on the previous status of the body (Nicol et al., 2012), clothing, the thermal environmental conditions and the intensity and period of temperature change in the surrounding environment (Nicol and Humphreys, 1973b). For example, a cool thermal sensation is uncomfortable when the body is already cold. However, it may be comforting when the body is overheated (Nicol et al., 2012). The thermal sensation of different parts of the body may vary (Nicol et al., 2012). The skin temperature of a comfortable person is around 33°C to 34°C (Fanger, 1967, ASHRAE, 2009) and the normal internal brain temperature is roughly 36.8°C (ASHRAE, 2009). Skin temperatures below 18°C and above 45°C cause pain (Hardy et al., 1952, ASHRAE, 2009) and internal body temperatures out of the range of 28°C to 46°C, particularly in the brain, may cause brain damage (ASHRAE, 2009). Internal organs such as the brain require a consistent temperature level. If the temperature of the brain falls out of the acceptable range, the body reacts in a physical way to retain the comfort temperature (Nicol et al., 2012).

In a warm environment, more blood is transported to the skin to increase the skin temperature and maximise the heat loss. In addition, the body loses heat through sweating and evaporative cooling effect of the sweat on the skin (Nicol et al., 2012). The body is capable of thermal storage, which is the ability to cope with heat for a short period of time. However, if this period increases, it affects health (Bluysen, 2009). In a cold environment, in order to

maintain a constant temperature in the central organs of the body, the blood circulation towards the outer parts of the body, such as hands and feet, is reduced, presented in Figure 20. When the body temperature drops, muscular tension increases and leads to shivering, which releases heat through the metabolic system to keep the body warmer. In the majority of workplaces, moderate heat and cold stress are expected, since severe hot or cold conditions are not usually the case (Nicol et al., 2012).

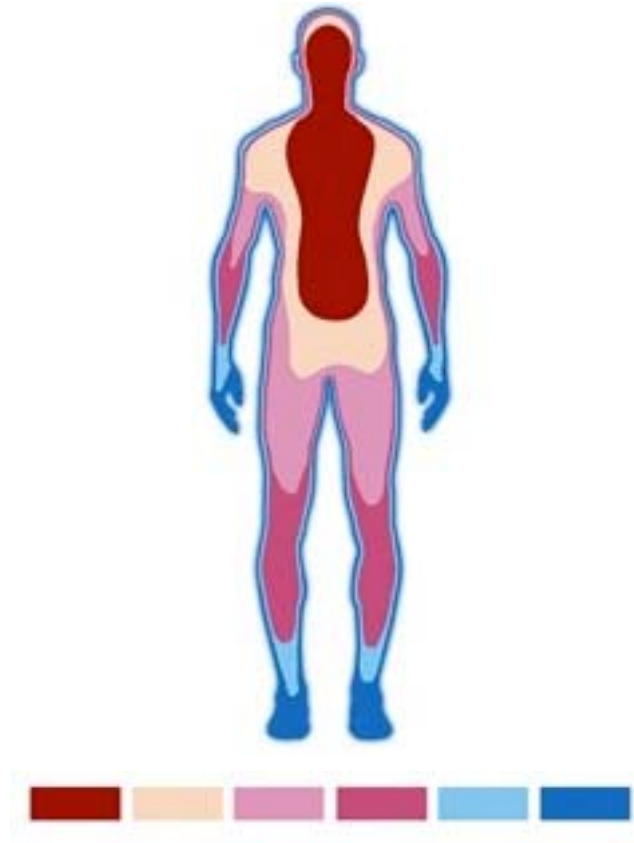


Figure 20: Body heat (Image source: <http://www.bbc.co.uk/schools/gcsebitesize/science/>)

3.1.2. Heat Balance

The human body releases heat mainly through the metabolic rate, physical activities and muscle tension, while it gains heat from the surrounding environment (Olgay, 1992). According to Olgay, the body gains heat through the following (Olgay, 1992):

- Producing heat, such as activity, digesting and muscle tension
- Radiation, such as the sun and radiators
- Conduction, such as warm air or objects close to skin
- Condensation of atmospheric moisture, which is rare

The body loses heat through the followings (Olgay, 1992):

- Radiating heat from the skin to the sky and colder environment
- Conduction to the cold air or objects in contact with the skin
- Evaporation through respiration and skin

Through the metabolic system in the body, the main part of consumed food converts into heat (Bluyssen, 2009, Nicol et al., 2012). This heat maintains the body temperature at a normal rate (Bluyssen, 2009) and it produces energy for muscular activities. Every activity, such as running and thinking, also produces heat. Blood transports the produced heat all over the body, to the heart, the skin and colder tissues (Nicol et al., 2012). The activity level has reverse impacts on the temperature of the internal organs and the skin. When the activity level is increased, the temperature of the internal organs increases, while the skin temperature drops. Low levels of metabolic rate result in body cooling or hypothermia and high levels of metabolic activity result in overheating or hyperthermia (ASHRAE, 2009). When the body is warmer than the environment, it gives off the extra heat to the environment and when it is cooler, it receives heat from the environment (Nicol et al., 2012). In order to sustain thermal balance between the body and the surrounding environment, the produced heat should be the same as transmitted heat (Bluyssen, 2009).

3.1.3. Definition of Thermal Comfort

The definition of ‘a good indoor climate’ is necessary to increase occupant comfort as well as to reduce energy consumption (Humphreys and Nicol, 2002a). Thermal comfort has been interpreted in different ways. Olgay defines thermal comfort as ‘the point that minimum expenditure of energy is needed to adjust himself to his environment’ (Olgay, 1992). He explains that the perception of thermal comfort varies according to age, sex, activity and climatic region (Olgay, 1992). Limb describes thermal comfort as ‘a condition of satisfaction expressed by occupants within a building to their thermal environment. The thermal comfort condition is a subjective feeling of satisfaction, building designers attempt to satisfy as many of the occupants as possible, usually 80% or more’ (Limb, 1992). Hawkes describes thermal comfort as an ‘intermediate point, when neither cold nor hot’ (Hawkes, 2002). The ASHRAE handbook has a similar description that ‘comfort occurs when body temperatures are held within narrow ranges, skin moisture is low, and the physiological effort of regulation is minimised’ (ASHRAE, 2009). The ASHRAE Standard 55-2004 defines thermal comfort as ‘that condition of mind that expresses satisfaction with the thermal environment’ (ASHRAE, 2004). So far the comfort definition described by the ASHRAE

Standard55-2004 is most widely used. This definition is very flexible and does not draw a line to limit comfort.

3.1.4. Discomfort Threshold

Bordass defines comfort as ‘lack of discomfort’ (Bordass et al., 1994). Thermal discomfort is the main driver of user behaviour (Nicol and Roaf, 2005). A sudden change in the temperature results in a change in thermal sensation. It takes roughly 15 minutes for the body to properly respond to the change. Based on the previous comfort condition, this change may be welcoming or bothering. For example, if previously a person has been uncomfortably warm, an extreme cold condition may be welcoming for a few minutes (Oseland and Humphreys, 1994). Occupants feel more comfortable when the indoor thermal condition does not fluctuate and is closer to a steady state (Humphreys, 1977). When the temperature fluctuates, it feels cooler or warmer than a steady state temperature that is equal to the mean temperature of the fluctuating condition (Sakurai et al., 1991). If the changes in temperature is less than 0.6°C per hour, it does not affect the state of thermal comfort and it is considered to be a steady state thermal condition. During the period that the temperature is changing, there is an inconsistency between thermal sensation and perceived comfort. This is dependant on the speed and extent of change (Oseland and Humphreys, 1994). For instance, the reaction of an individual to a cold condition is not only to the temperature, but also to the perception and duration of exposure to the cold condition (Berglund, 1984). In addition, the person’s response to increasing and decreasing temperature changes is different (Oseland and Humphreys, 1994).

The temperature of the body changes roughly one degree during the cycle of day and night. This variation is half a degree during the waking period. Therefore a similar change in the temperature of the surrounding environment that is experienced during that cycle is expected to maintain comfort (Oseland and Humphreys, 1994). Nicol explains that ‘temperature drifts within $\pm 1K$ of the customary temperature would affect little notice; $\pm 2K$ could cause mild discomfort among a small proportion of the occupants’ (Nicol et al., 2012).

3.1.5. Thermal Comfort Factors

The nature of comfort is indeed very complicated, as Hawkes explains. It cannot be ‘implied by simple prescriptions’ (Hawkes, 2002). Research in thermal comfort is criticised due to the complexity of numerous variables that influence user’s comfort, such as contextual and psychological factors (Nicol et al., 2012). Most studies isolate a few variables and investigate

their influence on user's comfort, however the impact of other factors cannot be denied. The ASHRAE demonstrates that thermal comfort is a cognitive process, influenced by many different factors influence it, such as environmental, physical, physiological, psychological, and other factors (ASHRAE, 2009). Auliciems has three categories of comfort factors: environmental, personal and contributing factors (Auliciems and Szokolay, 1997). Environmental factors include air temperature, air movement or velocity, humidity and radiation or mean radiant temperature (ASHRAE, 2009). They have a direct influence on comfort (Bluyssen, 2009). Personal factors include metabolic rate, activity and clothing (Auliciems and Szokolay, 1997, ASHRAE, 2009). Contributing factors include food and drink, acclimatisation, body shape, subcutaneous fat, age, gender, and state of health (Auliciems and Szokolay, 1997). The ASHRAE categorises thermal comfort factors into main and secondary factors. The main factors are similar to environmental and personal factors. However, the secondary factors include 'nonuniformity of the environment, visual stimuli, age, and outdoor climate', which influence thermal comfort (ASHRAE, 2009). Nicol identifies other factors that influence thermal comfort, such as climatic region, social and cultural aspects (Nicol et al., 2012). For instance, people living in warm or cool climatic regions have different thermal expectations and comfort levels.

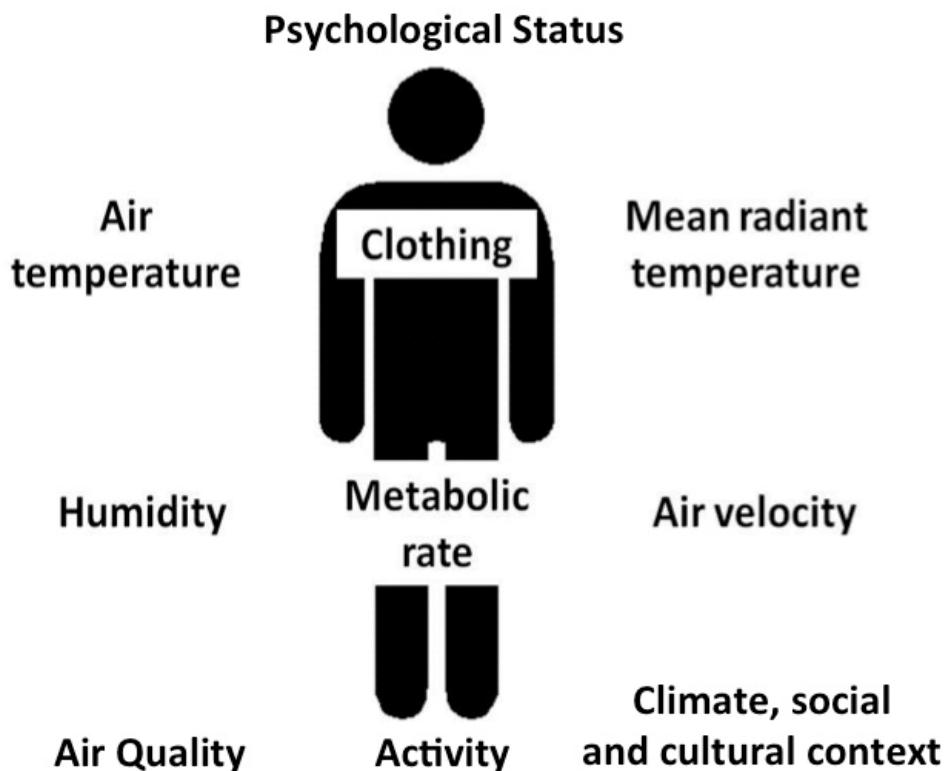


Figure 21: Thermal comfort factors (Image source: www.diamondenv.wordpress.com)

Auliciems indicates that air temperature is the most important factor with the greatest influence on thermal comfort (Auliciems and Szokolay, 1997). Although air velocity and humidity also influence comfort, their impact is not as significant as air temperature. Thermal comfort studies have been criticised for not accurately including humidity and air velocity in outlining comfort conditions (de Dear et al., 1991b, Nicol et al., 2012). De Dear found that 'high humidity may reduce the range of comfort temperature rather than shifting it up or down' (de Dear et al., 1991a, Nicol et al., 2012). Givoni explains that people who live in hot and humid regions are used to a moist skin. However, people who are not used to these conditions are often uncomfortable with a feeling of a moist skin (Givoni et al., 2004, Nicol et al., 2012). Although very high humidity levels are dangerous for health, normal humidity levels are actually beneficial for the body. In hot humid conditions, increased air movement improves comfort levels (Nicol et al., 2012).

The ASHRAE defines radiant temperature as 'the temperature of an exposed surface in the environment' (ASHRAE, 2009). A combination of different surface temperatures in an environment is the mean radiant temperature (ASHRAE, 2009). In a normal situation, the heat loss from the body to the environment through convection and radiation is the same (Bluyssen, 2009). However, if someone is sitting next to a window (Bluyssen, 2009) or fire (Nicol et al., 2012), they may feel the radiation in the form of a radiation draught. Nicol explains that in wintertime when a person is sitting next to a window, they feel the cold due to the 'radiation heat loss to a large cold surface'. However, most people confuse this with a 'draught' (Nicol et al., 2012).

Humphreys exposed the relationship between indoor comfort conditions and outdoor temperature (Humphreys, 1977, Humphreys, 1978, Humphreys and Nicol, 1995). He found that neutral thermal comfort is dependant on the outdoor mean temperature (Humphreys, 1979b). He explains that 'comfort occurs when the current level of the varying microclimate equals the current level of the varying requirement of the person exposed to it' (Humphreys, 1977). The closer the real environment and person's desired environment are, the more comfortable the person feels. Outdoor and microclimatic conditions have a direct impact on comfort. It is easier to cope with a steady microclimatic condition or a gentle gradual change rather than a sudden change (Humphreys, 1977). People change their clothing based on the microclimatic conditions, but they tend to keep the same clothing layers if the microclimate is steady (Humphreys, 1977). Clothing impacts the heat exchange and therefore heat balance of a person (Bluyssen, 2009). Clothing factors such as fabric, thickness and colour influence thermal sensation. For instance, wool, viscose and silk allow the individual to tolerate the humidity changes better than polyester or acrylic clothes (Oseland and Humphreys, 1994).

The ASHRAE has 0.5 and 1 clo for seasonal or different clothing to define the comfort zone based on clothing. A winter business suit is considered 1 clo of insulation while a short sleeve shirt is considered 0.5 clo (Bluyssen, 2009).

3.1.6. History of Thermal Comfort

The earliest written evidence of environmental design and comfort studies goes back to the first century BC (Hawkes, 2002). Marcus Vitruvius Pollio published his famous ten books entitled *De Architectura* during the Roman period (Pollio, 1968). Vitruvius explained how buildings are designed based on climate to provide comfort for occupants. In his sixth book, he presented the Vitruvian model of environment and comfort (Pollio, 1968, Hawkes, 2002), presented in Figure 22.

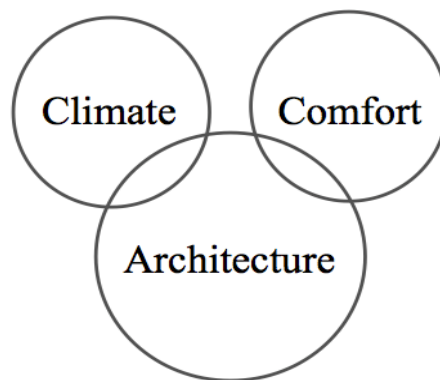


Figure 22: Vitruvian Tripartite model of environment (Hawkes, 2002)

At the end of the 19th century, thermal comfort was introduced as simply one of the environmental variables that influence comfort (Bluyssen, 2009). Bedford was one of the first researchers who actively investigated thermal comfort in context in several factories in the UK in 1936 (Bedford, 1936). Dufton applied experiments to measure surface temperature (Dufton and Marley, 1936) and heat exchange between the body and the indoor environment of a room, mainly the walls (Dufton, 1930). Houghten studied the effect of radiation on thermal sensation (Houghten et al., 1941) and ‘thermal exchange’ between the body and environment (Houghten et al., 1931). Yaglou researched thermal comfort and worked on ‘thermal standards in industry’ (Yaglou et al., 1950). Gagge and Hardy ran experiments to discover thermal sensation and comfort in response to different ambient temperatures (Gagge et al., 1967). Olgyay explained thermal comfort in his book, entitled *Design with Climate*, in 1963 (Olgyay, 1992). He introduced the ‘climate balance’ based on adjusting the building to the natural forces. He recommended using those potential forces to provide users with comfort and better living conditions. Olgyay suggested that architecture should ‘work with

the climate and not against it' (Olgyay, 1992). He resisted the belief common at the time that technological advances were the only solution. He highlighted the importance of designing the orientation, shape and arrangement of openings of the building (Olgyay, 1992). Banham held a similar view, as he considered architects mainly responsible for health and comfort of the occupant, rather than engineers or specialists. In fact, he recognised a contradiction between technological advances and the occupants' health and comfort (Banham, 1984).

3.2. Challenge: Steady State vs. Adaptive Comfort Theories

There is a challenge in the field of thermal comfort between the steady state and adaptive comfort theories. Although this challenge started in the early 20th century (Bluyssen, 2009), Fanger and Humphreys' findings in the 1970s clarified the gap between these two distinct approaches. In 1970, Fanger introduced the steady state theory. He experimented with the 'heat balance' process in order to find an 'optimum temperature' that would indicate comfort (Fanger, 1970). The steady state theory is based on the heat exchange between the human body and the surrounding thermal environment (Dufton and Marley, 1936, Houghten et al., 1941, Fanger, 1970) therefore it is also called the 'heat balance' theory (Fanger, 1970, Bluyssen, 2009). This is a scientific view of comfort generated from experiments in the laboratory (Fanger, 1970). In 1973, Nicol and Humphreys challenged the steady state theory and introduced the adaptive comfort theory (Nicol and Humphreys, 1973b). They criticised the experimental chambers for defining an optimum thermal condition and for ignoring the context (Nicol and Humphreys, 1973b). The adaptive comfort theory is based on the adaptive nature of the human. When the thermal environment changes, the person adapts to the change (Humphreys and Nicol, 2002a). This natural tendency, which influences user behaviour and their active role, is the basis of adaptive comfort theory. This approach is mainly researched in the actual building in order to investigate the natural behaviour of the occupant towards the thermal environment in a real life context (Bedford, 1936, Humphreys and Nicol, 2002a).

3.2.1.1. Steady State Theory and Experimental Chambers

This concept came to life mainly after the invention of the refrigerator, which was aimed at keeping food products fresh. The same principle was experimented and applied to building occupants to improve their comfort condition (Nicol et al., 2012). Fanger published the *Thermal Comfort* book in 1970 after five years of experimenting in a laboratory (Fanger, 1970). He introduced thermal comfort as a product in his book stating that 'in all cases thermal comfort is the 'product', which is produced and sold to the customer by the heating and air conditioning industry' (Fanger, 1970). He aimed to find an 'optimum' temperature for thermal comfort and introduced the 'steady state' theory (Nicol and Humphreys, 1973b). This theory is based on keeping the thermal conditions steady in order to achieve thermal comfort. For instance, air conditioning systems are very good examples of this theory. They are usually designed to keep the temperature within a narrow and limited range, usually 22 ± 2 °C (McCartney and Nicol, 2002). Fanger's approach focused on the physical reaction of the human body towards changes in the thermal environment of a given condition in a laboratory. Through the experimental chambers, he acquired knowledge of the relationship between the body and environmental factors, such as the temperature and humidity (Fanger, 1970). He

applied a scientific approach to measure the heat exchange between the body and its immediate thermal environment. Fanger's heat balance equation is as follows (Fanger, 1973):

$$\begin{aligned} \frac{M}{A_{Du}}(1 - \eta) - 0.35[1.92t_s - 25.3 - P_a] - \frac{E_{sw}}{A_{Du}} - 0.0023 \frac{M}{A_{Du}}(44 - P_a) \\ - 0.0014 \frac{M}{A_{Du}}(34 - t_a) &= \frac{t_s - t_{c1}}{0.18 I_{c1}} \\ &= 3.4 \times 10^{-8} f_{c1}[(t_{c1} + 273)^4] + f_{c1} h_c(t_{c1} - t_a) \end{aligned}$$

According to Bluysen, this is the most simple heat balance equation among the other existing models (Bluysen, 2009). She simplifies Fanger's heat balance equation as follows (Bluysen, 2009):

$$\text{Energy supply} + \text{Energy produced} = \text{Energy removed}$$

The 'energy supply' is the impact of the immediate thermal environment on the body, when it receives energy through radiation, convection, conduction and evaporation. The 'energy produced' is the energy that is released based on metabolic rate. The 'energy removed' is the energy that is released by physical activities as well as body heat loss by radiation, convection, conduction and evaporation to the surrounding environment. When the immediate air temperature is less than the skin temperature and no significant radiation is available, energy supply is eliminated from the equation (Bluysen, 2009). Although this simplified equation seems easy, many variables including clothing, metabolic rate, temperature, humidity, air velocity and mean radiant temperature that are included in Fanger's equation are not presented in Bluysen's simplified model.

Through calculating these variables, the overall thermal sensation of a person is calculated (Bluysen, 2009). When thermal sensation of a large group of people is calculated, it is called the 'predicted mean vote' or PMV (Fanger, 1970). The seven point scale that ranges from cold to hot is used for this survey. In addition, Fanger's heat balance equation is used in many studies to investigate occupants' 'predicted percentage of dissatisfaction' or PPD in a given environmental condition (Fanger, 1970, Bluysen, 2009). Fanger discovered that 'for practical purposes the neutral temperature is invariant'. For instance, age, sex, obesity and acclimatisation do not have a significant impact on it (Oseland and Humphreys, 1994).

The ‘oversimplifications of person-environment interactions’ of the experimental model is criticised and the practical application of its findings has been questioned (de Dear et al., 1991b). In order to highlight the importance of context, Nicol and Humphreys introduced field studies of thermal comfort where the research takes place at the actual building so that the context of real life is reflected in the study. They questioned the application of optimum temperature in different workplace contexts (Nicol and Humphreys, 1973b). Through the field studies, they discovered that building occupants are comfortable at a wider range of thermal conditions, which was predicted through experimental models (Humphreys and Nicol, 2002a). These experiments overestimate the feelings of warmth and coldness in temperatures outside the predicted range of comfort (Oseland and Humphreys, 1994). Oseland reports that Fanger’s predicted mean vote (PMV) model is not accurate for activities that are not deskbound (Oseland and Humphreys, 1994). In the context of daily life, occupants’ perception and the time of exposure to that condition influence their comfort level (Berglund, 1984).

3.2.1.2. Adaptive Comfort Theory and Field Studies of Thermal Comfort

Based on the field studies of thermal comfort, Nicol and Humphreys introduced the adaptive comfort theory in contrast with the steady state theory. Adaptive comfort is based on the fact that people adapt to the changes of the thermal environment outside the steady state comfort zone by adjusting themselves to the environment (McCartney and Nicol, 2002). The adaptive comfort principle indicates that ‘if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort’ (Nicol and Humphreys, 1973b, Nicol et al., 2012). This approach considers users active rather than passive, as they actively change their behaviour to restore their comfort (Ackerly and Brager, 2013). According to the climatic conditions of the buildings, occupants change their behaviour and adapt to the conditions (Nicol and Humphreys, 1973b, Humphreys and Nicol, 2002a). A simple example of behaviour is putting on or off layers of clothing to adjust body temperature to the thermal environment. The adaptive model allows occupants to identify and respond to the building failure. It recognises people’s desire and their effort to regain comfort and satisfaction and applies this knowledge to understanding thermal comfort (Hawkes, 2002).

Based on contextual studies, Humphreys demonstrated how people’s tolerance of the indoor conditions is related to the outdoor conditions (McCartney and Nicol, 2002), climatic region (Nicol et al., 2012) and time (Nicol and Humphreys, 1973b). Time is an important factor in changing behaviour, as it has an adverse impact on the behaviour. For instance, if the air temperature changes over a short period of time, the changes of clothing layers may not be

sufficient. In this case, the person is more likely to change their activities in order to restore the previous thermal sensation (Nicol and Humphreys, 1973b).

Bluyssen considers the steady state PMV model in air conditioned buildings ‘remarkably successful’ (Bluyssen, 2009). In contrast, predicting the satisfaction and comfort of occupants of naturally ventilated buildings is difficult as many parameters, such as psychological adaptation, influence comfort. The adaptive comfort theory was criticized for being too complicated (Bluyssen, 2009).

3.2.2. Comfort Zone vs. Adaptive Opportunity

The steady state and adaptive comfort theories present different solutions to the problem of how to provide thermal comfort for the occupant. The steady state model presents the universal or standard ‘comfort zone’ based on the ‘optimum temperature’. In contrast, the adaptive comfort model introduces the ‘adaptive opportunity’ based on the active role of the user.

3.2.2.1. Standard Comfort Zone

Thermal comfort standards are useful in building design so that the indoor thermal environment is closer to the acceptable range (Humphreys and Nicol, 2002a). Olgay describes the comfort zone as ‘a range of climatic conditions that physical and mental activity is on the peak’ (Olgay, 1992), presented in Figure 23. The standards to assess thermal comfort originated from the steady state or heat balance theory, which are examined in experimental chambers (de Dear and Brager, 1998, ASHRAE, 1992, ISO, 1994). However, recent thermal comfort standards consider both approaches. They introduced the ‘adaptive comfort standard’ for naturally ventilated buildings (ASHRAE, 2004, CEN, 2005, Nicol and Humphreys, 2005, Bluyssen, 2009). Therefore the impact of outdoor thermal conditions is considered in the new thermal standards (CEN, 2005, ASHRAE, 2010).

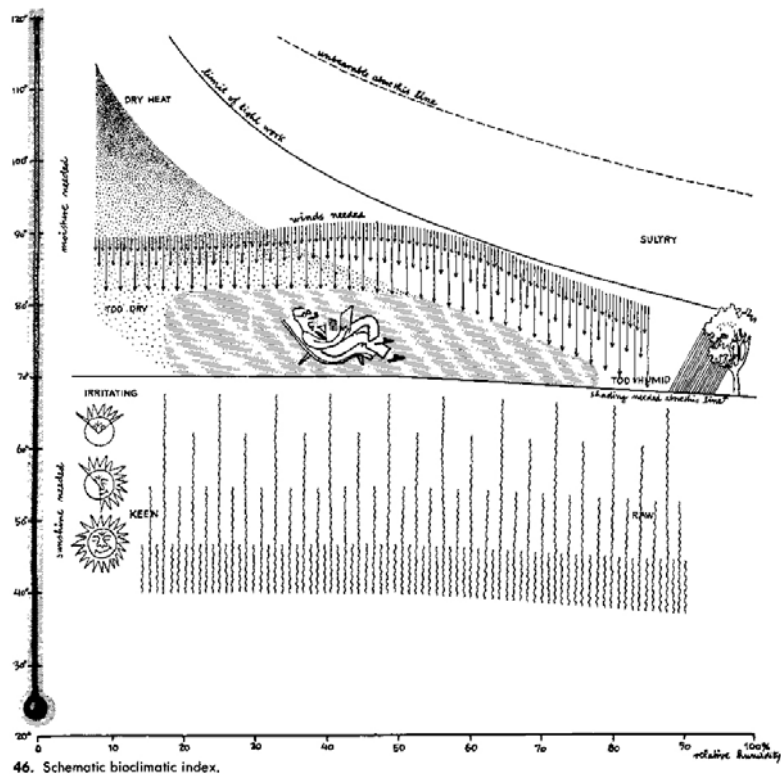


Figure 23: Bioclimatic chart (Olgay, 1992)

Although Nicol and Humphreys do not agree with all aspects of thermal standards, they explain that ‘thermal comfort standards are required to help building designers to provide an indoor climate that building occupants will find thermally comfortable’ (Humphreys and Nicol, 2002a). They explain that workplaces should be designed according to the thermal comfort standards (Humphreys and Nicol, 2002a). The further indoor thermal conditions are from the standard comfort zone, the more likely it is that occupants will be uncomfortable (Nicol and Humphreys, 2005). They stress the benefit of a good comfort standard for buildings as ‘indoor comfort conditions to help decide on the design and the sizing of heating or cooling systems or passive strategies’ (Humphreys and Nicol, 2002a). In their view, a good comfort standard indicate the following (Humphreys and Nicol, 2002a):

- ‘The indoor environments most likely to provide comfort
- The range of acceptable environments
- An acceptable rate of change’

There are different comfort standards, such as the CEN Standard 15251, the ISO Standard 7730, and the ASHRAE Standard 55. However, the majority of the worldwide thermal comfort studies, such as recent Chinese, Indian, Asian, European, Canadian, and American studies, discuss the ASHRAE thermal comfort standard (Fanger, 1973, Whittle, 1986, Schiller

et al., 1988, de Dear et al., 1991a, Fountain et al., 1994, Humphreys, 1996, Bauman and Arens, 1996, de Dear and Brager, 1998, Fanger et al., 1998, Bauman, 1999, Raw et al., 2001, Brager and De Dear, 2001, de Dear and Brager, 2002, Toftum, 2002, Chao and Wan, 2004, Zagreus et al., 2004, Olesen and Brager, 2004, Melikov, 2004, Haves et al., 2004, Rutman et al., 2005, Nicol and Roaf, 2005, Huizenga et al., 2006b, CIBSE, 2006b, Huizenga et al., 2006a, Fard, 2006, van Hoof and Hensen, 2007, CIBSE, 2008, Moujalled et al., 2008, Poirazis et al., 2008, Brager and Baker, 2008, Kosonen et al., 2008, Nicol and Humphreys, 2009a, Brager and Baker, 2009, Joo-Young et al., 2009, Kang et al., 2010, Orosa and Oliveira, 2011, Singh et al., 2011, Nicol and Wilson, 2011, Nicol, 2011, Zhang et al., 2011, Chan, 2011, Humphreys et al., 2011, Humphreys, 2011, Sourbron and Helsen, 2011, Emmerich et al., 2011, de Dear, 2011, Moezzi and Goins, 2011, Cigler et al., 2012, Halawa and van Hoof, 2012, Cole et al., 2012, Wang et al., 2013, van Marken Lichtenbelt and Kingma, 2013, Schellen et al., 2013, Schiavon et al., 2013). The ASHRAE uses the seven point scale system to survey thermal sensation, comfort and satisfaction as follows (ASHRAE, 2009):

- Thermal sensation; cold, cool, slightly cool, neutral, slightly warm, warm, and hot
- Thermal comfort; very uncomfortable, uncomfortable, slightly uncomfortable, neutral, slightly comfortable, comfortable, and very comfortable
- Thermal satisfaction; very dissatisfied, dissatisfied, slightly dissatisfied, neutral, slightly satisfied, satisfied, and very satisfied

This scale considers -3 as the feeling of ‘cold’, 0 as ‘neutral’, and +3 as ‘hot’ (ASHRAE, 2004). The ASHRAE seven point thermal sensation scale to assess thermal comfort is widely used and discussed in thermal comfort studies (Auliciems and Szokolay, 1997, Palmer and Rawlings, 2002, Charles, 2003, Nicol and Humphreys, 2005, Zhang et al., 2005, Arens et al., 2006, Humphreys and Nancock, 2007, Cheong et al., 2007, Arens et al., 2010, Liu et al., 2012, Bos and Love, 2013, Leyten et al., 2013). Based on the research on the ‘neutral thermal sensation’, the ASHRAE Standard 55-2010 has introduced the standard ‘comfort zone’, as presented in Figure 24. In order to evaluate the thermal condition of a room, the thermal measurements of the room are compared with the graph in Figure 24. Relative humidity, air velocity and operative temperature are required. The latter is a combination of the dry bulb air temperature and mean radiant temperature. The calculations are further explained in section 7.2.3, using the ASHRAE Thermal Comfort Tool.

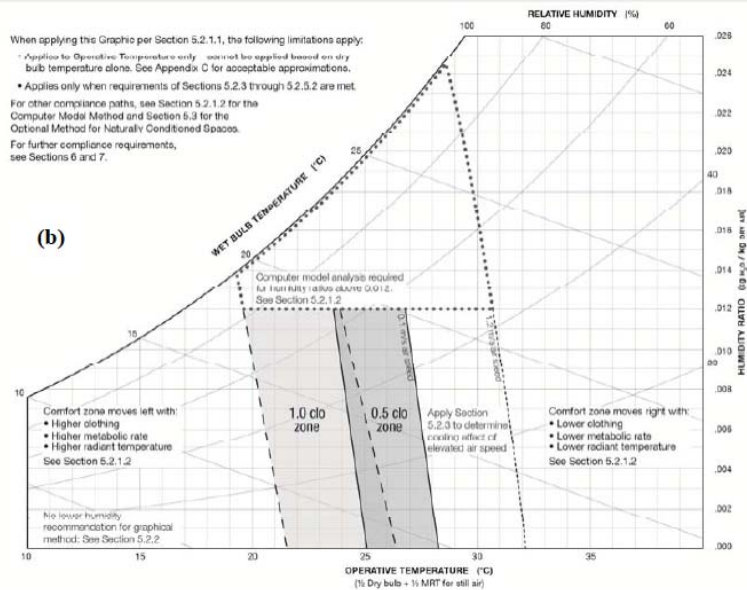


Figure 5.2.1.1 Graphic Comfort Zone Method: Acceptable range of operative temperature and humidity for spaces that meet the criteria specified in Section 5.2.1.1 (1.1 met; 0.5 and 1.0 clo)—(a) I-P and (b) SI.

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Figure 24: ASHRAE Standard 55-2010, comfort zone (ASHRAE, 2010), calculated based on operative temperature (combination of dry bulb air temperature and mean radiant temperature) and relative humidity

Comfort standards have been criticised (Humphreys and Nicol, 2002b). The ASHRAE Standard 55-2010 is not based on the active role of the user. However, the ASHRAE admits that comfort ‘depends on behaviours that are initiated consciously or unconsciously and guided by thermal and moisture sensations to reduce discomfort’. For instance, people may change their clothing layers, activity, location, posture, thermostat or they may open a window, complain or leave (ASHRAE, 2009). The comfort standards claim to apply to a worldwide context of different regions, cultures and building types (de Dear and Brager, 1998). Brager explains that ‘these biophysical relationships have been assumed to be universally applicable across all building types, all climate zones, and all populations’ (Fanger, 1970, Brager and De Dear, 2001). Bluysen explains that for the occupant an ideal workplace is where everybody is satisfied (Bluysen, 2009). The ASHRAE Standard 55-2004 aims at satisfying 80% to 90% of the occupants (ASHRAE, 2004). However, many researchers claim that no fixed temperatures are universally accepted (Humphreys, 1972, Baker and Standeven, 1995, Nicol, 1995, Humphreys, 1996, Baker and Standeven, 1997, Humphreys, 1995) . Humphreys explain that ‘people differ in the room temperatures they desire’ (Humphreys and Nancock, 2007). Olesen argues that comfort standards should not be used worldwide, but rather should be based on contextual differences in perceiving the thermal environment (Olesen, 2004).

Baker indicates that ‘in spite of the adoption of laboratory-derived comfort criteria for international standards, such as ISO 7730, there is growing evidence that occupant satisfaction with the thermal environment in real buildings is only poorly correlated with adherence to these standards’ (Baker and Standeven, 1995). Although the experimental equations to predict comfort are widely used by different standards, their results do not probably apply to the actual buildings (Humphreys and Nicol, 2002a, Humphreys and Nicol, 2002b). Other researchers also report the inaccuracy of the comfort standards (Baker and Standeven, 1997, de Dear and Brager, 1998, de Dear and Brager, 2001, Borgeson and Brager, 2011, Schellen et al., 2013). Schellen reports that operative temperature, which is used in the comfort standards, is not sufficient to evaluate thermal comfort (Schellen et al., 2013). Nicol and Humphreys explain that thermal standards have ignored the sustainable criteria. They recommend that future standards assess ‘the characteristics of a building, in terms of controls and building management, in relation to the local climate’, rather than ‘specifications of the indoor thermal climate’ (Humphreys and Nicol, 2002a).

Meir explains that the ASHRAE has a contradiction in presenting the comfort zone and defining thermal comfort. The latter is a state of mind and satisfaction, but ASHRAE leaves this open to interpretation (ASHRAE, 2009). However, the comfort zone is very precise with clear boundaries. Meir suggests that comfort is not so ‘clear cut’ (Meir et al., 2009). Other studies show that comfort is more complex than is suggested by comfort standards (Pati et al., 2006) Meir’s recommendation is to ‘bring thermal comfort out of what has been assumed in recent decades to be the task of HVAC engineers’ (Meir et al., 2009).

3.2.2.2. Neutral Thermal Sensation

Zhang states that ‘the comfort literature tends to focus on neutral and optimal temperatures’ (Zhang et al., 2011). Hawkes’ definition of thermal comfort is based on the ‘neutral thermal sensation’ (Hawkes, 2002). The ASHRAE seven point scale to assess thermal comfort is based on the ‘neutral thermal sensation’ (ASHRAE, 2010), presented in section 3.2.2.1. All the measurements, calculations and assumptions of thermal comfort are on this basis, such as Figure 25. The ASHRAE states that ‘acceptability is determined by the percentage of occupants who have responded neutral or satisfied (0, +1, +2, or +3) with their thermal environment’ (ASHRAE, 2009).

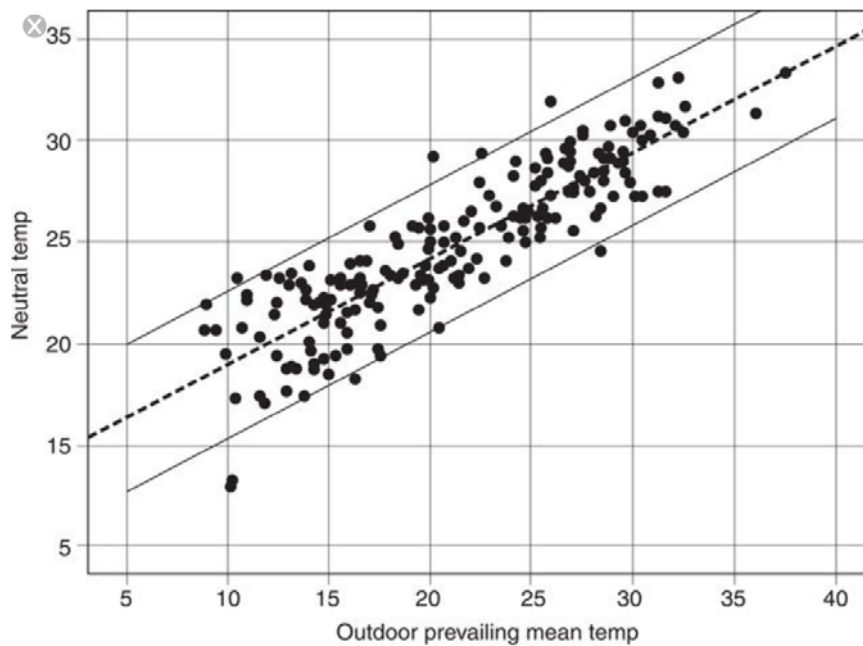


Figure 25: ‘Scatter of neutral temperature and the prevailing mean outdoor temperatures in buildings in free-running mode. Data collected from field surveys since 1978’ (Nicol et al., 2012)

Humphreys questions the application of the ‘neutral thermal sensation’, as he asks: ‘Do people want to feel neutral?’ (Humphreys and Nancock, 2007). De Dear also explains that using the ‘neutral thermal sensation’ on the PMV seven point scale ‘says nothing about whether the occupants are actually going to like it’ (de Dear, 2011). Humphreys reveals that ‘the data contain 868 comparisons of the actual and the desired sensation. On 57% of occasions the desired sensation was other than “neutral”’. He reports that ‘there were significant differences among the respondents in the thermal sensations they desired, confirming that some characteristically preferred to feel warmer than others’. He concludes that ‘if there is sufficient adaptive opportunity, people who feel ‘slightly warm’ perhaps desire at that time to feel ‘slightly warm’, while people who feel ‘slightly cool’ perhaps desire to feel ‘slightly cool’, and so on’. Han demonstrates that ‘people in hot climates may prefer thermal state as ‘slightly cool’, while people in cold climates may use the words ‘slightly warm’ to denote their thermal preference’ (Han et al., 2005). Finally, Humphreys questions the accuracy and application of the findings in the field of thermal comfort that are on the basis of the ‘neutral thermal sensation’, such as comfort standards (Humphreys and Nancock, 2007).

Some new scales are introduced to cover the difficulties of the ASHRAE seven point scale, such as ‘much too cool, too cool, comfortably cool, neutral, comfortably warm, too warm and much too warm’ (Nicol and Humphreys, 2009b). Humphreys explains ‘the need to ascertain more precisely the desired thermal sensation on the scale led researchers to supplement it with

a scale of thermal preference, which asked people whether they would prefer to feel warmer or cooler, or whether they desired no change' (Humphreys and Nancock, 2007). With the supervision of Humphreys, Nicol or de Dear, recently advanced research in thermal comfort is shifting away from the 'neutral thermal sensation' (Rijal et al., 2009, Lee et al., 2009, Arens et al., 2010, de Dear, 2011, Humphreys et al., 2011, Bos and Love, 2013). However, the majority of research is still based on thermal neutrality (Liu et al., 2012, Cigler et al., 2012, van Marken Lichtenbelt and Kingma, 2013, Schellen et al., 2013, Indraganti et al., 2013).

3.2.2.3. Adaptation

The history of mankind starts from a naked human who lived in nature by adapting to it (Banham, 1984). Mankind survived the harsh conditions of the environment, from deserts to the ice age. The key reason for this survival is the ability to adapt to the changes of the environment (Roberts, 2009). This adaptation to natural forces led to success in the process of biological natural selection (Hawkes, 2002). People learned to build tents to shelter from the rain and the cold (Banham, 1984). After some time they succeeded in constructing more permanent structures such as houses. Vernacular architecture often shows environmental adaptation in the form of buildings and cities (Hawkes, 2002). Finally in the modern period people went so far to adjust the indoor thermal environment to their needs by applying control systems (Banham, 1984).

3.2.2.4. Expectation

Although the early human survived because of the ability to adapt, is the situation still the same? Do people adapt to the environment because they like it or because they have to? Do people still want to adapt to the indoor environment or do they expect the environment to be comfortable in the first place? Do people expect the thermal environment to be adjusted according to their needs? Has people's expectation increased? Moezzi questions whether this is just a simple expectation or whether it has become the reality? Currently the problem in advanced societies is no longer basic requirements, such as food and shelter, but rather quickly becomes 'about nearly everything' (Moezzi, 2009).

Goins explains that 'when a mismatch occurs between users' expectations and operations processes, then complaints can arise' (Goins and Moezzi, 2013). Hellwig recognises different categories of user expectation regarding the building (Hellwig and Bux, 2013). Indraganti states that thermal acceptability is related to user expectation (Indraganti et al., 2013). Moezzi

states that people's expectations for a refined and controlled thermal environment is increasing. Based on Parkhurst's article on cars (Parkhurst and Parnaby, 2008), Moezzi explains that 'after the lack of the control of the physical environment and other stresses of office life, it seems very human that office workers will enjoy the thermal, acoustic, and physical control afforded by the personal car and learn to use high levels, because they can and because it is pleasurable' (Moezzi, 2009). Recent cars provide a high degree of control over the thermal environment, such as the ability to adjust the air temperature, air velocity and seat temperature separately for individual passengers and to warm up the seat. Moezzi explains that after a day of working in an office at the mercy of external controls, finally the individual finds comfort in their car with personal thermal settings (Moezzi, 2009). As discussed in section 3.1.4, Nicol and Oseland explain that a change of one or two degrees is not expected to cause discomfort, but anything beyond that may do (Oseland and Humphreys, 1994, Nicol et al., 2012).

3.2.2.5. Adaptive Opportunity

The adaptive comfort principle is about the occupant adapting to the changes of the thermal environment (Nicol et al., 2012). However, adaptive opportunity is about the building adjusting its thermal environment to meet occupants' needs (Baker and Standeven, 1995). Adaptive opportunity is the flexibility of a building to provide control for users so that they can adjust the environment to their needs (Humphreys, 1996, Leaman et al., 1998). 'An environment with high adaptive opportunity is likely to prove more comfortable than one with low opportunity, because people will take advantage of the actual and potential variations in room temperature' (Baker and Standeven, 1995, Humphreys, 1996).

What is the relationship between adaptive comfort, adaptive opportunity and ventilation systems? Although never precisely explained, whenever Nicol and Humphreys mention 'adaptive comfort' it is followed by naturally ventilated buildings and the ability of the occupant to adjust to the natural thermal changes in these buildings (Nicol et al., 2012). Humphreys criticises the older ASHRAE standards as being relevant only to air conditioned buildings, rather than naturally ventilated and sustainable buildings. Such buildings adjust the indoor climate to the outdoor conditions (Humphreys and Nicol, 2002a). On this basis, the ASHRAE Standard 55-2004 introduces adaptive comfort only for natural ventilated buildings (ASHRAE, 2004). Is adaptive comfort only relevant to naturally ventilated buildings?

The description of adaptive opportunity is broad. It explains how buildings provide the opportunity for occupants to adjust the thermal environment (Baker and Standeven, 1995,

Humphreys, 1996), which may apply to naturally as well as mechanically ventilated buildings. Generally the aim of mechanical ventilation, particularly air conditioning, is to provide a uniform and steady thermal environment for the building (Nicol et al., 2012). However, these systems can be adjusted according to occupants' needs, such as in the Scandinavian personal offices. Humphreys states that standards 'need to specify the adjustment potential of the controls, for range, speed and stability' (Humphreys, 1996). Leaman recommends the use of effective natural ventilation with the opportunity to use mechanical ventilation when required (Leaman et al., 1998). Leaman reports that users are more satisfied with naturally ventilated buildings, because they can apply control and immediately feel the change although the overall quality may not be so different from the air conditioned buildings (Bordass et al., 1994, Leaman and Bordass, 1996). He explains that complex systems, such as air conditioned buildings, usually have a better performance, but lower user satisfaction (Leaman et al., 1998).

3.3. Individual Thermal Control

Melikov highlights individual differences in perceiving the thermal environment. He explains that ‘the heating, ventilation and air conditioning (HVAC) of buildings today is designed to provide a uniform room environment. However, large individual differences exist between occupants in regard to physiological and psychological response, clothing insulation, activity, air temperature and air movement preferences, etc. Environmental conditions acceptable for most occupants in rooms may be achieved by providing each occupant with the possibility to generate and control his/her own preferred microenvironment’ (Melikov, 2004). Arens reports the relationship between occupants’ individual thermal control and ‘acceptance of their state’ (Arens et al., 2010). Kroner reports high user satisfaction when individual thermal control is applied (Kroner, 2006).

Nicol and Humphreys suggest that workplace design should focus on thermal control systems and their operation rather than on providing an optimum thermal environment (Nicol and Humphreys, 1973b). When buildings are designed to provide adaptive opportunities for their users, people tend to accept a wider range of thermal conditions, simply because they can adjust the environment (Baker and Standeven, 1997). Although building management may prefer automatic systems to make the thermal system easier, with no user interfering with it. However, in practice the opposite happens as occupants complain. ‘Less local control, more discomfort, and more management time to respond to complaints’ (Bordass et al., 1993). Hitchings argues that ‘instead of talking about what temperatures feel neutral in particular places when we have already accepted this to be dynamic, the ambition may now be to reveal which techniques people are willing to employ to get through particular periods more sustainably’ (Hitchings, 2009). Hawkes includes providing ‘users of buildings with the maximum opportunity to exercise control over their environment’ as one of the main principles of the ‘selective’ approach. The environmental control is based on automatic and manual means to control the environment through a mixture of artificial and natural features. Hawkes explains that the manual control is only for ‘fine-tuning’ in case of a system failure (Hawkes, 2002).

Bauman reports demands for temperature control from workplace tenants and their dissatisfaction when this feature is not provided (Bauman, 1999). Bordass explains that users require comfort and individual control with a quick response to adjust the thermal environment when they feel uncomfortable (Bordass et al., 1993). Baker recommends that buildings ‘provide adaptive opportunity by environmental variety and user friendly building controls, and allow visual access to outdoor climatic conditions and a simple ‘readable’

architectural design’ (Baker and Standeven, 1995). Leaman states that ‘perceptions of good control are often associated with better comfort and satisfaction’. Responsive, accessible, simple and user friendly environmental control systems increase user satisfaction (Leaman, 1993, Leaman, 1996). He discusses the idea that the “comfort” perception is dependant on the speed of building response to the perceived discomfort condition’ (Leaman, 1996). He reports that ‘buildings which are both thermally comfortable and have “rapid response systems” are almost invariably well-liked by occupants, even if the buildings themselves are scruffy or architecturally undistinguished’ (Leaman, 2003).

3.3.1. Different Types of Environmental Control

The *CIBSE Guidance Handbook* on control systems explains that “controls” is a more generic term, used for a collection of individual control elements, from sensors, valves and timers to control panels. It is often also used to mean a control system’ (CIBSE, 2005). It indicates that ‘controls are needed for all the various services and systems within the building’ (CIBSE, 2005), although mainly ‘automatic control operation’ systems are considered:

- Heating
- Cooling
- Ventilation
- Lighting
- Building electrical services
- Fire fighting and alarm systems
- Security systems
- Transport systems
- Water supply systems

In this research environmental control over heating, cooling, ventilation, noise, and lighting are discussed. However, many researchers report that temperature is the main factor that influences user comfort (Leaman and Bordass, 2005, Auliciems and Szokolay, 1997, Bauman, 1999, de Dear et al., 1991b, Nicol et al., 2012). Therefore particular emphasis is given to thermal control, which includes heating, cooling and ventilation. Various control systems exist, such as openable windows, thermostats, fans and switches.

3.3.2. Impact of Thermal Control

Bluyssen indicates that thermal control ‘has positive effects far beyond just thermal comfort’ (Bluyssen, 2009). In this section, the impact of thermal control on user satisfaction, comfort, health, and productivity as well as energy use of the building are explained.

There is a distinction between the meaning of comfort and satisfaction. Comfort refers to physical and psychological (Kolcaba and Kolcaba, 1991) ease and lack of pain, while satisfaction is mainly the psychological aspect of fulfilling one’s wishes and expectations. Satisfaction is a more general term, as a person is already at ease and happy to accomplish their expectations. Satisfaction is defined as the ‘pleasure or positive emotional state resulting from the appraisal’ of one’s experience (Locke, 1976). In addition, Meir explains that productivity and health should be distinguished, as management are concerned with productivity while occupants are concerned about health (Davara et al., 2006, Meir et al., 2009).

3.3.2.1. Satisfaction

Researchers report that environmental control, (Leaman, 1996, Bauman, 1999, Huizenga et al., 2006a, Wagner et al., 2007) in particular access to a window, increases user satisfaction, due to an outside view and natural light (Newsham et al., 2009). Brager describes when users have direct control over the windows in offices with a combination of natural and mechanical ventilation systems they have higher satisfaction levels (Brager and Baker, 2009). Lee also reports that personal environmental control increases job satisfaction (Lee and Brand, 2005).

3.3.2.2. Comfort

Researchers report that individual thermal control increases user comfort (Leaman, 1996, Melikov, 2004, Arens et al., 2010). Bordass suggests that modern environmental control systems are more likely to increase user comfort (Bordass et al., 1993, Bordass et al., 1994). He explains that ‘individual occupants require systems not only to provide comfortable conditions, but also to respond rapidly to alleviate discomfort when it is experienced’ (Bordass et al., 1993).

3.3.2.3. Health and Sick Building Syndrome

Marmot explains that control and health are related (Marmot, 2010). Rollins and Swift report that lack of environmental control causes building related symptoms. They highlight the

importance of control as ‘to be in control and not to be at the mercy of external forces’ (Rollins and Swift, 1997). Marmot reports the relationship between control, demand and support at work (Marmot, 2004). He explains that low control at work and lack of support from supervision and co-workers have a high risk of so called ‘metabolic syndrome’, which is a precursor to diabetes and potentially heart diseases (Marmot, 2010). Rayner reports that ‘people with most symptoms have least perceived control over their environment’ (Rayner, 1997). The next section explains sick building syndrome and its relationship with the thermal environment.

3.3.2.3.1. Sick Building Syndrome

In the 20th century, new science and technology on the one hand improved the quality of the workplace in terms of lighting, acoustics, electricity, heating, and cooling. On the other hand, the new material and mechanical improvements introduced diseases such as Legionnaires’ disease, formaldehyde and other building related diseases to the workplace (Bluyssen, 2009). In the 1980s difficulties with the health related issues in office buildings increased and the term sick building syndrome (SBS) was introduced. Sick building syndrome is commonly used to describe poor indoor air quality in office buildings (Niemela et al., 2006). However, different factors influence sick building syndrome, such as physical and psychological factors as well as age, sex, working position and social status (Bluyssen, 1992, Bluyssen, 2009). It may cause mild symptoms (Carnevale and Rios, 1995) such as tiredness, lose of concentration and depression. In addition, infections and allergic reactions such as irritated skin, sore throat, dry or watery eyes are possible bodily responses to an unhealthy environment as well (Bluyssen, 2009). In extreme cases sick building syndrome is responsible for Legionnaires’ diseases, cardiovascular problems and cancer, and in the worse cases it causes injury and death (Carnevale and Rios, 1995). The common symptoms include lethargy, headaches, dry skin, nasal, eye and mucous symptoms (Finnegan et al., 1984). Sick building syndrome not only affects the employees’ wellbeing, but also influences the productivity and efficiency of the organisation (Eaton, 1997), since it increases ‘absenteeism, hospitalisation and in severe cases long term health issues’ (Meir et al., 2009).

In the developed countries, people spend over 80% of their time in buildings living, working and studying (Meir et al., 2009). Therefore their health is dependant on the indoor condition of the buildings they occupy (Pearson, 1989, Meir et al., 2009). Meir states that ‘health is often taken for granted by architects when designing a glamorous building, eventually it receives insufficient consideration, such as poor indoor air quality and indoor environment quality’ (Meir et al., 2009). Toftum reports that the thermal environment affects building

related symptoms (Toftum, 2002). When the indoor environment is considered unhealthy, the body parts react to the source, such as light, heat, cold, and draught (Bluyssen, 2009). Although ASHRAE Standard 55-2004 does not indicate any lower limit for the humidity level, it mentions that low humidity, when dew point is less than 0°C, makes the skin and mucus surfaces dry, and eventually causes dry nose, throat, eyes, and skin (ASHRAE, 2009).

There is a debate about whether air conditioning is responsible for sick building syndrome, as the latter was introduced right after the application of the former. The relationship between the type of ventilation and sick building syndrome has been reported as contradictory by different researchers (Mendell and Smith, 1990). “Although researchers have compared air conditioned buildings to naturally ventilated offices in respect of building related symptoms (Jaakkola and Miettinen, 1995), any such findings concerning the relationship between ventilation typologies and sick building syndrome have been contradictory (Mendell and Smith, 1990). Many report a higher risk of building related symptoms in air conditioned buildings (Finnegan et al., 1984, Jaakkola et al., 1991, Rollins and Swift, 1997, Brasche et al., 2001)” (Shahzad, 2013a). Jaakkola reports that mechanical ventilation without air conditioned offices have higher risk of ocular, nasal, pharyngeal symptoms and lethargy (Jaakkola and Miettinen, 1995). Brasche reports that many employees in air-conditioned office buildings complain about the skin, mucous membranes and the nervous system (Brasche et al., 2001). Recirculation of the air on a large scale might cause sensory confusion and strain on the system (Jouni et al., 1994). “However, others argue that energy efficient buildings may suffer more from Sick Building Syndrome due to the high level of insulation to maintain temperature allied to a lack of ventilation (Rayner, 1997). The World Health Organization identifies buildings that ‘are energy efficient, kept relatively warm and have homogeneous thermal environment’ as having a higher risk of Sick Building Syndrome (Rayner, 1997, Chan, 2011)” (Shahzad, 2013a).

“Several studies show lower symptoms in naturally ventilated buildings (Jaakkola and Miettinen, 1995). However, there is a hazard in having an automatic expectation assuming that naturally ventilated buildings have a reduced incidence of sick building syndrome. Jaakkola’s research in Scandinavia reveals that air conditioned buildings do not increase symptoms ‘when functioning properly’ (Jaakkola et al., 1991)” (Shahzad, 2013a). Jaakkola reports lower rates of building related symptoms when ventilation rate is increased in mechanically ventilated buildings (Jaakkola et al., 1991). Rayner claims if air-condition systems are designed properly, they can be the best option with lowest rates of building related symptoms (Rayner, 1997).

3.3.2.4. Productivity

Thermal comfort affects mental and physical performance (Oseland and Humphreys, 1994). Many researchers indicate the relationship between the thermal environment and productivity (Olgay, 1992, Carnevale and Rios, 1995, Seppänen and Fisk, 2004). Black reports that decision making increases productivity level (Black, 2006). Studies show that increasing individual control improves health and productivity (Wilson and Hedge, 1987, Bordass et al., 1993, Hawkes, 2002, Martens, 2011). Marten explains that ‘creative thinking leading to insight is more likely with a prepared mind in a mentally relaxing environment where freedom, security and control are deeply experienced’ (Martens, 2011). Bordass reports that temperature has the highest impact on the productivity level (Bordass et al., 1993) and Figure 26 shows the impact of temperature control on productivity.

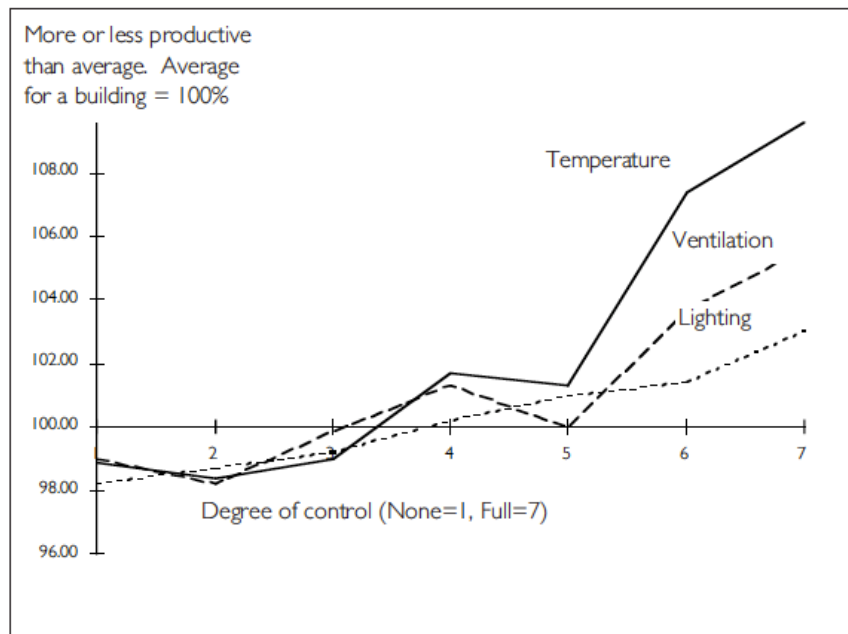


Figure 26: Productivity vs. degree of control (Bordass et al., 1993)

Although most researchers report the relationship between productivity and thermal control, there are contradictions in assessing productivity. Maarleveld reports that ‘satisfaction about the work environment has a fairly limited effect on the perceived productivity, when measured as the percentage of time that people think they are really productive’ (Maarleveld et al., 2009). In contrast, Kroner reports that occupants’ overall satisfaction with their workplace and individual control over the thermal environment improve their productivity up to 16% (Kroner et al., 1992, Kroner, 2006). In a study, Kroner investigated the impact of a high level of individual control over the thermal environment on productivity in the real life context of an office. Productivity was constantly measured by management before and after the move to the new building. Occupants were not aware of being monitored for productivity.

Environmentally Responsive Workstations (ERWs) in this study provided individuals with control over their thermal environment. For instance, every workstation included individual control over ‘the temperature, velocity and direction of air delivered to the desktop through two air diffuser towers; a radiant heat panel located below the desk top; a desk mounted task light; and a sound masking device’. This system proved to increase users’ productivity. When the system was purposefully turned off for duration of a week by the researcher, productivity decreased between 2% to 13%. He revealed that because of the high quality of control over the thermal environment and user satisfaction with the thermal environment, employees refused to work in other companies that would not offer the same control systems (Kroner, 2006).

3.3.2.5. Energy Consumption

In the developed countries, buildings consume 40 to 50% of their energy through thermal performance including lighting, heating, cooling and ventilation (Meir et al., 2009). In selective principle, Hawkes proposes that control systems that are properly designed can reduce the gap between users’ thermal requirements and the physical thermal environment. Such control systems can be efficient (Hawkes, 2002). Bordass states that ‘modern control and energy management systems offer the potential to improve individual comfort and reduce energy consumption at the same time’ (Bordass et al., 1993). Kroner reports that individual control reduces energy consumption although it is not quantified (Kroner, 2006). Bordass explains that buildings which have problems with controls have low user satisfaction and energy efficiency (Bordass et al., 2001b). Hawkes mentions that energy consumption is reduced when individual environmental control is increased (Hawkes, 1982, Bluysen, 2009). Nicol recommends the application of adaptive opportunity in the building design in order to tackle climate change, energy and economic challenges (Nicol and Stevenson, 2013).

3.4. Summary

This chapter discussed the challenge in the field of thermal comfort between the steady state and adaptive comfort theories, which is the main platform on which this thesis operates. These two views follow two separate approaches in achieving thermal comfort, respectively the universal ‘comfort zone’ and ‘adaptive opportunity’.

This research is based on the adaptive opportunity. A body of knowledge exists on environmental control, such as the pattern of use of lights (Mahdavi and Proglhof, 2008) and windows (Brager et al., 2004, Tuohy et al., 2007, Rijal et al., 2007, Huizenga et al., 2006b) as well as the influence of environmental control on users’ comfort and satisfaction (Bordass et al., 1993, Bordass et al., 1994, Leaman and Bordass, 1996, Leaman and Bordass, 2005, Bordass et al., 2007). Nevertheless, Cole reports that investigating individual control over the thermal environment and its impact on user satisfaction is complicated (Cole and Brown, 2009). The comparison between environments with high and low levels of individual control over the thermal environment has not been studied in the field of thermal comfort. This thesis focuses on the impact of individual control over the thermal environment on user satisfaction, comfort, health, and productivity. Chapter Four combines Chapters Two and Three regarding the individual thermal control in the Anglo-Saxon open plan and Scandinavian cellular plan offices.

CHAPTER 4

CELLULAR VS. OPEN PLAN OFFICES

4. Cellular vs. Open Plan Offices

This chapter combines the previous two chapters, regarding the workplace and thermal control. Chapter Two explained the history of office design. It showed that Anglo-Saxon and Northern European countries followed two separate paths based on organisational goals and user demands respectively. The latter includes control over the temperature, an openable window, outside view, natural ventilation and light. Chapter Three discussed the challenge in the field of thermal comfort between the steady state and adaptive comfort theories. It showed their distinct approaches, respectively ‘comfort zone’ and ‘thermal control’.

This chapter focuses on the practical application of these two approaches in the Norwegian cellular and British open plan workplace contexts. The two contexts are compared regarding their design, culture and regulations. Finally, the role of architecture and the future of individual thermal control in the workplace are discussed.

4.1. Two Approaches in Office Design

After World War Two, the UK and Scandinavia followed two separate paths in office design. The UK followed North American office design, modern technological advances and organisational changes. Therefore open plan offices were the main office design in the UK. In contrast, Scandinavians resisted the North American style and their office design was based on workers' rights, which included thermal control. Therefore full autonomy was given to every individual employee and the cellular plan office layout was reintroduced with much higher standards. Figure 27 and Figure 28 show the historic development of the cellular and open plan offices.

Office Concept	Office Philosophy	Period of Time	Number of People
Cellular Office	Representative arrangement	1950s	1-2 persons (Up to 4-6 persons)
Open Plan Office	Organisational flexibility	Mid 60s	>20 workstations
Group Office / Office Landscape	Ergonomic work environment	Late 60s	6-20 workstations
Combi Office	Communicative space structure	1980s	1 person cellular office + multifunctional zone

Figure 27: Development of office philosophies and office concepts in Europe (Harrison et al., 2004) based on (Gottschalk, 1994)






	Bürolandschaft offices	Traditional British speculative offices	New 'Broadgate' type of British speculative office	Traditional North American speculative office	The new North European office
					
No. of storeys	5	10	10	80	5
Typical floor size	2,000sqm	1,000sqm	3,000sqm	3,000sqm	Multiples of 2,000sqm
Typical office depth	40m	13.5m	18m and 12m	18m	10m
Furthest distance from perimeter aspect	20m	7m	9-12m	18m	5m
Efficiency: net to gross		80%	85%	90%	70% (lots of public circulation)
Maximum cellularization (% of usable)	20%	70%	40%	20%	80%
Type of core	Semi-dispersed	Semi-dispersed	Concentrated: extremely compact	Concentrated: extremely compact	Dispersed: stairs more prominent than lifts
Type of HVAC services	Centralized	Minimal	Floor by floor	Centralized	Decentralized: minimal use of HVAC

Figure 28: North American, British, and Northern European office layouts (Laing, 2006)

4.1.1. The Cellular Plan Office

As described in section 2.2.4.6, after the 1960s the Northern European countries resisted the North American managerial concepts, mass production and the open plan office layout. In the 1970s, the Worker's Council in Scandinavia protested in order to protect workers' rights, which included the right to access natural light and ventilation. Van Meel explains that 'the most radical reaction took place in Sweden, where it became common practice to give every employee a private office with individual climate control, daylight and an outside view' (Van Meel, 2000).

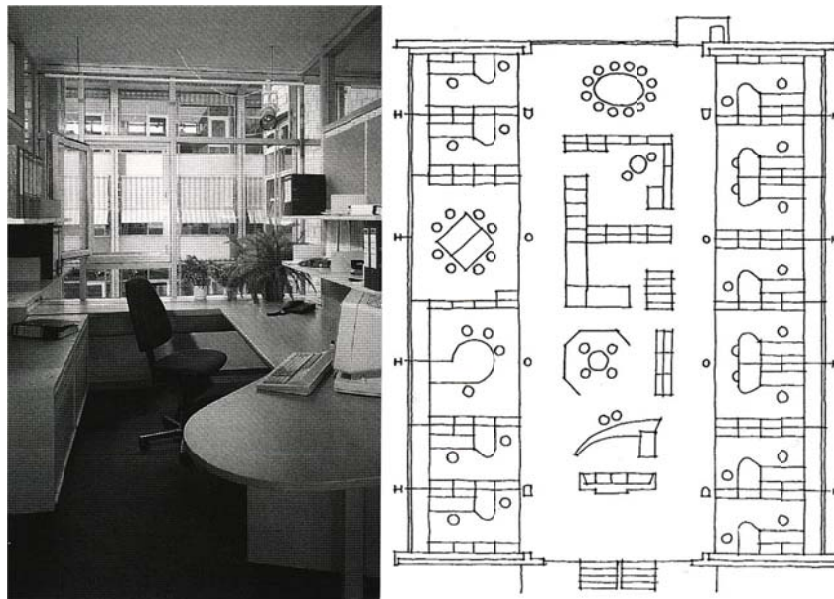


Figure 29: Edding Headquarter, Germany (Van Meel, 2000)



Figure 30: Commerzbank, Germany (Van Meel, 2000)

In order to design offices based on such strict rules, discussed in section 4.2.1, the Scandinavian office layout became highly cellularised in order to provide every occupant with a personal room. The size of every office was approximately 22 m² per person, explained in section 4.2.1. In addition, because every occupant had the right to access an openable window with an outside view, the office layout was designed in the shape of narrow floor

plates or narrow wings (Harrison et al., 2004). This created long corridors with only doors and nameplates on them (Duffy, 1966a), such as Figure 31. Some occupants complained about having to walk long distances to get to the service areas and staircases. Lack of communication and inefficiency in use of space are other disadvantages of the cellular plan office. In addition, the rigid and inflexible layout does not accommodate organisational changes, technological advances and economic challenges (Van Meel, 2000). However, cellular plan offices 'added value to organisational performance' (Laing, 2006). Duffy states that user friendly and 'custom built' offices were built with very high standards (Duffy et al., 1993). Every occupant was provided with individual thermal control so that they could regulate their personal office according to their requirements, explained in section 4.2.1.

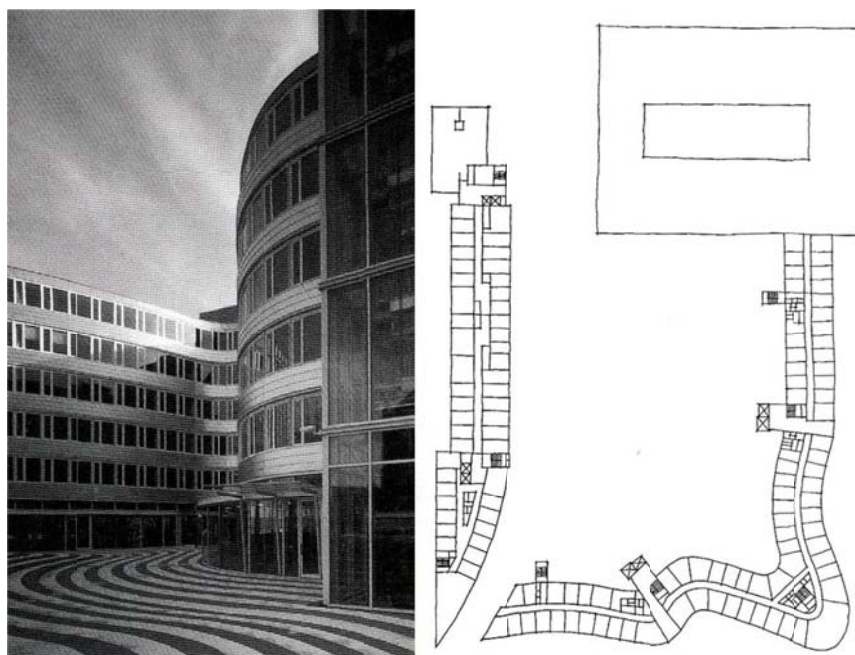


Figure 31: The Hague cellular plan office in Netherlands (Van Meel, 2000)

4.1.2. The Open Plan Office

At the beginning of the 20th century, the managerial and mass production concepts (Hookway, 2009) as well as technological advances, such as telephones and typewriters (Marmot and Eley, 2000), were the foundation of the open plan office. Lee and Brand explain that the Anglo-Saxon open plan layout was introduced as a flexible solution to many of these historic and contemporary challenges (Lee and Brand, 2005). As explained in section 2.2.4.1, the Bürolandschaft or landscape offices, which were based on communication and flow of paperwork, were the early formation of the open plan office. Duffy introduced the Bürolandschaft to the Anglo-Saxon countries. Technological advances drove this new design of the workplace into a flexible open plan layout, suitable for communication and new

technologies (Laing, 2006). The new American layout changed with private rooms for management and an 'open plan' for all (Laing, 2006). The invention of air conditioning (i.e. 1930s) and florescent lights (i.e. 1940s) allowed the possibility of deep open plan offices with no need for natural light and ventilation (Laing, 2006), such as presented in Figure 32. Duffy explains that in an open plan office, 'desks and equipment are arranged in ordered rows. Such offices are often very large, as staff work far from the windows, artificial light and ventilation are required' (Duffy, 1966a). Leaman and Bordass indicate that 'the deeper buildings get, the more worker satisfaction tends to decline' (Bordass et al., 2001a).



Figure 32: The Union Cambridge Headquarters in New York, 1959 (Klein, 1982)

Duffy reports that 'in the Anglo-Saxon world a limited kind of office environment, characterised by skylines from Chicago to Canary Wharf, has been dominant for over a century not because users want it (they are very rarely asked), but because such offices have been convenient to build, to manage and to exchange' (Duffy et al., 1993). Open plan offices in the form of the 'glass box' building were introduced as an international model that could be easily copied anywhere (Van Meel, 2000). Open plan offices were 'highly standardised' and designed for regular office work (Laing, 2006). Duffy explains that American architects 'are no longer paid to think. They cannot afford to invent. There is no time to listen to users. What the supply side dominated system forces them to do is to deliver the same formulaic buildings and interiors, over and over again, only ever more quickly and cheaply' (Duffy, 2001). The British open plan offices were very flexible so they could be rented to any client who required an office (Laing, 2006). However, architects mainly took the responsibility for designing the office 'shell', consequently the lack of 'practical interior design' led to decay of many open plan offices (Duffy, 1992). In addition, the glass façade caused overheating and difficulties in cooling (Van Meel, 2000).

Despite these difficulties as well as the fact that employees did not gain much from the open plan (Van Meel, 2000), organisations gained from this office design (Van Meel, 2000). For instance, ease of supervision, adaptability to change (Duffy, 1992), communication (Allen and Gerstberger, 1973), work and economic efficiency are the advantages in the open plan layout (Kubzansky, 1982, Pile, 1976). However, Duffy explains that users did not find this kind of office popular due to the unfriendly classroom type set up, distractions and lack of individual environmental control (Duffy, 1992). Other researchers indicate that the open plan layout reduces user satisfaction, engagement and motivation to work (Oldham and Brass, 1979, Marans and Yan, 1989, Brennan et al., 2002), perceived privacy (Brookes and Kaplan, 1972, Hundert and Greenfield, 1969, Becker, 1981), and physical stress (Brennan et al., 2002), and increases distractions (Brookes and Kaplan, 1972, Hedge, 1982, Ives and Ferdinands, 1974, Mercer, 1979, Nemecek and Grandjean, 1973, Oldham and Brass, 1979, Sundstorm et al., 1980). McCarrey relates low user satisfaction rates in open plan offices to lack of individual environmental control as well as to privacy and confidentiality (McCarrey et al., 1974, Brennan et al., 2002). Harrison states that the open plan layout is ‘more generic and less responsive to individual control’ (Harrison et al., 2004).



Figure 33: Interior of two open plan offices in the UK (Van Meel, 2000)

4.2. Culture and Regulation

This section is a comparison between cellular and open plan offices in terms of office regulations and culture.

4.2.1. Office Culture

Van Meel indicates that the Anglo-Saxon and Northern European office cultures are very different (Van Meel and de Jonge, 2006). He states that the British are very ‘class-conscious’ (Van Meel, 2000). The hierarchical system in the UK (Johnson and Moran, 1993) is reflected in the organisational culture and office design, which is based on organisational goals. In the UK, individual employees and their comfort are considered less important compared to Scandinavian countries, due to high rents and expenses, shareholder capitalism, hierarchical system, regulations and lack of adequate rights for workers (Van Meel, 2000). In contrast, in Scandinavia a democratic and less hierarchical culture, called the ‘Social Democratic Office’, is dominant (Myerson, 2008). Scandinavian culture is more concentrated on users’ demands so that they can influence the decision making of their organisation. For instance, employees have a representative in the senior board meetings (Van Meel, 2000). The employment culture is based on providing more pleasant environments rather than higher wages (Forty, 1986, Myerson, 2008), explained in section 2.2.4.6. This is reflected in Scandinavian office design. The traditional personal offices developed into a modern cellular plan layout with a high quality of indoor environment, such as the SAS Headquarters, presented in section 2.2.5.4.

Anglo-Saxon organisations are interested in creating a uniform ‘standard’ for office design (Van Meel and de Jonge, 2006). Similar offices in the form of air conditioned glass skyscrapers are constructed everywhere. They are quick, cheap and similar in design and plan layout. In addition, American engineers standardised the indoor thermal environment of offices (Nicol et al., 2012). Furthermore, the financial situation affects the workplace design to a high degree. Rent levels influence the design efficiency, space per person and social facilities. Global financial capitals, such as London, have very high rents, therefore space per person is very limited. In contrast, custom build offices are more common in Northern Europe. These offices are less space efficient and standardised, since the organisation’s culture and users’ requirements are the main drivers of their design (Van Meel and de Jonge, 2006). Duffy highlights the significant difference in ‘the quality of the working environment between the Anglo-Saxon developer-based offices and custom-built Northern European offices’ (Duffy, 1992).

City	Class A net rent 2003 (Euro/square metre/year)
Amsterdam	160
Brussels	190
Frankfurt	198
Copenhagen	201
Beijing	324
Stockholm	356
Mumbai, India	386
New York (Mid Town)	440
Hong Kong	485
London (West End)	725
Tokyo	941

Source: Colliers International, 2003.

Figure 34: Rent levels in different cities in 2003 (Van Meel and de Jonge, 2006)

Country	Space utilisation standard per worker (square metre)
Germany	22.5
Netherlands	21.0
Belgium	19.0
Paris	17.0
UK	10.5–11.5
US	20.7–22.1
Japan (Tokyo)	11.6
China (Hong Kong)	13.0
China (mainland)	10.0–12.0
India (Mumbai/Delhi)	12.0

Source: DTZ Research, 2002.

Figure 35: Space use per person in different countries in 2002 (Van Meel and de Jonge, 2006)

City	Average score
Frankfurt	7.7
Brussels	7.5
Barcelona	7.0
Paris	6.9
Amsterdam	6.6
Milan	6.4
Madrid	6.3
London	6.0

Source: Cushman Wakefield Healey & Baker, 2002.

Figure 36: Survey of employees ranking their offices in different cities in 2002 (Van Meel and de Jonge, 2006)

4.2.2. Workplace Regulations

Van Meel demonstrates the differences in regulations between Northern European and Anglo-Saxon countries (Van Meel and de Jonge, 2006). In the 1970s in Northern Europe, the

Workers' Council played an important role in passing regulations to protect workers' rights, including privacy, health, access to a window, personal offices, and 'personally controllable environments' (Harrison et al., 2004). These work regulations influenced the design of the workplace to ensure a high quality of indoor environment (Hookway, 2009). In contrast, Anglo-Saxon organisations value their business over their employees so that staff's requirements are valid only within the organisation's framework (Van Meel and de Jonge, 2006). In the 1970s, although British employees had similar demands to the Scandinavian workers regarding the quality of the indoor environment, they were overruled by the opposition of the British employers. Van Meel explains that 'the regulations concerning the design of the working environment remained largely unchanged as the British continued to use their Offices, Shops and Railway Premises Act of 1963, which gave relatively general requirements for the design of work spaces' (Van Meel, 2000).

In Scandinavia, employees sit up to 6 meters away from a window, in the UK up to 10 meters and in the US up to 16 meters. The majority of the Scandinavian countries have a regulation for the minimum size of a workstation, but the UK legislation only mentions 'sufficient floor area, height and unoccupied space for purposes of health, safety and welfare', which is vague and does not specify the minimum sizes (Van Meel and de Jonge, 2006).

4.2.2.1. Norwegian Regulations

Based on the Norwegian Employment Act, the employer's responsibility is to provide 'good lighting, minimise noise and vibrations and ensure that the indoor air quality meets a certain standard' (Wiersholm, 2008). There is an emphasis on providing a 'satisfactory work environment' (Wiersholm, 2008). Norway Environment Act 4-4 states that the workplace should provide satisfactory indoor air quality with fresh air excluding air contaminants (Arbeidstilsynet, 2003). Effective ventilation with a clean and fresh outdoor air supply is required, with a ventilation rate between 7 to 10 litres per second per person. Air movement in occupied zones should not exceed 0.15 m/s. The CO₂ concentration should be under 1000 ppm. Mechanical ventilation is recommended but the use of 'natural' ventilation, in which fans are not included, is obligatory. Workplaces should have 'openable' windows in addition to the available ventilation system (Arbeidstilsynet, 2003).

If the workplace is exposed to direct sunlight, blinds are required. External blinds are more effective in reducing the solar gain. Blinds should be user friendly to be adjusted easily and they should not prevent visibility. The indoor thermal climate depends on physical activity and clothing. It is recommended that the indoor temperature be kept below 22°C. For a light,

medium-heavy and heavy work respectively, temperatures between 19-26°C, 16-26°C, and 10-26°C are required. Daily temperature fluctuations over 4°C temperature as well as 3-4°C temperature differences between head and foot causes thermal discomfort. Relative humidity between 20 to 60% is acceptable. Individual control over the heating or temperature is required (Arbeidstilsynet, 2003).

4.2.2.2. British Regulations

Based on the Health and Safety Executive workplace regulations (HSE, 1992), reasonable temperature, ventilation and light should be provided for workplaces. Effective and sufficient ventilation for every workstation is required, fresh air supply is necessary, and draughts are avoided. The fresh air supply rate above 5-8 litres per second per person is required. The focus of the UK regulations is mainly on the safety of the openable windows rather than the necessity of natural ventilation. As explained: 'it should be possible to reach and operate the control of openable windows, skylights and ventilators in a safe manner'. Natural light is recommended, but not necessary. As explained: 'people generally prefer to work in natural rather than artificial light. In both new and existing workplaces workstations should be sited to take advantage of the available natural light. Natural lighting may not be feasible where windows have to be covered for security reasons or where process requirements necessitate particular lighting conditions' (HSE, 1992).

The Health and Safety Executive website states that in the UK 'law does not state a minimum temperature, but the temperature in workrooms should normally be at least 16°C, or 13°C if much of the work is physical' (HSE, 2013). Health and Safety Executive handbook explains that 'the temperature in workrooms should provide reasonable comfort without the need for special clothing' (HSE, 1992). 'The temperature in workrooms should normally be at least 16°C unless much of the work involves severe physical effort, in which case the temperature should be at least 13°C. These temperatures may not, however, ensure reasonable comfort, depending on other factors such as air movement and relative humidity. These temperatures refer to readings taken using an ordinary dry bulb thermometer, close to workstations, at working height and away from windows'. 'A sufficient number of thermometers should be provided to enable persons at work to determine the temperature in any workplace inside a building' (HSE, 1992). The British law does not state the maximum temperature for workrooms or workstations.

Overall, Norwegian workplace regulations are more specific and comprehensive regarding worker's rights compared to the UK regulations. In addition, individual environmental control

is valued in Norwegian regulations, while it is hardly mentioned in the British regulations. According to the Norwegian workplace regulations (Arbeidstilsynet, 2003), the use of openable windows, natural ventilation, user friendly blinds, and individual temperature control are requirements for workplaces. However, according to the British regulations (HSE, 1992), every workplace should have sufficient light, ventilation and comfortable temperature. This is vague and left open to interpretation. Although natural light is recommended, it is not obligatory. It should, 'so far as is reasonably practicable, be by natural light' (HSE, 1992).

4.2.3. Differences and Interests

This section describes the main factors that set apart the Scandinavian cellular plan and British open plan office layouts, based on the previous information. Scandinavian organisations are user oriented, while the British organisations are business oriented.

In Scandinavia, users' main interests, which influences the design of the Scandinavian workplace, are as follows:

- Privacy and confidentiality
- Individual environmental control, including temperature, light and ventilation
- Satisfaction
- Health
- Ownership of their workstation
- Socialising
- Less distraction from noise

These factors drive the design of the workplace towards a traditional highly cellularised office layout. Two of these factors, privacy and individual environmental control, are the main demand of personal offices. The latter is met through providing every individual occupant with an openable window, blind, thermostat, and door. In recent years, in order to improve communication and visual interaction between occupants, a glass wall is used to separate every personal office and the corridor. However, in order to maintain privacy, some companies provide a blind on the glass wall. The Scandinavian cellular plan layout is expensive and it lacks efficiency, communication and adaptability to meet new ways of working that the open plan layout offers. Recently the Workers' Council is losing its impact in Europe (Van Meel and de Jonge, 2006). Gadsjö explains that in Scandinavia there is a move from the cellular to the open plan layout, although there is resistance from employees and the public sector (Gadsjö, 2006).

The UK has more modern organisations trying to keep up with the new advances in technology as well as organisational changes, both locally and globally. Duffy has played an important role in encouraging new ways of working. This is reflected in the design of the British office layout, as the main driver is the organisations' goals as follows:

- Cost efficiency
- Productivity, get the job done
- Communication and knowledge transfer
- Teamwork
- Space efficiency
- Shared facilities
- Health, less absenteeism

The open plan layout meets most of these criteria, particularly efficiency and communication, although the health and productivity of individuals in the open plan layout are unclear.

Although the different approaches that led to these two distinct office layouts are mentioned above, some organisational and individual factors are shared between them. For instance, health is important for the individual as well as the organisation, as it means less absenteeism. Satisfaction is also important for both parties, as it is related to individual's rights as well as productivity (Van der Voordt, 2003) and it attracts a better workforce (Van Meel, 2000). However, sometimes there is a contradiction between the organisation and the individual's interests. For instance, organisations want to reduce the space use per person for economic reasons. However, users desire more space for comfort as well as status (Zalesny, 1987). Another example is individual control over the thermal environment. Organisations prefer to centralise systems so that individuals cannot tamper with the system (Roaf et al., 2004), while individuals prefer to be able to adjust it based on their requirements in order to be more comfortable (Melikov, 2004, Arens et al., 2010, Leaman, 1996).

4.3. Uniform Comfort Zone vs. Individual Thermal Control

The Anglo-Saxon open plan offices are based on standardising the layout (Laing, 2006) as well as providing a uniform and standard thermal environment (Nicol et al., 2012). The main thermal system is centrally controlled to ensure the indoor air quality. For instance, in a naturally ventilated office, occupants may not open the windows in the winter, which increases the carbon dioxide level. In this system, thermal control is provided as a secondary option so that if occupants are uncomfortable they have the ability to adjust the thermal environment (Bordass et al., 1993). In contrast, in Scandinavia individual thermal control is the main source of adjusting the thermal environment. Here centrally controlled mechanical ventilation with adequate air exchange operates in the background to ensure the temperature and indoor air quality are within the acceptable range (Arbeidstilsynet, 2003).

4.4. Architecture and Individual Thermal Control

Hawkes states that ‘in environmental design, prevention is better than cure’ (Hawkes, 2002). Banham recommends including comfort and environmental factors in architecture (Banham, 1984, Bluysen, 2009). He complains that modern architecture is handed over to specialists to provide comfort for occupants and architects no longer consider environmental criteria in their design. His criticism is that building facades have been more important than the quality of their indoor environment (Banham, 1984). Nicole explains that architects have passed the responsibility of providing thermal comfort in their designed buildings to engineers (Nicol et al., 2012), while the building envelope and design of thermal control for occupants has a significance influence on the thermal environment as well as user satisfaction. The Scandinavian cellular plan offices presented in this thesis are good practice examples of providing individual thermal control for every occupant through the architectural design and office layout. The architectural design provides every occupant with an openable window for an outside view, natural light and ventilation, in addition to blinds, a door and a thermostat to adjust the temperature. The Scandinavian cellular office layout respects individual differences and allows all users to adjust the thermal environment based on their individual requirements without interfering with other occupants’ thermal settings.

4.5. Future of Individual Thermal Control

Recently trade unions and Workers' Councils are losing their impact in Europe (Van Meel and de Jonge, 2006). In addition, office layouts with high levels of individual thermal control are being replaced by office designs with limited thermal control, as the Scandinavian cellular plan offices are being replaced by modern open plan offices (Axéll and Warnander, 2005). Marmot postulates that the open plan office is an old office layout, which is the only solution for the future (Marmot and Eley, 2000). However, Van Meel argues that today all forms of office design coexist, simply based on organisational requirements (Van Meel et al., 2010) 'representing different basic options for office design' (Harrison et al., 2004).

In practice, modern architecture is moving away from individual control over the thermal environment. Many modern and large organisations remove the users' direct environmental control and replace it with a facilities management service (Roaf et al., 2004). Furthermore, building management prefers automatic systems to eliminate users' impact on the system to make handling the thermal system easier for management (Bordass et al., 1993). Van Der Voordt reports user complaints in new offices regarding the lack of privacy and individual thermal and lighting control (Van der Voordt, 2003). Harris predicts that environmental control will be no longer required, and he explains that the future of the workplace will be as flexible as possible in terms of workstations, information technology, communication and services (Harris, 2006). However, Katsikakis predicts that in the future, computers and robots will take over routine jobs, while people are required for creative and caring positions. Therefore attracting a talented workforce will be the concern of future organisations (Katsikakis, 2006). In addition, the global economy increases competition between organisations to attract more talented workforce. Therefore organisations need to provide pleasant environments for workers. Moezzi states that 'occupants read organisational values into physical systems and care not only about doing their work, but also about how they are treated' and 'so many occupants find that their workspaces lacking and/or failing to meet expectations' (Moezzi and Goins, 2011). The workplace history in the past century shows that users value individual thermal control as one of the most important aspects of their workplace. For instance, work environments, such as SAS and NMB Headquarters, have been successful in attracting a talented workforce because of providing pleasant work environments and individual thermal control, presented in sections 2.2.5.4.

Leaman explains that in a world, where production and outcome is becoming increasingly important, productivity is highly influenced by thermal control (Leaman and Bordass, 2005). Furthermore, facilities and services are improving and people's expectations are increasing

over time. An inflexible thermal environment is unlikely to satisfy new generations even over a short period of time. Moezzi states that ‘comfort quickly becomes about nearly everything’. He also explains that people’s expectations of a refined and controlled thermal environment is increasing (Moezzi, 2009). Based on Parkhurst’s article on cars (Parkhurst and Parnaby, 2008), Moezzi explains that ‘after the lack of the control of the physical environment and other stresses of office life, it seems very human that office workers will enjoy the thermal, acoustic, and physical control afforded by the personal car and learn to use high levels, because they can and because it is pleasurable’ (Moezzi, 2009). Researchers are investigating the application of the ‘Personal Control System’ (Bauman et al., 1993, Zhang et al., 2008, Zhang et al., 2010), which provides individual thermal control in open plan offices. Clients request a flexible environment for their building and architects try to design a responsive environment that is adapted to the occupants’ needs (Leaman et al., 1998). Currently, the ‘cutting edge’ organisations provide individual thermal control (Worthington, 2006). Bordass explains the complexity and lack of research in the field of thermal control. He indicates that ‘the ways in which controls in buildings are actually perceived and used by people, both management and individuals, although vital to performance and to human comfort, has been little researched and is usually treated only incidentally’ (Bordass et al., 1994).

4.6. Summary

This chapter combined the previous two chapters regarding individual thermal control and separate approaches in office design based on users' demands and thermal control. This chapter compared the Norwegian cellular and British open plan offices more intensively regarding their design, culture, regulations, and the application of 'individual thermal comfort' in them. Furthermore, the future and necessity of individual thermal control is discussed.

Based on this chapter, the research question is refined as 'does thermal control improve user satisfaction in cellular and open plan offices? A comparison of Norwegian and British practices'. User satisfaction, comfort, health, productivity is compared in the Norwegian cellular plan offices with high levels of individual thermal control and the British open plan offices with limited control over windows and blinds.

CHAPTER 5

RESEARCH METHODOLOGIES

5. Research Methodologies

This chapter presents the research aim and question as well as the appropriate research approach, including methodologies, methods and analysis.

5.1. Research Aim

The main research question is ‘does thermal control improve user satisfaction in cellular and open plan offices? Norwegian vs. British practices’. This research investigates the application of thermal control on users’ satisfaction, comfort, health and productivity through a comparison between two office layouts with high and low levels of thermal control. Norwegian cellular plan offices provide high levels of environmental control for every occupant, including control over an openable window, blind, light, and door, in addition to the ability to adjust the heating or cooling. In contrast, British open plan offices provide limited thermal control over windows and blinds only for occupants seated around the perimeter of the building.

As explained in Chapter Four, Scandinavia and the UK followed two separate paths in designing office layouts. Workers’ satisfaction is the main factor in the design of the Scandinavian workplace. Therefore there is a great emphasis on providing individual control over the thermal environment for every Scandinavian occupant. This demand influenced the office design particularly in 1970s and 80s, so that the traditional cellular plan layout was improved to respond to the requirements of the time. In contrast, in the design of the British open plan layout there was much more emphasis on organisational goals rather than individual comfort and environmental control. Therefore, occupants of the British open plan office are provided with limited or no environmental control. This research compares the Norwegian cellular plan and the British open plan office layouts to investigate occupants’ health, comfort, satisfaction, and productivity.

5.2. Approach

This section discusses the research approach, including the appropriate methodologies, methods and analysis. In this study, the research objectives are refined through a process of literature review and pilot studies. Therefore, an appropriate and flexible approach is required to allow the development of the theory through the research process. Grounded theory is the main methodology, combined with a traditional quantitative methodology. Interview, questionnaire and environmental measurements are applied as methods. A quantitative analysis as well as an innovative qualitative visual recording technique are the analysis methods.

5.2.1. Methodology

Miller and Brewer explain that the methodology ‘connotes sets of rules and procedures to guide research’ (Miller and Brewer, 2003). Traditionally, quantitative methodologies have been used to research thermal comfort. The main methodologies in the field are experimental chambers and field studies of thermal comfort. However, Hitchings recommends the use of qualitative methodologies to achieve new results in thermal comfort (Hitchings, 2009). In this section, traditional methodologies as well as other relevant methodologies are investigated. Finally, appropriate methodologies are formulated, a combination of quantitative and qualitative methodologies with a particular emphasis on grounded theory.

5.2.1.1. Traditional Methodologies of Thermal Comfort

It is essential to recognize the methodologies that researchers are using in the field of thermal comfort and environmental control. This knowledge is an essential platform to build up a new methodology. An innovative approach is possible by combining mainly the existing methodologies and a new one. In Chapter Three, the challenge in the field of thermal comfort was introduced. This is the debate between steady state and adaptive comfort theories. These two theories are followed by two separate approaches although they are both quantitative. The steady state theory is investigated through experimental chambers (Fanger, 1970), while field studies of thermal comfort are applied to research the adaptive comfort theory. Experimental chambers are based on measurements of the physical environment in laboratories, whereas adaptive comfort studies are surveys at the actual building. Both of these methods include data collection techniques, such as measurements of the physical environment (Fanger et al., 1974, Fanger et al., 1998, Brager and de Dear, 1997, Humphreys and Nicol, 2002a) and survey questionnaires (Fanger et al., 1974, Fanger et al., 1998, Humphreys, 2005, Tuohy et al., 2007, Rijal et al., 2009) to record individuals’ responses. The main difference between

these two methodologies is the context. In the experimental chambers, context and its complexities are removed in order to have more control over the variables. However, in the field studies of thermal comfort, the context of real life is considered as an essential component of the research. Nicol explains that because experimental chambers have been overly simplified, their results do not apply to the real world context (Nicol et al., 2012). In contrast, he explains that although the context in the field studies of thermal comfort creates complexities, the results are more accurate. However, the results of one building may not apply to another building due to diverse contexts and cultures. Therefore he suggests more research in the field in various contexts to clarify and understand the complicated subject of thermal comfort (Nicol et al., 2012).

5.2.1.1.1. Experimental Chambers

In an experimental methodology, the theory becomes valid through a process of experimenting and testing (Groat and Wang, 2002). This is a scientific approach to measuring the physical environment and people's responses to it (Fanger, 1970, Rohles et al., 1986, Sakurai et al., 1991, Arens et al., 2006). In an experimental chamber, experiments take place in a room or laboratory that is specifically designed to apply different thermal conditions (Limb, 1992) in order to research their impact on a person's body and comfort. This method is very useful in investigating conditions and extreme cases that are difficult to measure at the actual site (Limb, 1992). For example, in a study on heating and cooling systems, the scholars built a small-scale model of a building or a room in order to measure its temperature in different conditions (Groat and Wang, 2002). The variables of the study are manipulated or controlled by the scholar in specific ways (Groat and Wang, 2002). For instance, Fanger investigates the physical reaction of human body towards the changes of the thermal environment. Factors are controlled and some, such as social, emotional and work-related influences, are eliminated. The end result of Fanger's research is a series of equations and graphs to predict comfort conditions and human response. For instance to achieve the heat balance equation, the person's activity and clothing are given, then the physical environmental factors of the lab changes such as temperature, humidity and radiation. According to these changes, the person's skin temperature and sweat are measured constantly to achieve the heat balance equation (Fanger, 1973). These complicated equations are discussed in section 3.2.1.1, Fanger's simplified heat balance model is as follows (Bluyssen, 2009):

Energy supply + energy produced = energy removed.

These experiments and equations are useful in exploring physical and psychological aspects of thermal comfort (Nicol and Humphreys, 1973b) and in understanding the human body in general and its reaction to the changes of the surrounding thermal environment (Fanger, 1970, Fanger et al., 1974, Fanger et al., 1998). Their approach is ‘directed towards the definition of optimum indoor climates for different levels of clothing and activity’ through heat exchange calculations (Nicol and Humphreys, 1973b).

Experimental chambers are useful for conditions that are difficult (Rutherford and Withington, 2001) or dangerous to experience in the real life context, such as the case of fire (Rutherford, 1997). In addition, due to controlling and limiting the variables, the results of the experimental chamber are often quite accurate (Bluyssen, 2009). However, the disadvantage of this methodology in thermal comfort studies is the absence of context (Nicol and Humphreys, 1973b). The context is complicated and active; it includes ‘time, climate, building form, social conditioning, economic and other factors as well as the immediate physical environment’ (Nicol et al., 2012). However, to ignore the context is to overlook valuable information that the context holds, which highly influences the occupants’ comfort. For instance, people change their clothing according to seasonal changes. Thus, to ignore the context is to overlook the impact of the outdoor conditions on the occupants’ comfort, which is the basis of the adaptive comfort theory (Nicol and Humphreys, 1973a, Humphreys, 1978, Humphreys, 1979a, de Dear, 1994). Another difficulty with this methodology and lack of context is the difference between the participants’ short and long term experiences. The participants’ immediate response towards a new situation may differ from their response when they have experienced that situation on a long term basis. For instance, they may feel excited at the time of the survey and feel positive about an issue, while after experiencing the same thing on a daily basis, they may identify some concerns. In contrast, some participants may experience difficulties in adjusting to a new environment, but in the long term they may get used to that condition and have no particular concerns. This is the main reason that in many studies of thermal comfort, where the occupants move to a new building, the researcher investigates users’ satisfaction after several months to allow occupants some time to settle in (Brennan et al., 2002, Kroner, 2006). De Dear demonstrates that results of experimental chambers based on thermal comfort conditions of ANSI/ASHRAE 55-1992 do not apply to real situations in offices (de Dear, 1994).

5.2.1.1.2. Field Studies of Thermal Comfort

According to Fidel, ‘field studies are investigations of phenomena as they occur without any significant intervention of the investigators’ (Fidel, 1984). Usually the aim of thermal comfort

studies is to improve the comfort standards and prediction models (Nicol and Roaf, 2005), to find the conditions that the majority of people find comfortable (Nicol, 2004). Nicol explains the importance of the subjective response as ‘the aim is often to predict the subjective impression from a knowledge of the physical environment’ (Nicol, 2004). The context and time play an important role in thermal comfort studies, so that they rely on instant environmental measurements and reports. Users report their ‘short term memory’ such as their instant thermal sensation at the time of environmental measurements (Nicol and Roaf, 2005). Participants are researched in the context of their familiar everyday life, with their normal choice of clothes and behaviour (Nicol, 2004).

Field studies of thermal comfort is very close to case study methodology, which investigates a phenomenon or setting in its real-life context. Case study methodology is useful when the boundaries between the object of study and its context are not clear and there is limited control over the event (Yin, 1994). This methodology is useful when the subject is explanatory and the research question is ‘how’ or ‘why’ (Yin, 1994, Bickman and Rog, 1998). It is a suitable way to explain the causal links, theory and development of meanings and generalizing the theory through using multiple sources. Yin believes the best method to develop a theory or hypotheses is the case study method (Yin, 1994). However, Stake explains that ‘case study is not a methodological choice, but a choice of object to be studied’. A case study can be quantitative or qualitative (Stake, 2003). In an exploratory research with poor basic knowledge, a pilot study is recommended (Bickman and Rog, 1998). A case study methodology has multiple sources of evidence, including direct observation and systematic interviewing, and it can rely on a mixture of qualitative and quantitative evidence (Yin, 1994). It includes ‘the nature of the case, historical background and context, such as economic, political, legal and aesthetic aspects’ (Stake, 2003). Stake presents the following steps as the process in a case study method (Stake, 2003):

- Hypothesis regarding the object of study
- Research question including issues and theme
- Looking for patterns of occurring the phenomenon
- Triangulating data collection techniques such as observation and interview
- Interpretation
- Generalising

Yin describes a case study researcher as a detective, who arrives on a scene after a crime has occurred. The researcher must be sensitive, flexible, adaptive to change, a good listener and able to interpret the information (Yin, 1994). Sometimes a case study methodology is used to

generalise a theory (Campbell, 1975), however this generalisation should not reduce the importance of the aspects of the particular case in hand (Stake, 2003).

Many researchers have applied the case study methodology to examine the complexity of context (Bedford, 1936, Merriam, 1988, Stake, 1995, Gillham, 2000). Bromley defines the case study methodology as ‘a systematic inquiry into an event or a set of related events, which aims to describe and explain the phenomenon of interest’ (Bromley, 1990). Johansson defines it as ‘the case study should have a ‘case’, which is the object of study. The ‘case’ should be a complex functioning unit, be investigated in its natural context with a multitude of methods, and be contemporary’ (Johansson, 2003). Stake explains that ‘the power of case study is its attention to the local situation, not in how it represents other cases in general’ (Stake, 2006). Meyer criticises the case study methodology, as it is overly open to interpretation and there is no particular guidance on how to formulate and apply this methodology. This makes this methodology vulnerable and open to criticism particularly regarding the quantitative results (Meyer, 2001). However, its flexibility and tailor-made aspects allow the researcher to formulate methods that suit the research question (Meyer, 2001). Zucker explains the advantage of this methodology in ‘its evidence base for professional applications’ (Zucker, 2009).

5.2.1.2. Non-Traditional Methodologies

In order to achieve new results, it is useful either to revise the traditional methodologies and combine them with other methodologies or to choose a completely different approach. Although Hitchings recommends the use of qualitative methodologies in the field of thermal comfort, he warns against losing the connection with previous studies. Therefore he suggests a gentle move towards the qualitative methodologies rather than completely flipping over (Hitchings, 2009). In this research, in order to be innovative in approach, other methodologies are investigated. Grounded theory is selected as the main qualitative methodology, therefore it is explained in detail in section 5.2.1.2.1. The other methodologies that have been researched are briefly mentioned in section 5.2.1.2.2.

5.2.1.2.1. Grounded Theory

Grounded theory was introduced by Glaser and Strauss (Glaser and Strauss, 1967, Glaser, 1992, Glaser, 2007). In this methodology, there is no certain theory to prove (Glaser and Strauss, 1967). Instead, there are several hypotheses to research (Groat and Wang, 2002). The researcher begins with an area of study and allows the theory to emerge from the data (Groat

and Wang, 2002, Hunter and John, 2008). It refers to real life situations and people (Star, 2007). Grounded theory is useful for generalising a theory and applying it in many settings (Groat and Wang, 2002). Grounded theory includes the constant comparative method. The latter is a back-and-forth act between comparing, redesigning and retesting (Glaser and Strauss, 1967). This approach generates the theory in a systematic way, including simultaneous data collection and analysis, to test the hypotheses (Charmaz and Bryant, 2007). The goal of this methodology is not to prove the cause or universality. It is useful when it is not possible to clarify the object of the study completely 'on the first take'. This methodology is designed for temporary testing. It is a reformation of some hypotheses and redefinition of the phenomena. It is a cycle between data collection, analysis and theory building. Through this process the theory emerges (Glaser and Strauss, 1967) and irrelevant information are eliminated (Hood, 2007). The stages of constant comparative method are as follows (Glaser and Strauss, 1967):

- Comparing incidents applicable to each category
- Integrating categories and their properties
- Delimiting the theory

Grounded theory is very flexible and relevant to this research as the research does not start with a certain theory, instead several hypotheses are included. In addition, a new approach is desirable in this research through combining different techniques rather than relying solely on existing methods that have already been applied in the field. Therefore several pilot studies are applied to test different data collection techniques and analysis methods in order to improve the techniques, redesign the approach and apply it again. Through this testing cycle, the exact research plan is formulated for the actual fieldwork. In addition, analysing the collected data from different pilot studies is useful to refine the research question. Regarding the evaluation of a building, Baird explains 'the task of developing and deciding on a method is probably best thought of as an iterative exercise-start with a possible method, and return to it from time to time as other tasks are addressed and further ideas occur' (Baird et al., 1996). Pilot studies and the research plan are discussed, respectively in sections 6.1 and 6.3.

5.2.1.2.2. Other Methodologies

In this section, other quantitative and qualitative methodologies, which are not traditionally used in the field of thermal comfort, are studied in order to formulate and improve the approach.

5.2.1.2.2.1. Qualitative Methodologies

Qualitative methods illuminate ‘behaviour in context’ (Jick, 1979) in a systematic way (Huberman and Miles, 1994). They are the way to investigate how people make sense of their environment in everyday life. These methodologies study and interpret phenomena in their natural settings. Thus, the phenomena should not be removed from their actual context (Groat and Wang, 2002). Nevertheless, qualitative methods have some weaknesses. Results of a qualitative strategy are not easily generalised. Furthermore, the interpretive and descriptive nature of qualitative research means the credibility of the documentation depends on accuracy of recorded data (Groat and Wang, 2002), explained in Figure 37.

Strengths	Weaknesses
<p>Capacity to take in rich and holistic qualities of real life circumstances</p> <p>Flexibility in design and procedures allowing adjustments in process</p> <p>Sensitivity to meanings and processes of artifacts and people's activities</p>	<p>Challenge of dealing with vast quantities of data</p> <p>Few guidelines or step-by-step procedures established</p> <p>The credibility of qualitative data can be seen as suspect with the postpositivist paradigm</p>

Figure 37: Strengths and weaknesses of the qualitative research (Groat and Wang, 2002)

According to Groat and Wang, in addition to the grounded theory, other qualitative methodologies include interpretivism and ethnography. Interpretivism methodology is ‘the understanding of understanding’, which means trying to understand the meaning of social events in the way that others see them, but not from the researcher’s point of view (Geertz, 2000). Ethnography methodology emphasises on ‘discourse-in-context’, so observations and spontaneous conversations that occur in the context are essential (Denzin and Lincoln, 2003, Denzin and Lincoln, 1998, Hammersley and Atkinson, 2007). The subject of an ethnographic study is generally the meaning, function and behaviour of human action in everyday life (Groat and Wang, 2002). Bluysen recommends ethnographic methodology in researching environmental control, as it gives more insight and an in depth understanding of user behaviour and their use of environmental control (Bluysen, 2009). Nevertheless, this methodology is very qualitative, while quantitative methodologies are mainly used in thermal comfort studies. Although researchers are encouraged to use qualitative methodologies, loosing the connection to the previous studies is not recommended either (Hitchings, 2009). Limited access to the necessary data is usually a difficulty in this methodology (Hammersley and Atkinson, 2007). A long period of observation is required, since there is no control over the situation, as it is uncertain when the particular phenomenon or behaviour under the study

happens in daily life (Bluyssen, 2009). In addition, generalising the results is not easy, since the results may only apply to that particular settings (Groat and Wang, 2002).

In this research, ethnography is experienced in pilot studies as a data collection technique rather than a methodology. A combination of video recording and measurements is applied for observation in context and amazing results could be expected, explained in section 6.1.5. However, due to difficulties in timing, accessing the buildings and sensitivity of some of the case studies, such as an oil company, this method was not applied in the main case study buildings.

5.2.1.2.2.2. Quantitative Methodologies

According to Groat, quantitative methods deal with the precise and systematic measurement of quantitative verifiable (Groat and Wang, 2002). Quantitative methodologies are useful for generalising, but the participant’s ‘voice’ and the context of study are not included (Creswell and Plano Clark, 2011). In a quantitative research the subject of the study is usually the patterns in the study, generalizing the theory, studying a virtual environment through computer simulation, or translating the observations into another language, such as mathematical equations (Groat and Wang, 2002). These quantitative methodologies are presented in Figure 38.

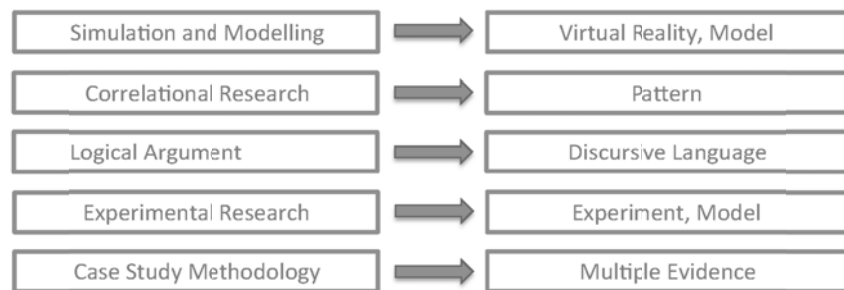


Figure 38: Simplified explanation of quantitative methods

Simulation and modelling methodology is useful in virtual reality, where scale and complexity are the objectives of the study (Groat and Wang, 2002). Bluyssen recommends simulation to involve users in the process of design (Bluyssen, 2009). Simulation is sometimes applied in studies of user behaviour and occasionally thermal comfort (Mahdavi and Proglhof, 2008), (Nakamura et al., 2008). For example, Mahdavi applies simulation in monitoring the occupant behaviour and use of control devices (Mahdavi and Proglhof, 2008). In these studies, the pattern of behaviour is the subject of study therefore simulation is useful.

Correlational research is a methodology to study and clarify patterns of relationships between two or more variables involved in the circumstances under the study. In this methodology, the subject of study is people's attitudes and their perception of others' behaviours, which is useful for studies, such as urban design (Groat and Wang, 2002). Logical argument is a methodology, in which theory is discussed through a systematic analysis and explanations using a discursive language, like computer programmes, mathematics and equations. The research outcome is generally a wide explanatory through a conceptual system (Groat and Wang, 2002). This methodology is useful for engineers that research thermal comfort to produce algorithms and computer software to predict comfort conditions. For example, ASHRAE Standard 55, 2010 provides many comfort equations and even presents a computer tool to examine acceptability of the given conditions (Huizenga, 2011).

5.2.1.2.2.3. Multi-Methodology Design

Sometimes a combination of qualitative and quantitative methodologies is required in research rather than the use of an individual methodology (Creswell and Plano Clark, 2011). Creswell describes combined strategies as advantageous due to better understanding of the concept being tested or explored and to combine qualitative and quantitative approaches in a single study (Creswell, 1994). According to Groat and Wang, three categories of multi-methodology approaches are as follows (Groat and Wang, 2002):

- The mixed-methodology design
- The two-phase design approach
- The dominant-less dominant approach

In mixed-methodology design, both methodologies are equally important. In a two-phase design, the qualitative and quantitative phases of the study are completely separated, and in a dominant/less dominant design, the key methodology is applied entirely, while no more than a few components of the other methodology influences the research design (Groat and Wang, 2002), presented in Figure 39.



Figure 39: Simplified explanation of combination of methodologies

5.2.1.3. Selected Methodologies

Methodology is very important as it clarifies the research approach and directly influences the findings. Therefore, there has been a particular emphasis on selecting the approach and innovation in combining traditional and non-traditional methodologies in thermal comfort studies. A multi-methodology, which is dominant/less dominant, is selected for this research with a combination of quantitative and qualitative methodologies. Field studies of thermal comfort as the traditional quantitative methodology and the grounded theory as the innovative non-traditional qualitative methodology are combined, with a particular emphasis on the latter. Field studies of thermal comfort highlight the importance of context and apply specific methods to collect data in the field. The grounded theory emphasises the importance of the research process and how to refine the research question and plan through this process. In addition, the grounded theory is a flexible qualitative methodology that allows a tailor made approach that suits this particular research. The grounded theory is the overriding methodology in this research.

5.2.2. Methods

Schwandt explains that method ‘denotes a procedure, tool, or technique used by the inquirer to generate and analyse data’ (Schwartz, 2001, Adams, 2007, Beadle, 2008). In order to formulate appropriate methods for this research, the relevant fields of study are studied. These subjects include field studies of thermal comfort, Post Occupancy Evaluation and sick building syndrome.

According to Nicol, the difference between the field studies of thermal comfort and post occupancy evaluation is their aim and objectives (Nicol, 2004, Nicol and Roaf, 2005). The former focuses on the occupant and aims at refining the ‘optimum temperature’ or ‘comfort zone’ to satisfy occupants. In contrast, the objective of the latter is the building performance and its aim is to improve this performance (Nicol, 2004) or direct recommendations and reports for a particular organisation (Preskill and Russ-Eft, 2004). In both of these studies, similar methods are applied, but with some modifications based on different objectives. For instance, they both apply a questionnaire to record occupant’s view. However, in the Post Occupancy Evaluation, occupant’s ‘long term memory’ is used and considered as the ‘building’s memory’. For instance, questions like ‘how often’ the thermal environment of their building is uncomfortable are asked. In contrast, in the field studies of thermal comfort, this questionnaire records user’s ‘short term memory’ for investigations, such as to understand which temperatures occupants find comfortable (Nicol and Roaf, 2005).

5.2.2.1. Field Studies of Thermal Comfort

This research is based on the field studies of thermal comfort, which is also considered as part of the methodology. Therefore its methods and objectives are particularly important. Different techniques have been applied to measure user's comfort and satisfaction with the thermal environment in the field studies of thermal comfort. In 1936 Bedford applied a thermal comfort survey in several factories. He used measuring devices such as a globe thermometer and katathermometer. In addition to measurements of the thermal environment he even measured the skin temperature of occupants' feet, hands and head and at the same time he records individual's responses about their thermal sensation and comfort. He used statistical methods to analyse the data. He concluded that the skin temperature was not as useful as predicted (Bedford, 1936). In the early 1970s Nicol and Humphreys introduced the field studies of thermal comfort. In this approach the research takes place at the natural environment (Nicol and Humphreys, 1973b). Humphreys uses mean monthly outdoor temperature for the adaptive comfort research (Humphreys, 1978).

In the ASHRAE Standard 55-2010, operative temperature and relative humidity are used as the main factors to measure the thermal environment, presented in section 3.2.2.1. Operative temperature is the mean of dry bulb temperature and mean radiant temperature (ASHRAE, 2010). The ASHRAE seven point scale question regarding occupant's thermal sensation is widely used in thermal comfort studies, explained in section 3.2.2.1. These seven scales represent the followings (ASHRAE, 2010):

- -3 is 'cold'
- -2 is 'cool'
- -1 is 'slightly cool'
- 0 is the 'neutral thermal sensation'
- +1 is 'slightly warm'
- +2 is 'warm'
- +3 is 'hot'

When users' response is '0' or the 'neutral thermal sensation', the occupant is considered to be thermally comfortable (ASHRAE, 2010).

The traditional measurements and data collection techniques in thermal comfort studies are manually done. In this way, the collected data is presented in spreadsheets or is used in

computer softwares. The labour and possible mistakes during this process are the difficulties. The traditional parameters of thermal comfort studies include (McCartney and Nicol, 2002):

- Air temperature (°C)
- Radiant temperature (°C)
- Relative humidity (%RH)
- Air velocity (ms^{-1})

In a study, McCartney and Nicol measure air and radiant temperature, relative humidity, air velocity, CO₂ levels, noise level and light level. A questionnaire was used to record users' satisfaction with these environmental factors (McCartney and Nicol, 2002). Brager applies similar measurement and questionnaire, in addition to recording 'clothing and metabolic estimates' (de Dear and Brager, 2001).

Nicol explains that in the field studies of thermal comfort, three levels of survey are usually applied (Nicol, 2004):

- 'Simple measurements of temperature'
- 'Measurements of the thermal environment and subjective response to it'
- 'Surveys, which include all factors needed to calculate the heat exchange between a person and the environment, together with subjective response'

Overall, different methods are used in the field studies of thermal comfort, including:

- Transverse questionnaire
- Longitudinal questionnaire
- Measurements of the environment, including dry bulb air temperature, mean radiant temperature, relative humidity, outdoor temperature, air velocity, carbon dioxide, light, and sound levels

In these studies, the longitudinal questionnaire and instant measurements of the thermal environment are applied simultaneously at every workstation under the study. The most important question is occupant's thermal sensation, which is based on the ASHRAE seven point scale. Then thermal condition and user's thermal sensation are compared in order to refine the 'optimum temperature' or thermal comfort zone that satisfies over 80% to 90% of the occupants.

5.2.2.2. Post Occupancy Evaluation

In this thesis in order to record the building performance of the case study buildings, Post Occupancy Evaluation techniques are studied. Although these methods are very useful, the purpose and audience in an evaluation is different from this research. For instance, the results are often used in a different way, such as direct recommendations and reports for a particular organisation (Preskill and Russ-Eft, 2004). In order to understand this difference and its applications as well as to select suitable methods for this research, the Post Occupancy Evaluation definition, brief history and methods are explained in this section.

The systematic investigation of a building performance after it is constructed and occupied is called Post Occupancy Evaluation (POE) (Nicol and Roaf, 2005, Meir et al., 2009). The aim of a POE is to improve occupants' quality of life, to increase the knowledge about the interrelation between occupants and their environment (Shibley and Schneekloth, 1996), to improve building performance of new and old constructions (Derbyshire, 2001, Meir et al., 2009), and reports for the occupying organisation (Preskill and Russ-Eft, 2004). According to Nicol and Roaf, POE reflects 'the changing nature of the relationship between people, the climate and building' (Nicol and Roaf, 2005). This evaluation is a systematic process that is purposeful and planned in advance, it questions everyday issues in a building (Preskill and Russ-Eft, 2004) after it has been occupied (Meir et al., 2009). Usually the physical aspect of the environment is emphasised, such as indoor air quality and thermal performance. However, more subjective aspects can be the subject of study as well, such as space use and user satisfaction (Meir et al., 2009, Nicol and Roaf, 2005).

The history of the Post Occupancy Evaluation starts after the Second World War. At this time, dissatisfaction and inefficiency of the building production increased. This situation required research to discover difficulties of existing constructions in order to improve their quality as well as to produce guidelines for further development (Derbyshire, 2001, Meir et al., 2009). The importance of the POE was highlighted after the crisis in 1970s and the global warming issue. Furthermore, when the building related ill health in 1980s was revealed, research in this field became unavoidable. Bill Bordass started the Probe project, which was a systematic research on POE, and his efforts influenced this field to a great extent (Derbyshire, 2001). The aim of these studies is to improve energy efficiency, user comfort, productivity and health in new developments (Derbyshire, 2001, Nicol and Roaf, 2005). An evaluation helps establishing criteria, standards, measurements, benchmarks and recommendations (Preskill and Russ-Eft, 2004). After a great data set is collected and analysed the results of different POE studies, a databases is created as a benchmark in order

to produce design protocols (Meir et al., 2009). By increasing the quality of the buildings, the need to demolish and refurbish buildings is more likely to reduce (Meir et al., 2009).

Researchers use various methods of Post Occupancy Evaluation in evaluating a building. Baird divides the evaluation of a building into two categories (Baird et al., 1996):

- Exploratory: broad and shallow
- Focused: precise and deep

Exploratory evaluations are broad and shallow, they do not seek any solution to the problems of a building, rather they discover opportunities and difficulties of the building performance or facilities in general (Baird et al., 1996). This kind of evaluation may investigate a few aspects in a wide sample of buildings (Meir et al., 2009). In contrast, the focused evaluation is an in depth analysis of particular aspects in an individual or a small group of buildings (Meir et al., 2009). POE includes quantitative and qualitative methods. The quantitative techniques include measurements, monitoring the indoor environment and air quality, while qualitative methods contain observations, walkthrough and questionnaires (Meir et al., 2009). Baird states that in post occupancy evaluation, 'quantitative information is preferable because it allows a more precise and specific performance evaluation' (Baird et al., 1996). He explains that buildings are complicated and the interrelation between user and their building increases this complexity. Accordingly, a combination of relevant techniques are required to evaluate a building based on the research objectives (Baird et al., 1996). For instance, in some studies regarding the thermal performance of a building, measurements of heating and ventilation are combined with a thermal comfort survey (Meir et al., 2009). Different categories of tools are presented as follows (Baird et al., 1996):

- Background and review of published research (Bordass and Leaman, 2004)
- Observation tools, such as notes, photographs, video recording (Baird et al., 1996) and checklists (Bordass et al., 2001a, de Dear and Fountain, 1994)
- Survey tools, such as questionnaire (Wagner et al., 2007, Langston et al., 2008, Menzies and Wherrette, 2005, Baird, 2010), online questionnaire (Abbaszadeh et al., 2006, Kosonen et al., 2008, Zagreus et al., 2004), walkthrough (Bordass et al., 2001a, Meir et al., 2009, Morhayim and Meir, 2008, Baird, 2010), focus groups, energy surveys (Bordass et al., 2001a, Bluyssen, 2009), structured and semi-structured interviews (Buhagiar, 2004, Davara et al., 2006, Shibley and Schneekloth, 1996, Baird, 2010)

- Physical measurement tools, such as temperature, relative humidity, air velocity (Baird et al., 1996), smoke (Bordass et al., 2001a), carbon dioxide, light and noise levels to monitor the thermal performance, indoor air and environment qualities (Meir et al., 2009)
- Data analysis tools, such as computer software to analyse the collected information (Baird et al., 1996) and plan analysis (Meir et al., 2009)

Although this list is very helpful to acknowledge different techniques, some methods are not precise or relevant and some of them are too demanding or time-consuming (Bordass et al., 2001a). Roaf explains that it is important to carefully select quick and efficient techniques that do not require too much time and patience from the participants (Roaf et al., 2004). The techniques must be relevant and reliable so that when used by other researchers, similar results are achieved. In addition, the possibility for cross comparison of the results with similar cases is useful. To rely too much on environmental measurement and justifying its results should be avoided, since the data is often difficult to interpret (Roaf et al., 2004).

Individual and institutional motivations in a building evaluation provide the context, in which knowledge and information are produced. Motivation of an evaluation leads to formulation of relevant methods suitable for that particular evaluation. For example, when the aim of a POE is to increase the boundaries of knowledge, data collection techniques, such as environmental measurement, observation, interview and questionnaires are usually applied (Shibley and Schneekloth, 1996). In order to research how occupants perceive newly developed sustainable workplaces, Baird applies a combination of interview, seven point scale questionnaire, walkthrough and measurement (Baird, 2010). The questionnaire includes two pages and it is based on BUS questionnaire, including the following questions to evaluate the building performance (Baird, 2010):

- Background information; such as age, sex, period of time at the building and ‘whether or not they see personal control of their environmental conditions as important’
- Operational information; such as required space and relevant facilities
- Environmental information; such as overall comfort level, light, noise, seasonal temperature and air quality
- Individual control; over ‘heating, cooling, ventilation, lighting and noise’
- Satisfaction; over their workplace design, requirements, health and productivity

5.2.2.3. Sick Building Syndrome Research

The most relevant method to study building related symptoms is a questionnaire to collect relevant information regarding users' health and the indoor environment. Raw et al uses the 'Office Environment Survey', which is a questionnaire to research building related symptoms. It includes 'dry, itchy or watery eyes, blocked, stuffy or runny nose, dry throat, headache, tiredness or lethargy, flu-like symptoms, difficulty breathing and chest tightness (Raw, 1995). Leaman applies a questionnaire as well to record occupant's health symptoms. It includes skin irritation or rash, flu-like, runny nose, dry or itchy eyes, dry skin, blocked nose, dry throat, headache and lethargy (Leaman, 1996). Bluysen's survey has a section on the sick building syndrome for occupants who worked more than four hours at a time in the office. It has similar questions to Raw's questionnaire, such as dry or watery eyes, blocked or runny nose, dry or irritated throat, chest tightness, dry or irritated skin, headaches, lethargy or tiredness, pain in neck, shoulders or back. She asks how often the occupant experiences the symptoms and some options are available such as often, regularly, sometimes and never (Bluysen, 2009).

5.2.2.4. Selected Methods

In this section, selected methods are presented and explained, including background, walkthrough, questionnaire, measurements, and interview.

5.2.2.4.1. Background

Information regarding the site, construction, energy use and maintenance are essential. This sort of information is collected through building owners, the architect, the technical engineer, the management of the company, the facilitator manager and employees (Kernohan et al., 1992). Furthermore, building certificates, any existing building report such as Probe, thermal comfort studies and BSRIA Energy Assessment are valuable. Based on the collected data on history of the building possible causes of discomfort and the indoor difficulties are predicted (Baird et al., 1996).

5.2.2.4.2. Walkthrough

A walkthrough is a common technique in a Post Occupancy Evaluation (Roaf et al., 2004), such as the evaluation of the Brass High School in Falkirk (2005). The walkthrough or touring interview is designed to understand the building performance as a whole (Baird et al., 1996). Kernohan explains walkthrough or 'touring interview' as a conversation on the move

or a combination of observation and interview. The researcher asks simple questions, listens, and takes notes and photos (Kernohan et al., 1992). Becker suggests to collect organisational, technological and design information regarding the office building during the walkthrough (Becker et al., 1996). Roaf recommends to involve building management in a 'real-world approach' instead of simply investigating technical aspects of a building (Roaf et al., 2004). In order to understand the building performance, it is required to collect the knowledge and judgement of an expert, who has been trained to address the technical aspects (Baird et al., 1996). Therefore the key person for the walkthrough is the facilities manager, who holds extremely useful and valuable information regarding the building performance and its difficulties.

5.2.2.4.3. Questionnaire

Bluyssen explains that questionnaires are useful to investigate user's satisfaction with the surrounding environment. People can evaluate and prioritise different aspects (Bluyssen, 2009). A questionnaire usually covers comfort, health, satisfaction, age and sex (Roaf et al., 2004). In thermal comfort studies, questionnaire is the most commonly applied method (Rijal et al., 2009, Bluyssen, 2009). The ASHRAE seven scale thermal sensation question is widely used, explained in section 3.2.2.1. Humphreys uses a questionnaire to record occupant's self assessment productivity level compared to their normal status (Rijal et al., 2009). Oseland applies a sophisticated questionnaire to measure productivity (Oseland, 2004). In Post Occupancy Evaluation Studies, the Probe recommends a brief questionnaire as the most effective way to collect users' information on their building (Roaf et al., 2004). Bordass explains that a questionnaire includes user's background information, such as age and sex, the building overall and how it responds to requirements, individual control over the thermal environment, health, productivity, occupant's comfort regarding temperature, air velocity and quality, lighting, noise and overall comfort (Bordass et al., 2001a). Bordass recommends not to change the basic questionnaire (Bordass et al., 2001a) in order to create a database with the ability to cross comparison between different office buildings (Leaman, 1996). Probe's basic questionnaire has eight categories, including thermal comfort, sick building symptoms, satisfaction with facilities, productivity and time spend in the building and at the workstation (Leaman, 1996). 100 to 125 occupants answer this Probe questionnaire in every building (Bordass et al., 2001a). Similar questionnaires are used in other POE studies as well (Baird et al., 1996, Becker et al., 1996). In the sick building syndrome studies, questionnaires are the most common method as well, explained in section 5.2.2.3.

5.2.2.4.4. Measurements

Schiller explains two types of measurements of the thermal environment, including general and local (Schiller et al., 1988). The general measurement investigates the performance of the building as a whole and to distinguish different thermal zones. In contrast, the local measurement focuses on the instant interior condition and occupants response to the situation. This reading includes measuring the following in a rough priority order: temperature, humidity, CO₂, radiant temperature, light and noise levels (Schiller et al., 1988). In thermal comfort studies, different instruments are used, such as thermocouple, globe thermometer, anemometer, have been used for thermal comfort studies (Oseland and Humphreys, 1994). Melikov applies environmental measurements very close to the occupant's seat to record the thermal condition that they experience. In addition, measurements are applied at different levels, such as floor, desk and above the head of a standing person (Melikov et al., 2005).

5.2.2.4.5. Interview

When the topic of the research is occupants and their issues, the 'voice' of occupants becomes very important (Shibley and Schneekloth, 1996), and it need to be reflected in the methods and research plan. Kernohan highlights the importance of user participation in evaluating buildings, since people's knowledge about their building is an important source of information (Kernohan et al., 1992). Although experts' judgement in a building evaluation is important, documentary evidence reveals that building occupants, who are non-experts, are more aware of every day issues. They report problems such as how to use the building, air quality and temperature more accurately (Baird et al., 1996). Although the only way to investigate users' 'voice' is through asking the occupants, careful scientific methods should be applied to record their knowledge (Shibley and Schneekloth, 1996). Occupants' knowledge is often contradictory (Roaf et al., 2004), unstructured and informal, therefore scientific methods are required to record and analyse these data (Shibley and Schneekloth, 1996).

5.2.2.5. Triangulation

Smith describes that triangulation is mainly used in military and navigation. Triangulation is to locate the exact position of an object through multiple reference points (Jick, 1979). In research, triangulation is to combine different methods 'in the study of the same phenomenon' (Denzin and Lincoln, 1998). Jick explains that 'researchers can improve the accuracy of their judgments by collecting different kinds of data bearing on the same phenomenon' (Jick, 1979). According to Guion, triangulation increases the validity of

findings of qualitative research. Validity ‘refers to whether the findings of a study are true and certain. ‘True’ in the sense that research findings accurately reflect the situation, and ‘certain’ in the sense that research findings are supported by evidence’ (Guion et al., 2002). Oliver-Hoyo has similar explanation that ‘triangulation involves the careful reviewing of data collected through different methods in order to achieve a more accurate and valid estimate of qualitative results for a particular construct’ (Oliver-Hoyo and Allen, 2006).

The advantage of using different methods make the overall methodology stronger, as they complete one another to maximise strengths and minimise weaknesses of each method (Creswell, 1994). However, Morse explains that in order to take advantage of qualitative and quantitative methods in triangulation and to avoid conflicts in diverse analysis systems of each method, consistency in ‘the purpose of the research, research question and interpretation of results’ is required (Morse, 1990). Qualitative methods are particularly important in triangulation. The collected data through qualitative methods such as observation in context, in addition to qualitative analysis function ‘as the glue that cements the interpretation of the results of multi-method research design’ (Jick, 1979). Qualitative methods are beneficial in terms of first hand observation and personal experience (Jick, 1979).

In this research, occupants’ perception of their thermal environment is recorded through a questionnaire and empirical building performance through the measurement of the thermal environment. These traditional techniques are further reinforced with semi-structured interviews to investigate the environmental control. The latter investigates the research question in a qualitative way and functions ‘as the glue that cements the interpretation of the results’ (Jick, 1979) of the traditional quantitative methods in this research.

5.2.3. Analysis

Traditionally, mainly quantitative analysis is used in the field of thermal comfort to produce algorithms (McCartney and Nicol, 2002) and computer software, such as the CBE Thermal Comfort Tool (Hoyt et al., 2013), and ASHRAE Thermal Comfort Tool (Huizenga, 2011). Fanger applied quantitative analysis on his experiments and achieved equations, as presented in section 3.2.1.1

Although the quantitative analysis is useful to understand the field better and generalise the findings, it overlooks the context and meaning, further explained in section 10.2. In addition, Nicol recommends architects to take back the responsibility of providing thermal comfort for occupants through the design of the building envelope. Currently engineers are the main

facilitators and researchers in the field of thermal comfort (Nicol et al., 2012). The traditional analysis techniques that engineers apply, such as equations, are based on ‘mathematical language and logic’ (Gaucherel et al., 2011), which may not appear as convenient to architects (Shahzad, 2013b). This thesis introduces the use of a qualitative method to analyse the collected data in regard to the context and meaning.

This visual recording technique, which is presented in Figure 40, is the final product. It was produced through a process of analysis on the pilot study information. The process of producing this visual recording technique is presented in section 6.1.6. This qualitative method is applied in Chapters Eight and Nine, which are the interpretation and analysis of the fieldwork information. The significance of applying this visual recording technique is explained later in sections 6.1.6 and 10.2.

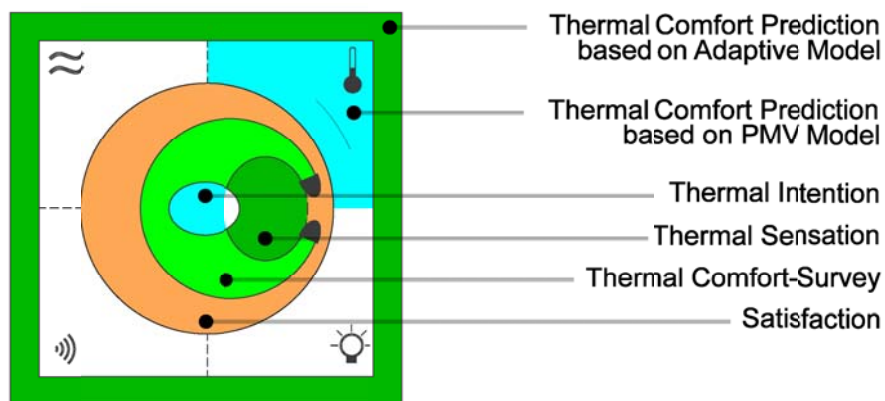


Figure 40: Visual recording technique: Expressing the information regarding a workstation on the plan (Shahzad, 2013b)

5.2.4. Initial Research Plan

Based on the selected methodologies and methods, the research plan is designed. According to the grounded theory as the main methodology, this initial research plan will be modified and refined in the process of researching various pilot studies, explained in Chapter Six. Therefore an initial research plan is presented in this section, while the finalised research plan is presented later in section 6.3.

The initial research plan includes three stages, including preliminary investigation, embedded investigation and analysis (Baird et al., 1996). The preliminary investigation is mainly the building history collected prior to the site visit. The embedded investigation is the application of methods during the actual site visit. Finally, the last stage is analysis and comparison of the data across the buildings.

5.2.4.1. Stage A: Preliminary Investigation

This stage is initially planned to collect the key building information and the building history prior to the site visit (Bordass et al., 2001a). According to Hedge, knowledge of the history of the building is important before the actual fieldwork takes place (Hedge, 1996). The first step is to contact management or administrative people in the selected office building and explain the purpose of the study in order to get access to the building (Becker et al., 1996). They may have difficulties with some of the findings and consequently make the process of the research difficult (Bordass et al., 2001a). Prior to the site visit, some information regarding the plan, layout and energy use of the building is required and a pre-visit questionnaire is applied, presented in Appendix B. These data can be collected to a preliminary visit before the actual fieldwork (Bordass et al., 2001a). The purpose of this questionnaire is a general understanding of the building, occupants and possible difficulties in the building prior to the visit. The site visits are arranged with occupier rather than the architect (Bordass et al., 2001a). Then interview with the key people in the building are arranged (Becker et al., 1996). A checklist is useful to collect necessary information at the site (Bordass et al., 2001a).

5.2.4.2. Stage B: Embedded Investigation

This stage takes place during the actual fieldwork. It includes an introductory meeting, walkthrough, observation, checklist, selecting the participants, measurements, and questionnaires. At the site visit, the first step is an introductory meeting with the management or the building owner to describe the research purpose and procedure. In return, they may describe some part of the building history, previous or present difficulties in the building. The second step is a walkthrough or touring interview with the facilities manager. This is a conversation on the move, which includes recording, photos and notes (Kernohan et al., 1992). This stage is about getting to know the building, its plant room and control systems. It includes the heating, cooling, ventilation system, changes, difficulties and occupants' general complaints.

The next step is a combination of observation and checklist, which is a visual inspection of the building in order to prepare for data collection and survey. Plans and sections of the building are required at this point. A checklist that holds information such as the site, space, internal environment, and building service attributes, which is based on the CBPR checklist, as well as photos are useful to record this visual inspection (Baird et al., 1996). At this stage, the suitable locations to place the data loggers to record temperature and humidity are identified. In order to document the general thermal performance of the building and different thermal zones, horizontal and vertical readings are required. To capture the thermal condition

that users experience, data loggers are placed on the desks in the horizontal measurements. In order to capture the vertical thermal differences, the data loggers are placed on the floor level, desk level and close to the ceiling.

It is essential to invite occupants to participate in the research at an early stage, in order to prepare a schedule based on their availability to respond to the instant questionnaire. The participation in this research is based on willingness, like other similar studies (Schiller et al., 1988). However, a balance between genders, age and location are desirable. Based on Schiller’s research, the following criteria in a priority order are applied in selecting the occupants: willingness, close to other participants’ location, availability of control devices, locations in the building (according to the thermal zone and distance from windows), equal number of male and female and variety of age groups (Schiller et al., 1988). This selection does not require to represent the building as a whole, but to demonstrate a variety of individuals in the building that represent the particular layout (Schiller et al., 1988). For example, in open plan offices individuals are selected from different locations preferably from a single floor plate based on their distance from windows. In this way the selection of workstations covers the ranges, such as next to a window, away from windows but have an outside view, and far from windows and no outside view. The same procedure applies to selecting individuals with different genders and age groups.

Based on the schedule, the selected occupants are monitored daily. Every individual is required to fill in a brief questionnaire, presented in Figure 311 in Appendix B. Simultaneously the condition in the workstation is measured in terms of temperature, humidity, CO₂, light and sound levels. Overall the steps of the stage B are presented in the timetable in Figure 41.

Day	Start Time	End Time	Action	Comment
1st Day	09:00	12:00	A tour of the building	
1st Day	09:00	17:00	Horizontal measurement (temperature & humidity) of the building	
2nd Day	09:00	12:00	Checklist	
2nd Day	09:00	17:00	Vertical measurement (temperature & humidity) of the building	
3rd Day	09:00	10:00	First 10 workstations, Questionnaire+Measurements (temperature, humidity, light, CO2)	Every workstation will take almost 5 minutes
3rd Day	11:00	12:00	Same 10 workstations, Questionnaire+Measurements (temperature, humidity, light, CO2)	Every workstation will take almost 5 minutes
3rd Day	14:00	14:00	Same 10 workstations, Questionnaire+Measurements (temperature, humidity, light, CO2)	Every workstation will take almost 5 minutes
3rd Day	16:00	17:00	Same 10 workstations, Questionnaire+Measurements (temperature, humidity, light, CO2)	Every workstation will take almost 5 minutes
4th Day	09:00	17:00	Another set of 10 workstations like the 3rd day, Questionnaire+Measurements (temperature, humidity, light, CO2)	Every workstation will take almost 5 minutes
5th Day	09:00	17:00	Another set of 10 workstations like the 3rd day, Questionnaire+Measurements (temperature, humidity, light, CO2)	Every workstation will take almost 5 minutes

Figure 41: Timetable of the initial research plan

5.2.4.3. Stage C: Analysis

The collected data from the field, regarding the building history, walkthrough and interviews, are analysed to measure the building performance and user behaviour. A particular emphasis is given to control devices, their performance and occupants’ satisfaction, which is through

observations and the two questionnaires. Thermal performance of the building is analysed and visually presented on the plans and sections. Overall, users' satisfaction, comfort and health are analysed and compared. Through this analysis, the research question is refined and narrowed down. Based on that, the research plan, data collection and analysis techniques are refined in order to be re-applied in the field.

5.3. Summary

In this chapter, research aim and approach are presented. The aim of this research is to investigate the application of individual thermal control and its' impact on occupants' satisfaction, comfort, health and productivity in the workplace. The Norwegian cellular plan offices with high levels of environmental control are compared with the British open plan layout with limited thermal control.

In order to define the approach, traditional and non-traditional approaches are studied. A multi-methodology design is applied in this research, which is a combination of field studies of thermal comfort and grounded theory. The latter is a qualitative methodology, which defines the overall approach. In the grounded theory, the research question and plan are developed through the research process, including the replication of data collection, analysis and design of the research plan. From the traditional quantitative methodology, which is the field studies of thermal comfort, mainly the methods are adopted in this research, including questionnaire and measurements of the thermal environment. These traditional quantitative methods are triangulated with a qualitative semi-structured interview in order to further investigate the application of individual thermal control in the field. Finally, the initial research plan is presented in this chapter, which is subject to change. According to the grounded theory, several pilot studies are applied to finalise the research question as well as the research plan, which are presented in the next chapter.

CHAPTER 6

PILOT STUDIES AND RESEARCH PLAN

6. Pilot Studies and Research Plan

This chapter finalises the research plan based on the pilot studies. It introduces the pilot studies, analysis, refined objectives, the refined research plan, measuring equipment, and the criteria used to select the case study buildings.

In Chapter Five grounded theory was selected as the main methodology for this research. In this methodology, the research plan and theories are finalised through a process of investigation, analysis and refinement of the methods. In order to finalise the research plan prior to the actual fieldwork and to narrow down the focus of the study and objectives, several pilot studies are applied.

6.1. Pilot Studies

This section includes various pilot studies, such as observation in context, measurements, questionnaires, interviews, video recording, and analysis. Several buildings were included in these pilot studies, including the G2G3 office, the Victoria Quay, an anonymized building in Sweden, Minto House and Evolution House at the Edinburgh College of Art.

6.1.1. Observation in Context

An observation in context was applied in a small office near Edinburgh, called G2G3, in summer and winter for a period of three weeks each in 2011. The aim of these two pilot studies was to understand the field better by spending time in the actual context of an office to observe user behaviour. Based on this observation, several issues were raised, such as ‘discomfort thermal threshold’ and ‘neutral thermal sensation’. These issues influenced the research question and analysis, which are presented in Chapters Eight and Nine.

Through this observation, the ‘discomfort thermal threshold’, which is presented in Figure 44 was clarified. This is the moment when the participant feels thermally uncomfortable and starts changing their behaviour, such as opening a window, taking off extra layers, having a cold drink, changing the thermostat, adjusting the fan, or complaining. Further investigation and comparison with the recorded thermal measurements showed a strong connection between sudden changes in temperature and the ‘discomfort thermal threshold’. This was further researched through applying an ethnographic method, including simultaneous video recording and measurements, presented in section 6.1.5. Based on the ‘discomfort threshold’, the instant questionnaire was re-designed to apply three times a day to cover the temperature changes during the day, including morning, early and late afternoon, which is discussed in section 6.1.3. In addition, ‘thermal intention’ was included in the questions, which is an important part of analysis in Chapters Eight and Nine.

Another observation was the comparison between thermal measurements, the occupant’s thermal sensation and their thermal intention. Several occupants had a thermal sensation other than neutral. However, they were quite happy and did not want any change in the temperature. For example, a female participant felt slightly warm and very comfortable so that she did not want any change in the temperature. She was sitting in the mezzanine, where the temperature was higher compared to the rest of the office as well as to the comfort zone defined by the ASHRAE Standard 55-2004. This observation was the basis for questioning the application of the ‘neutral thermal sensation’ as the basis of thermal comfort studies and standards, which is discussed in Chapter Eight. In addition, this observation questioned the

accuracy of the worldwide comfort zone standards, such as the ASHRAE Standard 55-2010, which is also examined in Chapter Eight.

Another observation was made in one of the pilot study buildings, when a few occupants felt cold and uncomfortable in their office. So they complained to the facilities manager, who came to investigate the situation. He measured the temperature, which was 22°C. Then the facilities manager stated that ‘according to the standards, the temperature is fine and the occupants’ complaint is irrelevant’ and he left.

6.1.2. Measurements

Measuring equipment are presented in section 6.4. Environmental measurement of the pilot study, the G2G3 office, was applied in summer and winter. A sample of this measurement is presented in Figure 42. As presented in Figure 47, the outdoor temperature is not recorded in the initial measurement in the summertime, which is represented in purple. This pilot study showed that in order to analyse the thermal performance of the building, it is necessary to record outdoor conditions at all times. This provides a basis to compare the recorded measurements of the interior of different parts of the building with the actual temperature and humidity outside the building. In addition, the adaptive comfort theory relates the comfort ranges for indoor operative temperature to the mean outdoor air temperature (ASHRAE, 2010, CEN, 2005). De Dear demonstrates that indoor temperature is directly dependent on the outdoor temperature, particularly in naturally ventilated buildings (de Dear and Brager, 2001). All of the selected case study buildings in this research have openable windows, explained in section 6.5. Thus a data logger is placed outside in order to constantly measure the outdoor temperature and humidity. Therefore, outdoor measurements are considered in the next pilot study in wintertime, presented in Figure 51, and in the research plan.

In addition, different thermal zones were recognised in the building, presented in Figure 47. For a general understanding of the thermal performance of the building, constant horizontal and vertical measurements were applied, presented in Figure 47, Figure 48, Figure 51, Figure 52, and Figure 53. For the vertical measurements, data loggers were placed at floor, desk and ceiling levels, similar to Melikov’s techniques (Melikov et al., 2005). For the horizontal measurements, data loggers were placed on the desks. Furthermore, instant environmental measurements of workstations were applied when the occupant was responding to the instant questionnaire.

6.1.3. Questionnaire

Three pilot studies were applied to finalise the two questionnaires, including the general and instant questionnaire, which are presented in Appendix B. The instant questionnaire was prepared to collect information regarding users' immediate feeling of comfort and satisfaction as well as their behaviour. This instant questionnaire is followed by simultaneous environmental measurements, explained in section 6.1.2. This questionnaire is mainly based on (Rijal et al., 2009), (Bluyssen, 2009) and the ASHRAE thermal sensation, comfort and satisfaction (ASHRAE, 2009), the latter is explained in section 3.2.2.1. The answers are based on seven scales of the ASHRAE model (ASHRAE, 2004) with the additional option of 'No strong opinion'. The aim of the general questionnaire was to collect information, such as age, gender and building related symptoms as well as recording the respondent's view of thermal control.

A pilot study in the architecture department at the University of Edinburgh was carried out to examine users' understanding and response to both questionnaires in order to reduce any ambiguity. Participants' responses to the environmental control questions showed contradictions. This was a paper-based questionnaire; thus some respondents have simply ticked both boxes. In response to 'Would you like to have an automatic temperature control system or would you prefer to set the temperature yourself?' several participants responded 'both'. In a follow-up conversation, participants explained their preferences, which was very useful. For example, some of them preferred to have both options to use according to the situation. Some preferred an automatic system because they did not want to be distracted by changing the temperature. However, they preferred to have the option to change the settings if needed. Therefore, this part needed to be refined, as the questionnaire could not explain the complexity of this matter. The refined method is presented in section 6.1.4. In addition, respondents complained about the length of the questionnaire, which included 48 questions and required so much of their time. For example, these comments were often received: 'Do you really expect me to answer all these 48 questions?', 'So this is just the first part of your research?', 'How much time do you expect me to spend on your research?', and 'I am sorry, I don't think I have the time to participate in your research'. As mentioned in section 5.2.2.2, Roaf explains that careful planning is required so that participants are not required to spend too much time on the research (Roaf et al., 2004).

Another pilot instant questionnaire was applied in G2G3 office, in which participants did not respond to every question. This made the analysis and cross comparison difficult, as some necessary information was missing. Other researchers report similar difficulty (Baird, 2010).

Therefore, the paper-based instant questionnaire was modified into an online questionnaire using Bristol Online Survey. Respondents cannot submit the questionnaire if they have not answered to all of the 'required' questions. Brager explains that online surveys are useful tools to study building performance from the occupant's point of view. They are quick and inexpensive, allow more detailed questions and provide an easier data storage, analysis and comparison of the results (Brager and Baker, 2009). In this research, for the ease and speed of data collecting, the online questionnaire was presented on an iPad. Participants showed much more enthusiasm. In addition, this method ensured that all the questions were answered.

In the third pilot questionnaire, an international student at Edinburgh College of Art participated in responding to the general or pre-visit questionnaire. Her immediate reaction when she saw the 48 questions was to avoid participation. Therefore the researcher offered to read the questions for her. This proved extremely useful as her thinking out loud and the reasons why she chose one option over the other were more useful than the question itself. For instance, her response to the environmental control question clarified the ambiguity, as she preferred an automatic system, with an option to apply control in case she found the temperature inconvenient. This pilot questionnaire was very helpful, as it showed that a conversation is far more useful to clarify complicated matters like environmental control. These pilot studies regarding the general questionnaire called for a change in data collection technique. The general questionnaire was changed into a semi-structured interview, which is presented in the next section.

6.1.4. Interviews

The management of Victoria Quay building did not agree to the general questionnaire, instead they allowed five minutes of interview per respondent. Therefore, the general questionnaire was modified into 10 simple questions as follows:

- Are you male/female? Year of birth?
- How long have you been working at this building and workstation?
- Are you completely deskbound?
- What do you think you are more tolerant of, too hot or too cold conditions?
- What do you do when you feel hot/cold?
- Do you prefer to change the temperature at your desk or would you like the temperature to be set automatically?
- Would you like to have an outside view?
- How often do you have dry/watery eyes or nose?

- How do you usually feel at work during summer and winter in terms of temperature and comfort?
- How is the light level at your desk? Do you change it often?

This pilot interview was very successful. The qualitative results were more explicit than the general questionnaire. Therefore, the general questionnaire was redesigned into a semi-structured interview. The questions are presented in section 6.3.5. Respondents' explanation clarified the importance of individual thermal control in the workplace and the importance of sharing an office with other occupants. Most of the participants mentioned their individual differences in perceiving the thermal environment and that no particular temperature would satisfy both them and their neighbouring colleagues. The occupants sitting around the perimeter of the building, who had access to openable windows, did not use this control system as often, since the 'other' colleagues did not like it. For instance, one occupant liked to have the window open at all times in order to have fresh air, while his neighbouring colleague did not like the draught. Another occupant had a fan on his desk, while his immediate colleague wanted to feel warmer. They explained their individual differences and the obstacle in satisfying all with one particular temperature in an open plan layout. This part is further researched in section 9.2.1.

In Victoria Quay, the interviews took place at participants' workstations in the open plan office. This exposed a difficulty, as participants seemed uncomfortable when responding to some of the questions, particularly associated with their 'other' colleagues. This was adjusted in the research plan, to take the interviews to a room or a more private place. Based on this pilot interview, the semi-structured interview was modified, which is presented in section 6.3.5.

6.1.5. Ethnographic Video Recording

Several ethnographic pilot studies were applied to investigate user's behaviour towards the changes of the thermal environment and how they use environmental control systems. Simultaneous thermal measurements and observation were combined in this study. The latter included different methods of observation, including direct observation as well as video recording using a camera, iPad and laptop. The most useful method of observation was the video recording on a laptop using the iMovie software, as it has the benefit of recording the natural behaviour, ease of analysis and comparison. In a pilot video recording, shortly after the recording started, the participant simply forgot that he was being recorded, as a laptop is usually not associated with a camera or a recording function. He felt so comfortable and

behaved naturally to the extent that he actually slept for half an hour on his chair during the pilot study. The iMovie software allows a frame by frame examination of the situation and it shows the real time of the recording on every frame. This is very useful as each frame can be compared to the exact thermal condition, which is recorded by data loggers. Samples of these recordings are presented in Figure 42, Figure 43 and Figure 44. The frame that includes the participant opening the window is compared to the simultaneous thermal readings. This happens to be the time of a sudden increase in the temperature due to solar gain, as presented in Figure 44. This is in line with the ‘discomfort thermal threshold’, which is discussed in section 6.1.1.

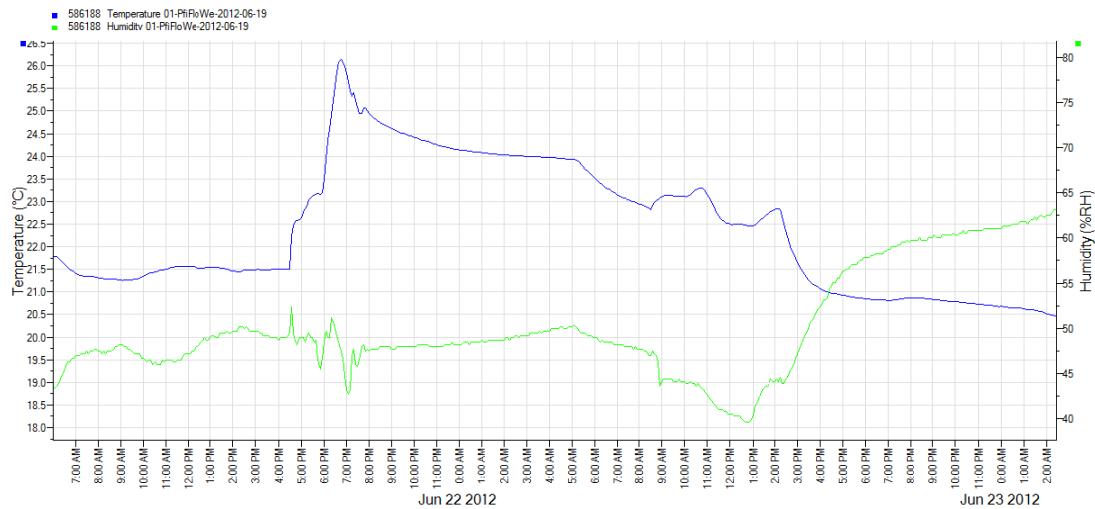


Figure 42: Pilot study: Thermal measurements, including temperature and humidity

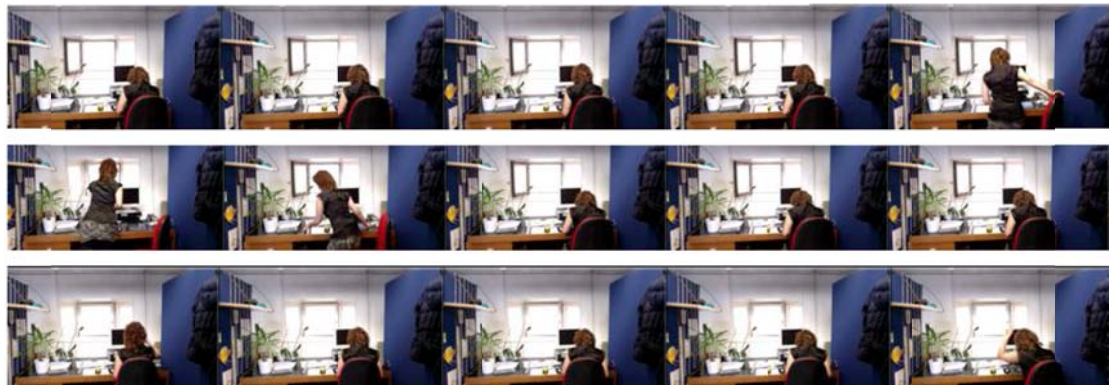


Figure 43: Pilot study: Video recording of user behaviour



Figure 44: Pilot Study: 'Discomfort Threshold', video recording and temperature measurement

Although the video recording technique seems to provide useful qualitative information, this method was not applicable in the case study buildings in this research, due to sensitivity of the nature of the buildings, such as the oil company. Therefore, this method was not included in the research plan. However, this method is useful and recommended for further research in the field, particularly to investigate user behaviour and environmental control, explained in section 11.5.

6.1.6. Analysis

The data collected in the pilot studies are analysed in order to narrow down the research question and redesign the research plan. As a quality control, Bickman recommends avoiding inclusion of the analysis of a pilot study in the final research analysis (Bickman and Rog, 1998).

The aim of this section is to present a quick view of the process of developing of the visual recording technique as well as the main questions that were raised and helped developing the hypotheses. Therefore analysing the data is avoided, as it is not the focus of this section. The detailed analysis and techniques are presented in Chapters Seven, Eight and Nine. The focus of this analysis is building performance and user behaviour. Environmental measurements and observations are presented on the plans and sections using colour codes. The selected colours are based on traffic lights, so green stands for an acceptable condition, while yellow is middle ground and orange represents an unacceptable condition. For example, when the thermal environment is acceptable based on the ASHRAE PMV prediction model, the colour is green. The colours of the thermal sensation and preference are blue, green and red, which respectively represent cool, comfortable and warm conditions. Figure 45 and Figure 46 show the horizontal and vertical air movements in the building. The colours of the arrows show where the air is warm and where the air is cool.

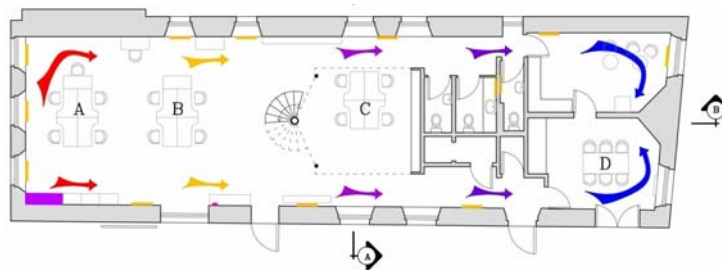


Figure 45: G2G3 pilot study: Air movement analysis on the plan

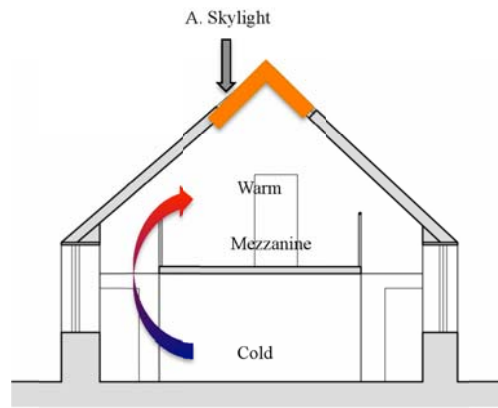


Figure 46: G2G3 pilot study: Air movement analysis on the section

Figure 47 and Figure 48 demonstrate thermal zones in the building, according to summer and winter readings. In these two figures, purple is used when data is missing. So the outdoor temperature reading was not applied in the first pilot study in the summertime. This was corrected in the second pilot study in the wintertime, discussed in section 6.1.2.



Figure 47: G2G3 pilot study: Thermal zones on the section in the summertime

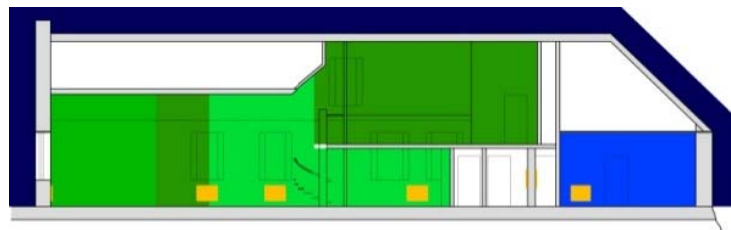


Figure 48: G2G3 pilot study: Thermal zones on the section in the wintertime

Figure 49 compares the thermal recordings of separate parts of the building against the comfort zone indicated in the ASHRAE Standard 55-2004. Figure 50 compares this analysis to the comfort vote of the participants, which shows that majority of respondents are uncomfortable regardless of the ASHRAE acceptable comfort zone.

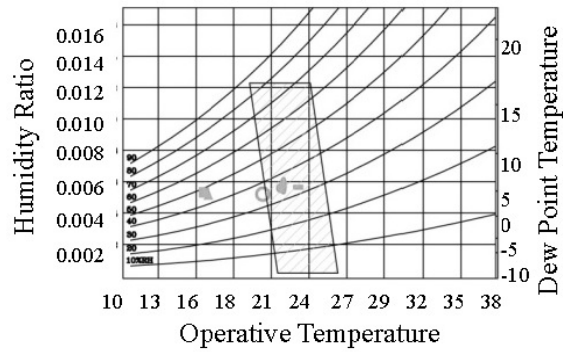


Figure 49: G2G3 pilot study: Thermal comfort analysis of wintertime based on the comfort zone, ASHRAE Standard 55-2004

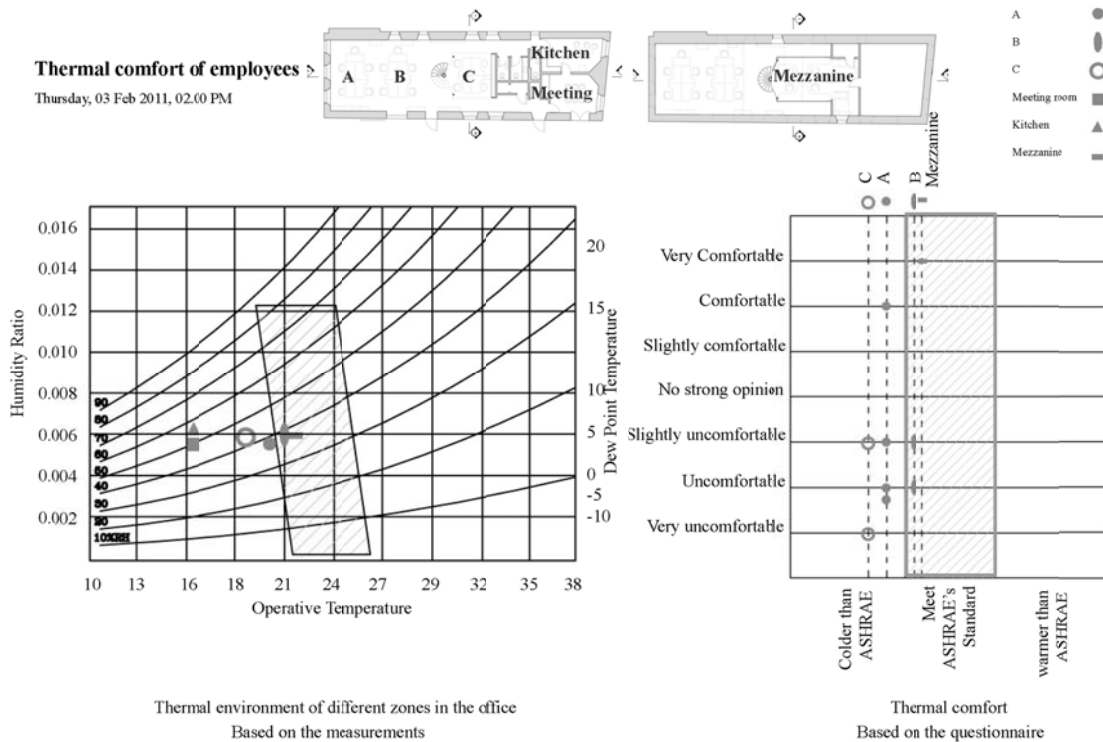


Figure 50: G2G3 pilot study: Comparing user comfort and ASHRAE Standard 55-2004

Figure 51 presents the temperature and humidity analysis based on the ASHRAE Standard 55-2004 on the plans, sections and the diagram. Figure 52 compares the thermal performance of the building and thermal zones against participants' clothing over two days. The measurements are applied four times a day in order to analyse the changes in the situation and clothing.

Thermal analysis

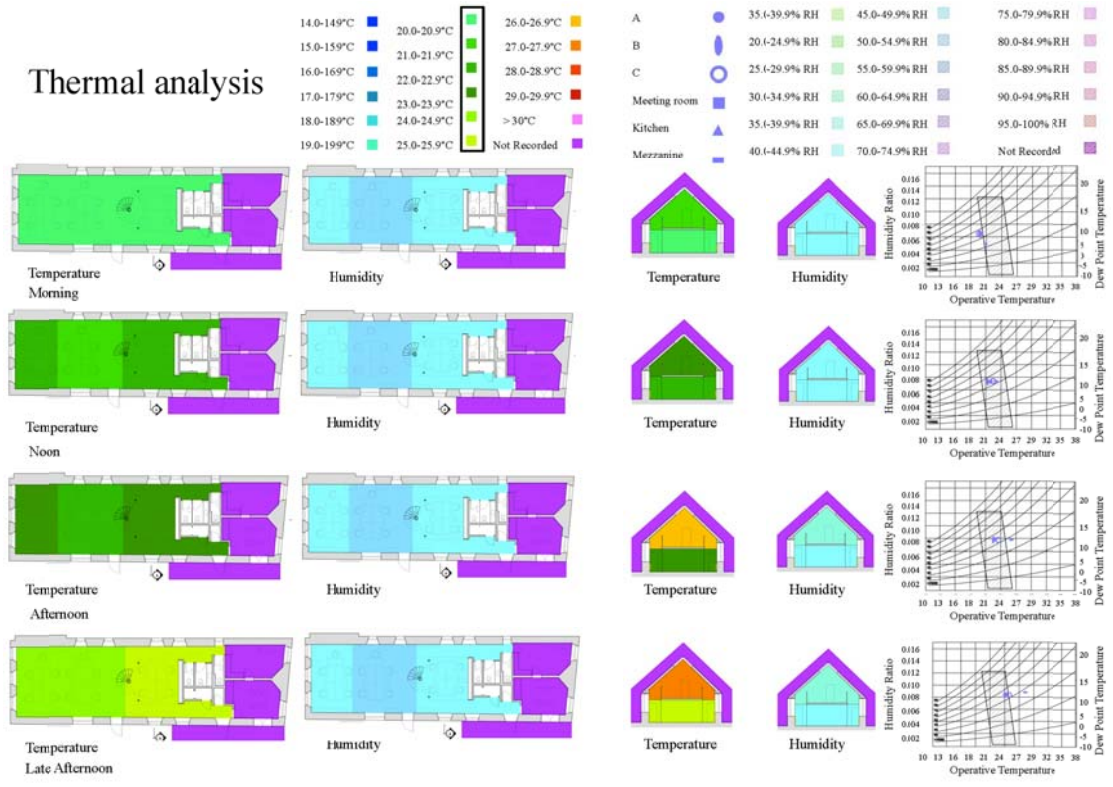


Figure 51: G2G3 pilot study: Thermal analysis

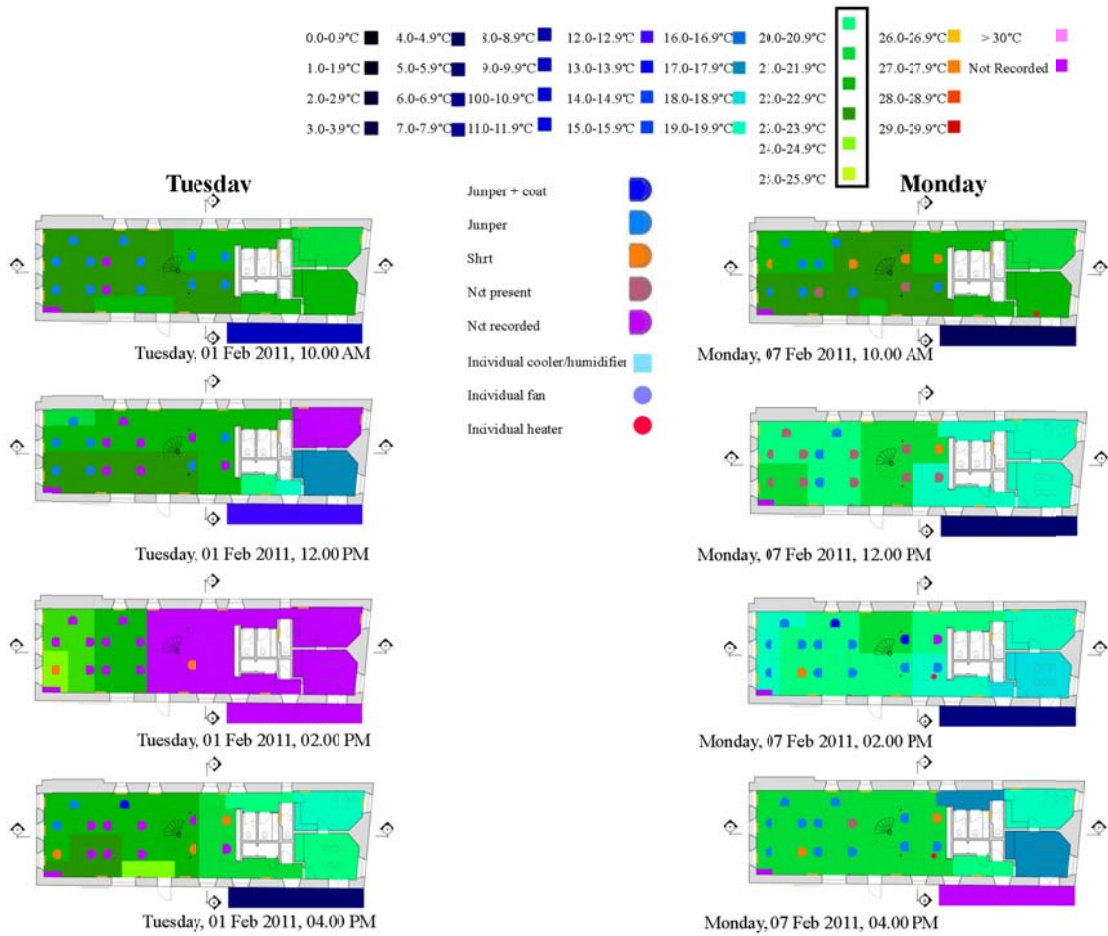


Figure 52: G2G3 pilot study: Thermal analysis and participants' clothing

Figure 53 compares participants' clothing, their thermal sensation and the thermal environment measurements. Figure 54 compares this analysis to the respondents' comfort, clothing, thermal sensation and intention. Some contradictions appear in this stage. For example, a respondent, who is wearing a jumper, feels warm in a thermal environment that is predicted as comfortable. Further analysis reveals that the person is very comfortable and does not want any change in the thermal environment. This shows a risk of misjudgement, when the information regarding a particular respondent are separated and analysed in a quantitative way. This is further investigated in Chapters Eight, Nine and Ten.

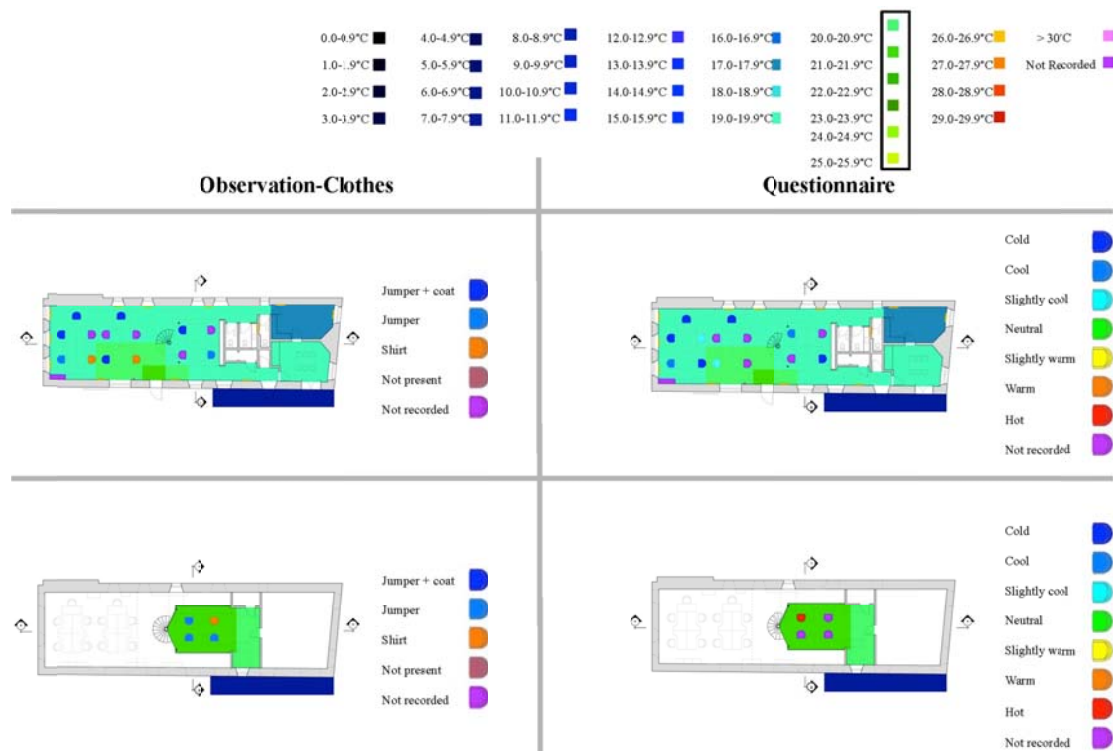


Figure 53: G2G3 pilot study: Initial visual recording analysis based on the thermal measurements, clothing observation and thermal sensation survey

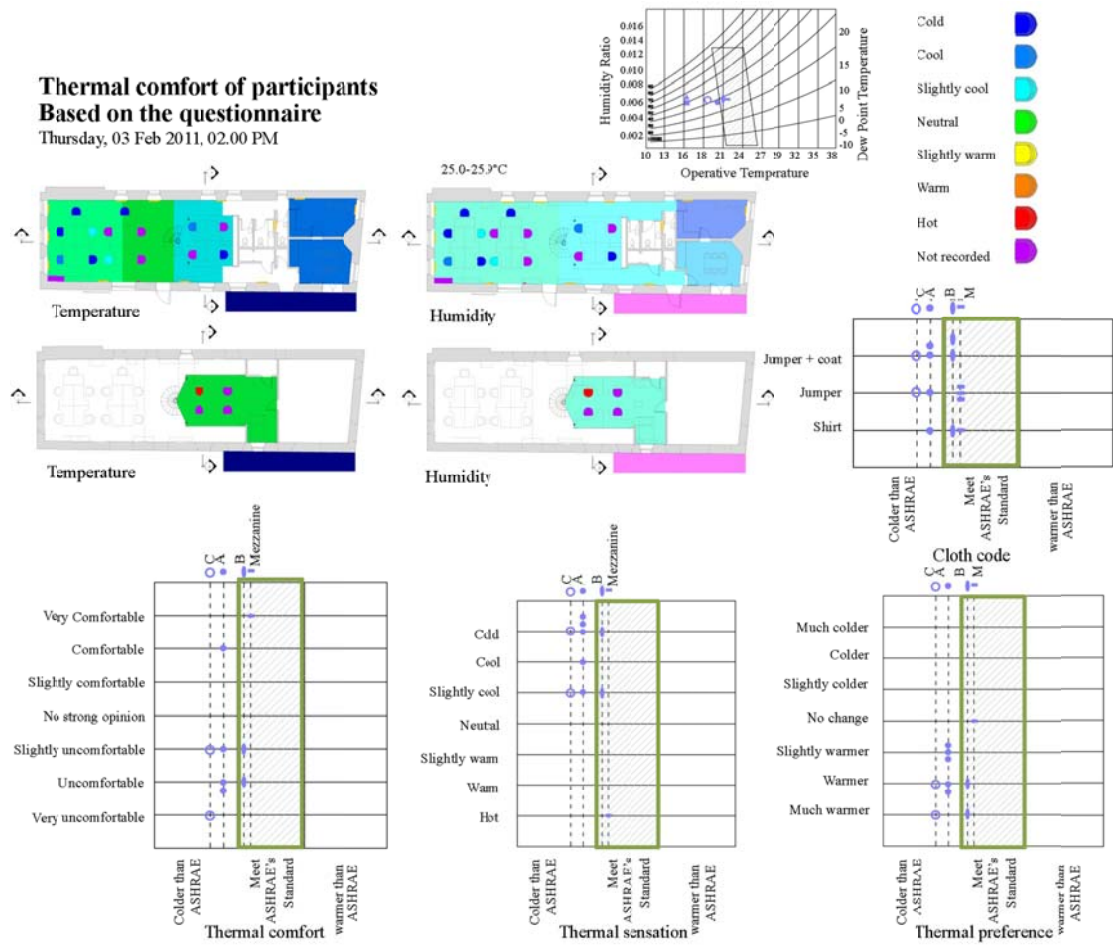


Figure 54: G2G3 pilot study: Thermal comfort analysis

As discussed, Figure 50 and Figure 54 present diagrams regarding the comparison between surveyed thermal sensation and the ASHRAE Standard 55-2004. These diagrams are redesigned and developed into boxplots, which are presented in Chapter Nine. In addition, the visual recording technique is improved. Figure 55 shows the initial sketch of developing the pictograms into a more meaningful graphic that represents the user rather than a chair. This sketch is a top view of a seated person at the workstation. The respondent's view of the thermal environment recorded in the questionnaire is mapped on different body parts in the pictogram using colour codes. For instance, the arms of the person, which are presented in orange in Figure 55, demonstrate the comfort level of the respondent. According to the colour code for comfort level in Figure 57, orange indicates that the respondent feels 'uncomfortable' at the time of the questionnaire.

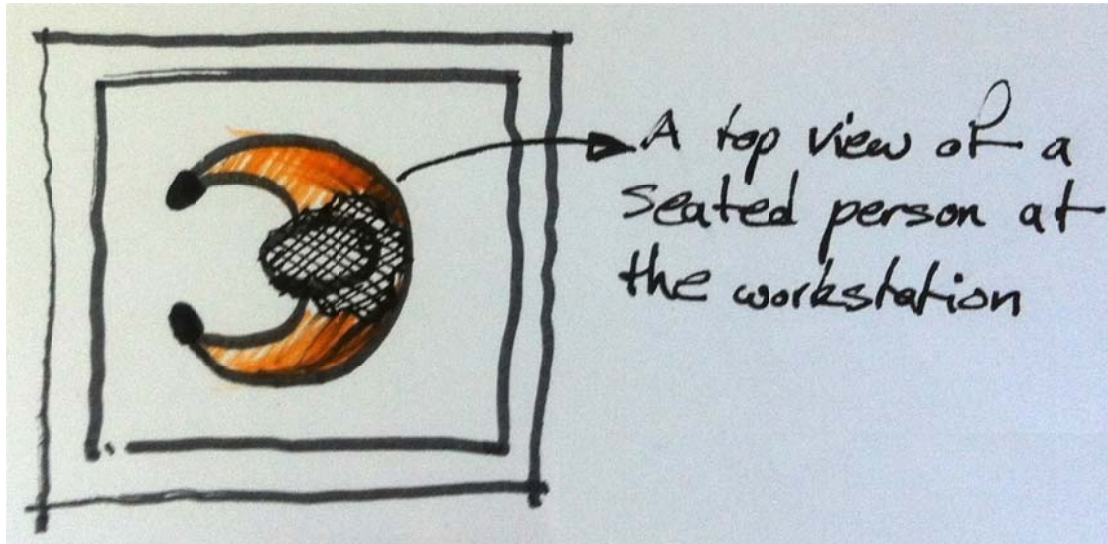


Figure 55: Early sketches of the visual recording technique showing a top view of a seated person at the workstation

Figure 56 is the finalised graphic for the visual analysis technique. This is also a top view of a seated person. The information regarding each user is mapped on the pictogram using colour codes, as presented in Figure 57. The colours inside the squares show the environmental measurements at the time of the survey questionnaire. This information is analysed and compared to the relevant standards, then mapped on the pictogram using colour codes, which is presented in Figure 57. The main environmental information includes the PMV and adaptive thermal comfort predictions based on the thermal measurements at the workstation and analysis using the ASHRAE Thermal Comfort Tool. As explained, the environmental measurement is placed inside the rectangles, as presented in Figure 56.

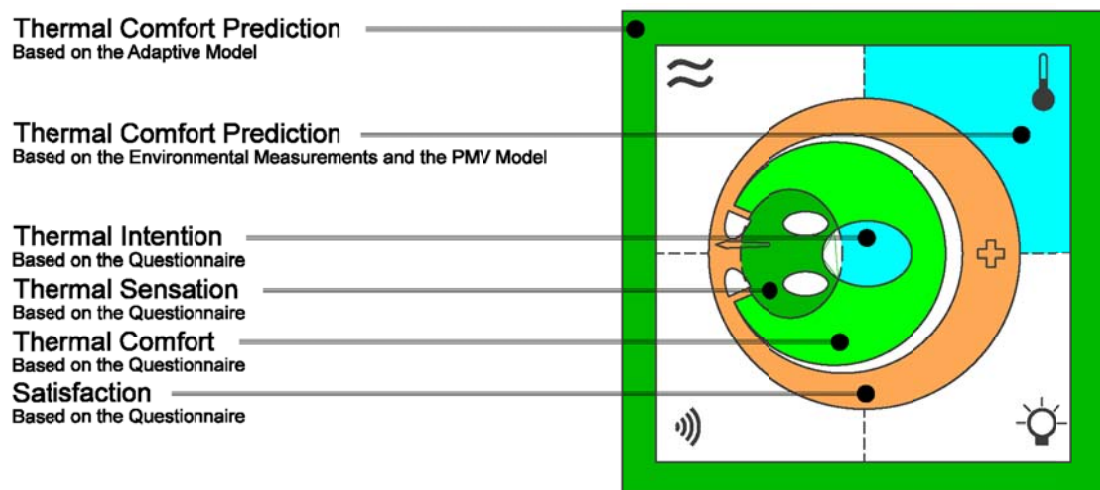


Figure 56: Visual recording technique: mapping the information of a workstation on the plan

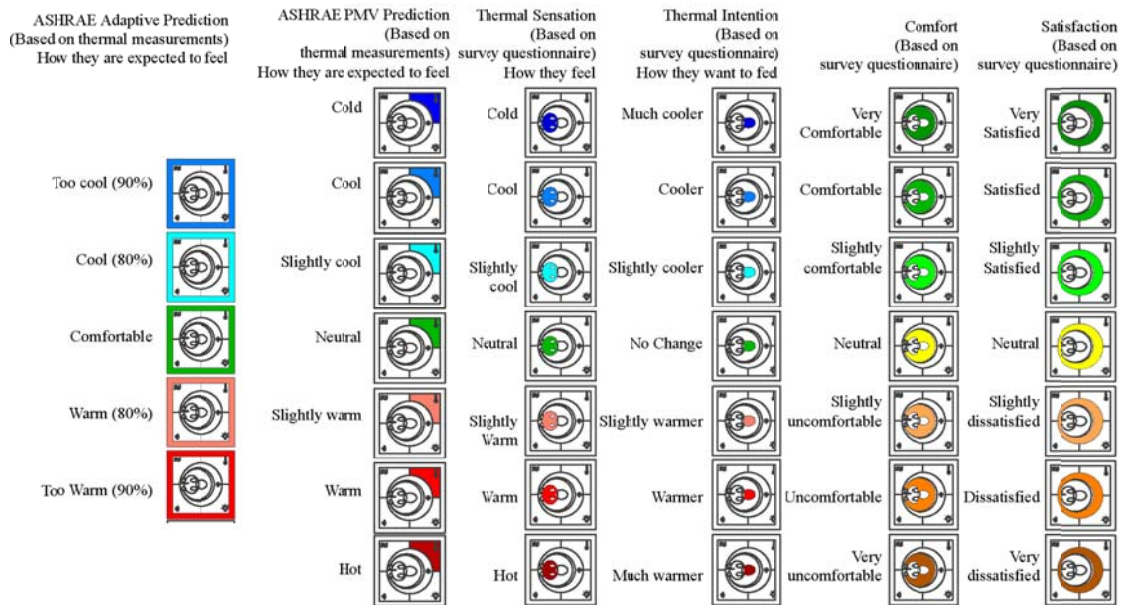


Figure 57: Colour codes of the visual recording technique

In Figure 56, the ellipses symbolise the respondent’s body. Each body part represents person’s response to one of the questions recording respondent’s view of the thermal environment at the time of the environmental measurements at the particular workstation. For example, the colour of the person’s head shows their ‘thermal intention’, which is their desire to change the temperature. The person’s arms, the space in between the arms, and the circle around the arms respectively indicate the person’s ‘comfort’, ‘thermal sensation’ and ‘satisfaction’.

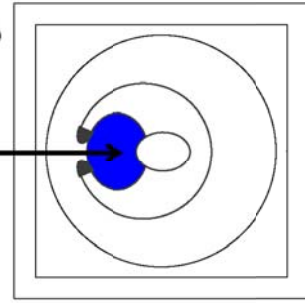
Most of the information is collected with the ASHRAE seven point scale, -3, -2, -1, 0, +1, +2, and +3, presented in section 3.2.2.1. In order to simplify understanding of the colour codes, green has been selected as an acceptable condition. Blue, red and orange respectively demonstrate a cold, warm and unacceptable situation, as presented in Figure 57. In some cases ‘0’ is the acceptable situation (e.g. thermal intention) and in some others ‘+3’ is the acceptable condition (e.g. comfort and satisfaction). For instance, in thermal sensation, ‘0’ shows a ‘neutral’ thermal sensation, which is acceptable based on the ASHRAE Standard 55-2010 (ASHRAE, 2010), discussed in section 3.2.2.2. In this research, a neutral thermal sensation is represented in green, as presented in Figure 58. In the ASHREAE seven point scale, ‘-3’ indicates ‘cold’, and ‘+3’ shows ‘hot’ thermal sensations. In this case, blue and red represent cold and hot thermal sensations, respectively. Figure 58 and Figure 59 demonstrate simplified examples on how to read the colour code information presented in the pictograms regarding thermal sensation and thermal intention of the respondents.

Q: **Thermal sensation** (How does the respondent feel regarding the thermal environment?)
A: The respondent feels **cold** regarding the thermal environment
(Based on the colour code for thermal sensation, **deep blue** indicates 'cold')

In short:

Q: **Thermal sensation:**

A: Deep blue = **cold**

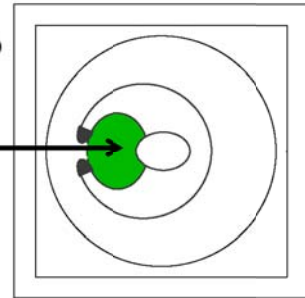


Q: **Thermal sensation** (How does the respondent feel regarding the thermal environment?)
A: The respondent feels **neutral** regarding the thermal environment
(Based on the colour code for thermal sensation, **green** indicates 'neutral')

In short:

Q: **Thermal sensation:**

A: Green = **neutral**



Q: **Thermal sensation** (How does the respondent feel regarding the thermal environment?)
A: The respondent feels **hot** regarding the thermal environment
(Based on the colour code for thermal sensation, **deep red** indicates 'hot')

In short:

Q: **Thermal sensation:**

A: Deep red = **hot**

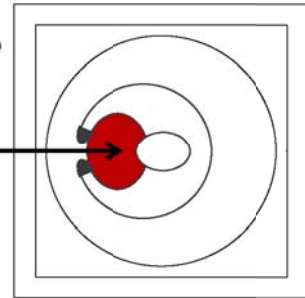
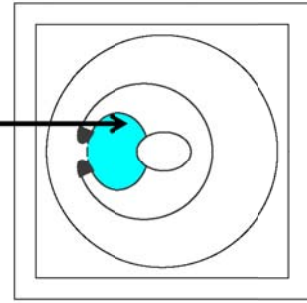
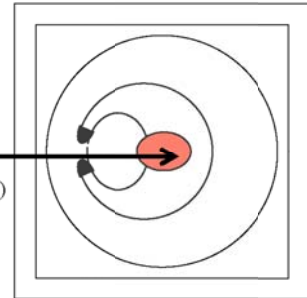


Figure 58: Simplified examples of thermal sensation: 'cold', 'neutral' and 'hot' responses

Q: **Thermal sensation** (How does the person feel regarding the thermal environment?)
 A: The person feels **slightly cool** regarding the thermal environment
 (Based on the colour code for thermal sensation, **light blue** indicates 'slightly cool')



Q: **Thermal intention** (Does the person want any change in the temperature?)
 A: The person wants a **slightly warmer** temperature
 (Based on the colour code for thermal intention, **light red** indicates 'slightly warmer')



Q: **Thermal sensation:**
 A: Light blue = **slightly cool**
 Q: **Thermal intention:**
 A: Light red = **slightly warmer**

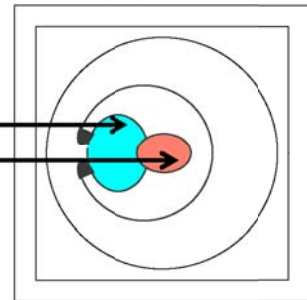


Figure 59: Simplified example: 'slightly cool' thermal sensation and 'slightly warmer' thermal intention

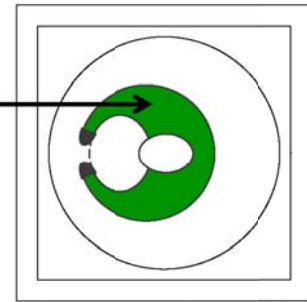
In other cases, such as 'comfort', '+3' is regarded as the acceptable condition. For example, regarding the comfort level, '+3', '+1', and '-2' indicate 'very comfortable', 'slightly comfortable', and 'uncomfortable', respectively. These qualities are represented in dark green, light green, and orange, respectively. Figure 60 demonstrates simplified examples on how to read the colour code information presented in the pictograms regarding comfort levels of the respondents.

Q: **Comfort level** (Is the person comfortable regarding the thermal environment?)
A: The person feels **very comfortable** regarding the thermal environment
(Based on the colour code for comfort, **dark green** indicates 'very comfortable')

In short:

Q: **Comfort level:**

A: Dark green = **very comfortable**

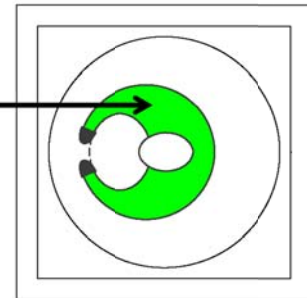


Q: **Comfort level** (Is the person comfortable regarding the thermal environment?)
A: The person feels **slightly comfortable** regarding the thermal environment
(Based on the colour code for comfort, **light green** indicates 'slightly comfortable')

In short:

Q: **Comfort level:**

A: Light green = **slightly comfortable**



Q: **Comfort level** (Is the person comfortable regarding the thermal environment?)
A: The person feels **uncomfortable** regarding the thermal environment
(Based on the colour code for comfort, **orange** indicates 'uncomfortable')

In short:

Q: **Comfort level:**

A: Orange = **uncomfortable**

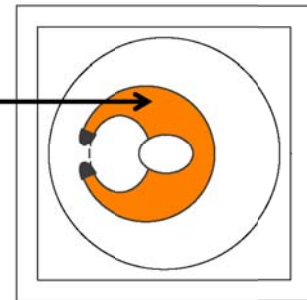


Figure 60: Simplified examples for comfort level: 'very comfortable', 'slightly comfortable' and 'uncomfortable' responses

The pictogram is originally designed with the ability to present all the information collected in the field: users' view of the thermal environment through questionnaires as well as building performance using environmental measurements. In order to analyse particular variables, the pictogram allows turning off the layer of the unnecessary variables, which will appear in white. This is to simplify the process when analysing two or three variables.

All this information is not used on the pictograms in this thesis for two main reasons. Firstly, a small group of variables play no part in the thesis, as they do not follow the main stream of the thesis argument. Secondly, qualitative analysis technique was not required in the analysing some information. For instance, the information regarding the carbon dioxide, noise and light levels has a particular place on the pictograms with their symbols representing them, as demonstrated in Figure 61. However, this information is not used on the pictograms in this thesis, as it is analysed using quantitative analysis techniques, such as frequency analysis and bar charts in section 7.2. The results of the quantitative analysis indicate good qualities of the indoor environment according to the standards. In addition, majority of the respondents

reported satisfaction with carbon dioxide, noise and light levels in the questionnaires and during the interviews discussed in Chapter Seven and section 7.3. Therefore this information is not presented on the pictograms in the thesis.

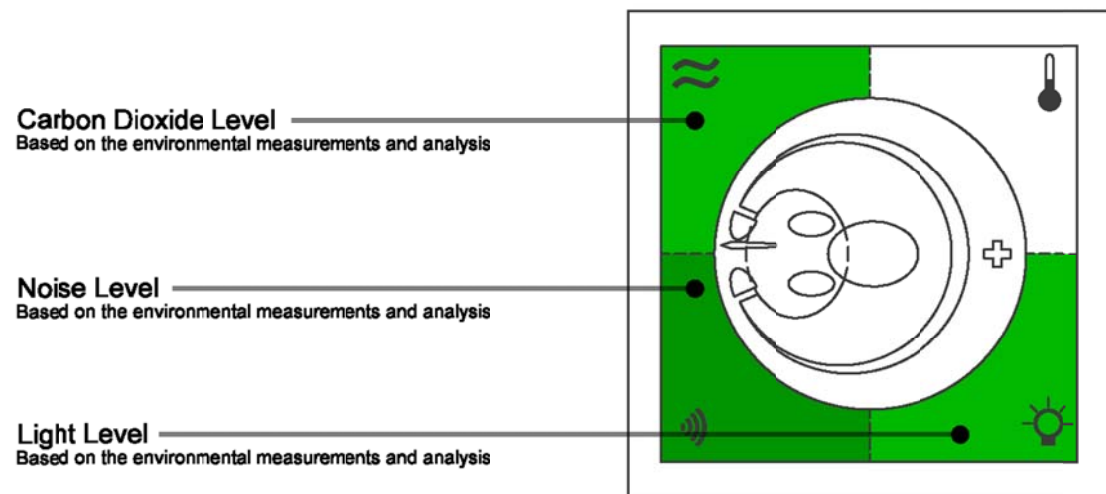


Figure 61: Environmental information that is not used in the pictograms of the thesis: carbon dioxide, noise and light levels

The information regarding the thermal sensation of the face, hands and feet of the respondent plays no part in communicating information, since they did not follow the main stream of the thesis argument. Therefore this information is not discussed or represented in the thesis, although the design of the pictograms includes this data, as presented in Figure 62. In order to simplify the analysis, the layers holding the information for these particular variables are turned off during the analysis as well as presenting in the thesis. Therefore they appear white in the pictograms. Although this information is not used directly in the body of the thesis, it is not eliminated from the pictograms. Some information are used in further analysis in publications, such as the analysis of sick building syndrome presented in ASHRAE IAQ Conference 2013, presented at the end of the Appendix section.

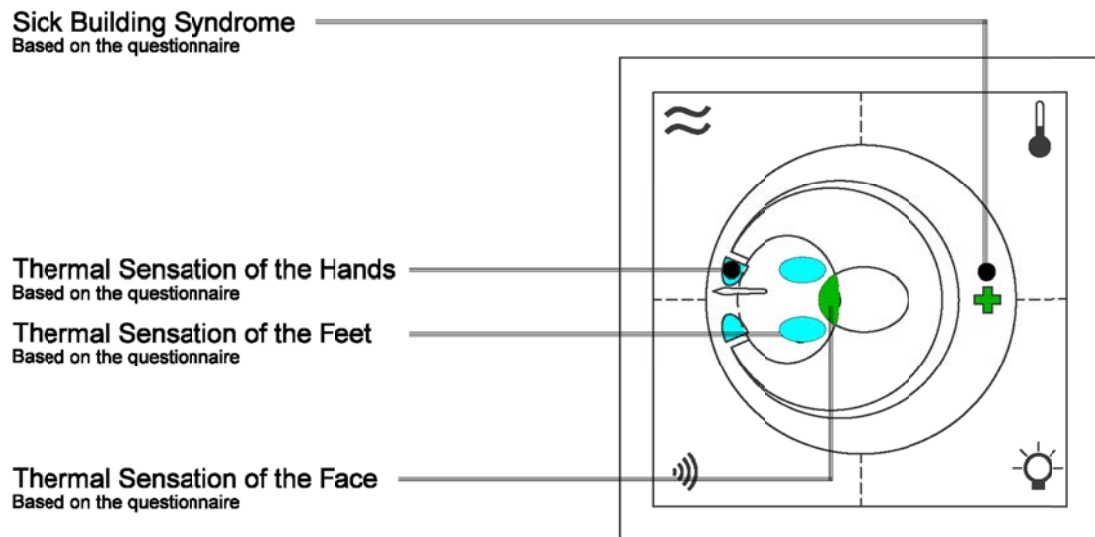


Figure 62: Thermal sensation of the body parts: face, hands and feet as well as sick building syndrome according to the questionnaire: not used in the thesis

Based on the questionnaire, users' evaluating the thermal environment is recorded and this information is presented inside the ellipses in the pictogram, such as the arms of the person representing comfort level. Building performance is evaluated based on the environmental measurements at the time of the questionnaires and comparing this data with the standards. Then this information is turned into colour codes and represented in the rectangles. For instance, the colour of the space between the two rectangles shows the adaptive prediction according to the ASHRAE Standard 55-2010 using the ASHRAE Thermal Comfort Tool, the methods and calculations are presented in section 7.2.3.

Figure 63 shows an example of analysing the pictogram according to the colour codes, presented in Figure 57. The pictogram reads as follows:

Environmental condition of the workstation, according to environmental measurements and analysis:

- The adaptive comfort model predicts that the occupant will feel 'neutral' regarding the thermal environment. This information is presented in green on the pictogram. The thermal measurements (i.e. air temperature, relative humidity and radiant temperature) of the workstation were measured and later analysed using the ASHRAE Thermal Comfort Tool. The result predicts that the occupant will feel 'neutral' regarding the thermal environmental condition.
- The PMV comfort model predicts that the occupant will feel 'slightly cool' regarding the thermal environment. This information is communicated with light blue on the pictogram. The process of analysing the PMV model is similar to the adaptive model.

Respondent's view of the thermal environment in the workstation, according to the survey questionnaire:

- The respondent feels 'slightly satisfied' and this is communicated with a light green colour on the pictogram.
- The respondent feels 'comfortable' and this information is presented in green.
- The respondent has a 'slightly warm' thermal sensation, as is presented in light red.
- The respondent wants a 'slightly cooler' temperature, which is presented in light blue.

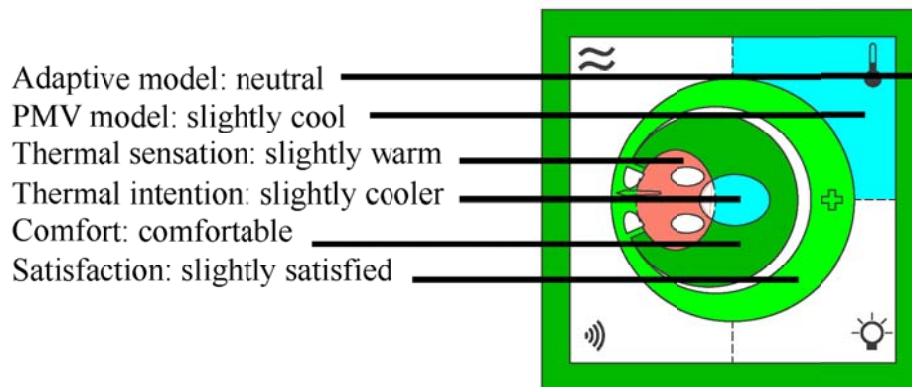


Figure 63: Example: how to read the pictogram

Figure 64 shows an example of using the pictogram in context, as four respondents at their workstations are demonstrated. They share the same thermal environment, which is the reason the adaptive comfort and PMV models predict similar responses for all four occupants, neutral and slightly cool, respectively. However, they feel different thermal sensations, as respondent 'a' feels neutral, respondent 'c' feels slightly cool and the other two feel slightly warm. Only respondent 'b' wants a change in the temperature, while the other three occupants are quite happy with the current temperature and want no change. Only respondent 'b' feels uncomfortable and dissatisfied, while the other three users feel comfortable/very comfortable and satisfied/very satisfied. This brings to light the possibility of a connection between thermal intention of the occupant and variables including comfort and satisfaction. This is further investigated in Chapter Nine, section 9.1.

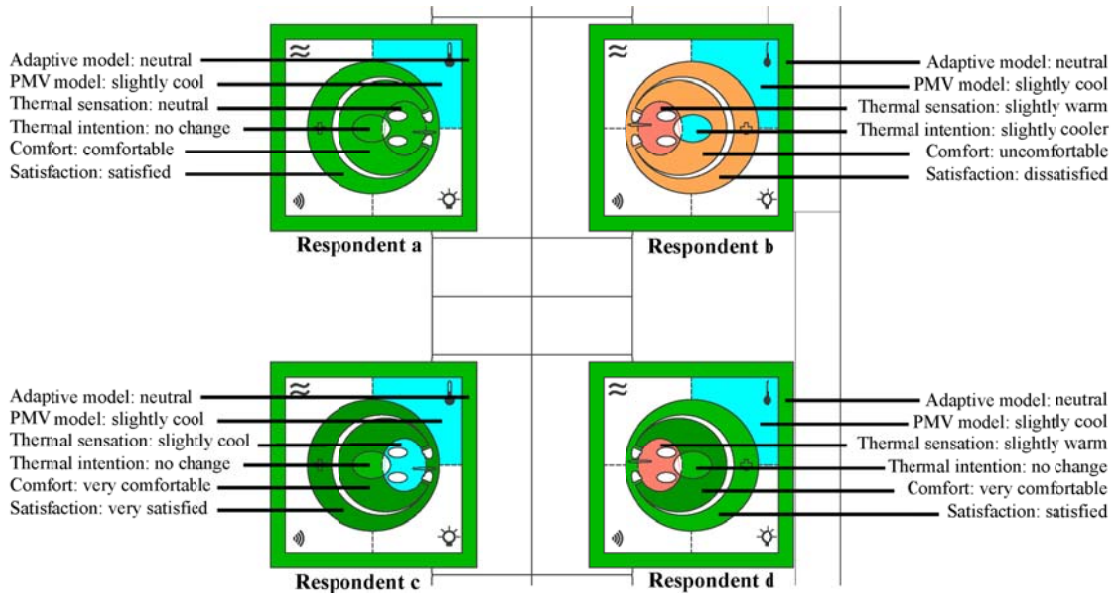


Figure 64: Example of using the pictogram in context

6.2. Refined Research Objectives

The analysis and findings of the pilot studies indicate individual differences in perceiving the thermal environment as well as their willingness to apply environmental control, explained respectively in sections 6.1.4 and 6.1.6. In this section, the research objectives are refined, based on the pilot studies and analysis.

Two main objectives are distinguished, including challenging the concept of the ‘comfort zone’ and investigating the application of ‘individual thermal control’ in the workplace. The former challenges the view of the ‘comfort zone’ in an endeavour to satisfy everyone, which is presented by comfort standards and researchers in the field. In order to examine this challenge, three objectives are identified for further investigation. Firstly, the accuracy of the most widely used ‘comfort zone’ presented by the ASHRAE Standard 55-2010 is examined. Secondly, the application of the ‘neutral thermal sensation’, which is the basis of thermal comfort standards and studies, is questioned. Thirdly, the consistency of occupant’s thermal preference throughout the day is studied.

In order to investigate the application of ‘individual thermal control’ in the workplace, two objectives are clarified. Firstly, the influence of thermal intention of the occupants in applying environmental control on their satisfaction and comfort are studied. Secondly, the application of thermal control in two office layouts with high and low levels of environmental control is researched. This is the basis for this thesis, and the research question refers mainly to this part. Based on this objective, satisfaction, comfort, health, and productivity of the users of Norwegian cellular and British open plan offices are compared. The former provides high levels of environmental control for every occupant, while the latter has limited thermal control for occupants around the perimeter of the building.

6.3. Refined Research Plan

Based on the pilot studies, the research plan is finalised. Environmental measurements are applied to analyse building performance, while interviews and questionnaires are used to record users' response and behaviour towards their thermal environment. The length of a site visit is approximately one week per building. The stages of the research plan as well as the measuring equipment are presented in this section. These stages include a meeting with management, walkthrough, measuring the building, schedule user participation, semi-structured interviews, and surveying workstations.

6.3.1. Meeting with Management

The first step is to set a meeting with the management of the building. This meeting usually happens prior to the field study visit in order to gain access to the building. The research purpose and plan will be discussed in this meeting and management may talk about the history or difficulties of the building. The facilities manager is the key person to have the meeting with, as he holds valuable information regarding the building performance and occupants' complaints, explained in the next section. In order to inform the staff about the research, an introductory letter was provided to inform them about the research and invite them to participate. This electronic mail is sent to the management to be sent out to their staff. It is particularly important to mention how much time they are expected to spend for the research, which is less than 15 minutes to encourage staff to participate in the research.

6.3.2. Walkthrough

This is a touring interview with the facilities manager, which can be combined with the previous step, the meeting with management. This is an important part of the fieldwork to understand the building performance. Plant room, different parts of the buildings and sometimes the roof are visited and the building performance is explained and documented by recording and taking photos. A checklist is prepared to cover the essential information as follows:

1. Facilities manager's contact details, preferably email address
2. Plans and sections of the building, including the plan of the plant room if available
3. News or published journal articles regarding the building
4. Energy supply and performance
5. Energy bills

6. Who controls the building services and comfort? How do they measure occupants' comfort?
7. How is the building performance? How many complaints they receive?
8. Has there been any refurbishment, regarding the building and its services?
9. Timing of the centralised systems, morning/evening, weekdays/weekend
10. Availability of environmental control for users and user manual
11. The air supply, inlet and outlet in the personal rooms or the open plan office
12. Location of duct work, horizontal and vertical

6.3.3. Measuring the Building Performance

The measuring equipment are presented in section 6.4. Two different environmental measures are applied to record the building performance, including constant and instant readings. The latter is explained in section 6.3.6, which is the simultaneous instant measurement and questionnaire at each workstation. The continuous measurement of the building is mainly temperature and humidity recorded using data loggers. The data loggers are spread horizontally as well as vertically for the duration of a day each. This is useful to understand the thermal performance of the building overall and particularly to identify unacceptable thermal settings in different parts of the building. The horizontal measurement is used to identify different thermal zones within the building, presented in section 7.2.2. Therefore data loggers are located in both the north and south parts of the building as well in the middle part. As explained in section 6.1.2, a data logger continuously measures the outdoor temperatures. Figure 65 shows an example of the horizontal measuring points in the building.

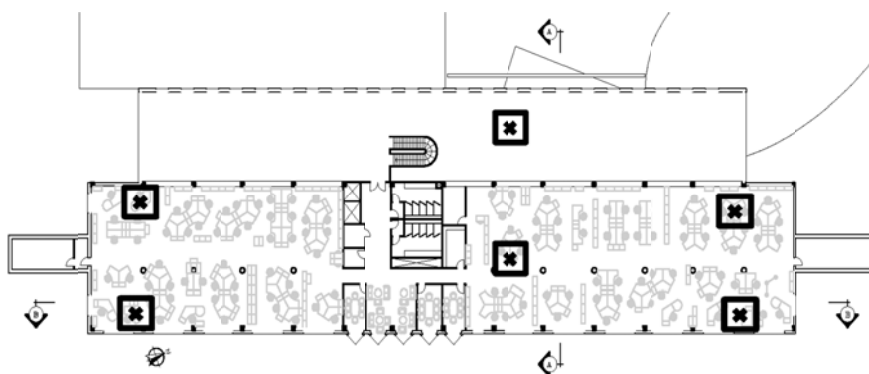


Figure 65: An example of horizontal measuring points: Building C

To record the vertical thermal performance of the building, data loggers are spread in different floors. Figure 66 shows an example of the vertical measuring points in the building.

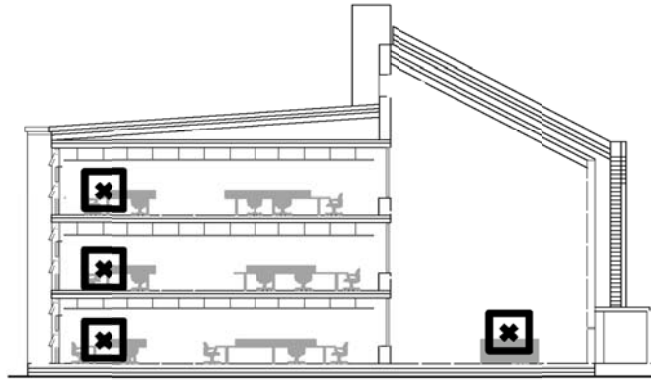


Figure 66: An example of vertical measuring points: Building C

The last three days of the fieldwork, the instant survey of the workstations is applied. In order to calculate the mean radiant temperature, measurements of the surface temperature are required, explained in section 7.2.3. Therefore, three data loggers are located vertically in three levels: floor, desk and ceiling. A typical example of the vertical measuring positions is shown in Figure 67. Due to limited number of data loggers, two locations in the opposite parts of the building are selected and measured. A data logger is in the corridor or in between these two locations, presented in Figure 68.

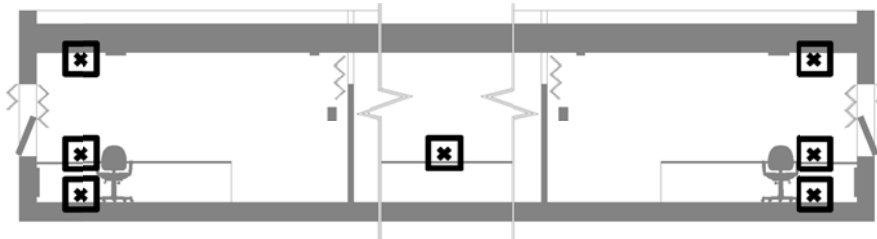


Figure 67: An example of measuring points: Building B

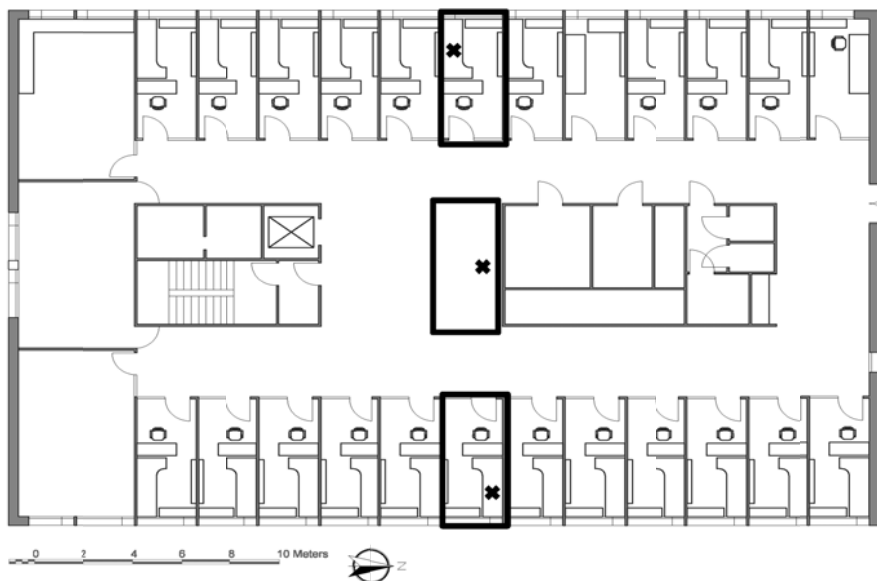


Figure 68: A sample of horizontal measuring positions: Building B

The main instant survey of the workstations includes the following:

- Survey questionnaire of the occupant, presented in section 6.3.6 and Figure 70
- Instantaneous measurements: temperature, humidity, carbon dioxide, light, and noise. The equipment are presented in section 6.4.2
- Observation: such as clothing, which is a passive adaptive method that users apply to adjust themselves to the thermal environment so that they feel comfortable.
- Researcher's online questionnaire to record the instant measurements and observations, presented in Figure 71
- Surface measurements: floor, desk and ceiling. Eight data loggers are used, which are presented in section 6.4.1
- Outdoor measurements: one data logger is always kept outside the building to record the outdoor temperature and humidity to be used as a basis for comparing the indoor measurements.

6.3.4. Schedule Participants' Availability

Occupants are informed about the research by management prior to the site visit, explained in section 6.3.1. At the site visit, the availability of the participants for the interview and questionnaire is scheduled. It is useful to manage this schedule as early as possible, due to complexity and limited timing. The interview can be scheduled anytime, but the questionnaire is applied three times in a particular day, including morning, early and late afternoon. Therefore it is important to schedule the questionnaire on a day in which the participant has a more flexible working day. Often the participants are not present at their workstations and the researcher needs to come back to apply the survey. This schedule is particularly important and careful consideration is required, since the site visit is limited to a few days and overall 30 participants are surveyed three times a day, in addition to their interviews. This is a very heavy schedule and a professional time management tool is required to avoid extra complexities. In this research, online Smartsheet software is used, which is a useful and user friendly tool, illustrated in Figure 69. Based on the experience in the pilot studies, in order to avoid extra effort to find the participants at their workstations, their time of entrance and departure as well as their unavailable time, such as meetings and lunch break, are included in the schedule. In case the participant is available only for a very short period between meetings, their survey is prioritised with red circles. After every survey, it is ticked off in the schedule to keep track of accomplished tasks.

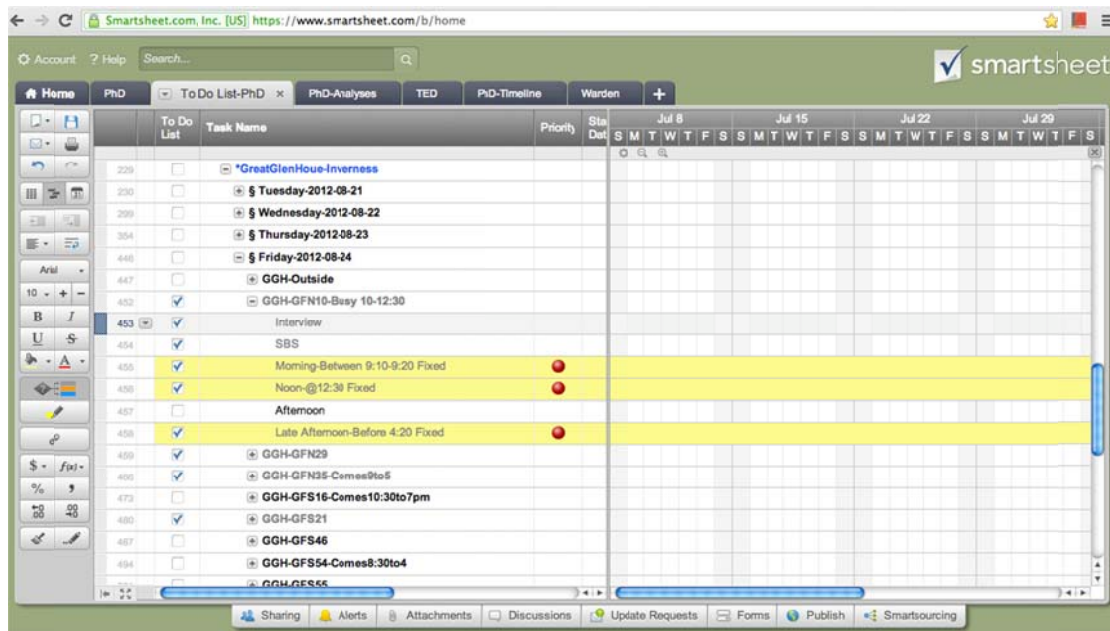


Figure 69: The scheduled time management of the survey, using Smartsheet

6.3.5. Semi-Structured Interviews

The interview focuses on the occupant's general satisfaction, thermal preference and environmental control. Preferably, the order of the questions is based on the natural flow of the conversation, as participants often cover other questions when answering a particular question. For instance, temperature and light are usually covered in the first question regarding their general satisfaction with the building. The following questions are included in the semi-structured interview:

1. General
 - 1.1. Are you male or female?
 - 1.2. What is your decade of birth?
 - 1.3. What is your nationality?
2. How long have you been working in this building?
 - 2.1. At this particular workstation?
 - 2.2. Are you on a full time basis?
 - 2.3. How often are you at your workstation?
3. How do you consider the building overall?
4. How do you consider the temperature, light, noise, and air quality in your workstation?
5. What do you do when you feel warm or cold at the office?
6. How much control do you have at the office? What sorts of control do you have?
7. Generally speaking, do you tolerate cold or warm conditions better?

8. In the ideal world, would you like the temperature settings at work to be automatically so that you don't do anything about it, or would you like to set and change it yourself?

8.1. Why?

8.2. What sort of control would you like to have?

8.3. How often would you change the settings? Once a year, season, month, week, day, or more?

9. Have you noticed any pattern of temperature changes in the office?

9.1. Seasonal, day and night, beginning and end of the week

10. Do you have any comments or feedback?

6.3.6. Surveying Workstations

This part records occupant's response to the immediate thermal environment as it changes throughout the day. The researcher met each occupant three times a day (i.e. morning, early and late afternoon) so that the respondent fills in a survey questionnaire while the researcher records environmental measurements at the particular workstation, explained in section 6.1.2. The process of preparing the questionnaire is presented in section 6.1.3 and the initial questionnaires that led to the design of this questionnaire are presented in Appendix B. This is an online questionnaire, which is presented to the occupants on an iPad. Most occupants enjoy using this device, the ease and speed of collecting data and the long lasting battery of this device are very beneficial in this research, explained in section 6.1.3. A copy of the questionnaire is presented in Figure 70. These questions record users' view of the thermal environment at the time of the measurements. The questions include user comfort, satisfaction, thermal sensation and thermal intention based on the ASHRAE seven point scale (ASHRAE, 2009), discussed in section 3.2.2.1. The respondent's view of indoor quality is examined by questioning adequacy of the air movement, fresh air and light level. A productivity question is included based on McCartney's transverse questionnaire (McCartney and Nicol, 2002). Thermal sensation is the main question to indicate thermal comfort of the user in the studies of thermal comfort and thermal intention is included to examine this application as well as the neutral thermal sensation, discussed in sections 8.1 and 8.2. Satisfaction and comfort are other measures to show users' view of their environment. The relevance of these questions to the 'thermal environment' is specified in the questions and reinforced by the researcher at the time of the survey to reduce the influence of other factors on users' comfort and satisfaction.

The environmental measurements include instant readings of the temperature, humidity, carbon dioxide, noise, and light levels, discussed in section 6.3.3. The measuring equipment

is presented in section 6.4.2. This information in addition to observations, such as the occupant's clothing, position of the windows and blinds, are recorded on another online questionnaire by the researcher, which is presented in Figure 71. Bristol Online Questionnaire is used to manage these two questionnaires and the respondent cannot submit the questionnaire unless all the necessary questions are answered.

Individual Comfort

1. Code

2. What is the date today

 (DD-MM-YYYY)

Time

If you selected Other, please specify:

3. Currently at my desk, I feel

- Very comfortable
 Comfortable
 Slightly comfortable
 Neutral
 Slightly uncomfortable
 Uncomfortable
 Strongly uncomfortable
 No strong opinion

4. The current temperature at my desk is

- Very cold
 Cool
 Slightly cool
 Neutral
 Slightly warm
 Warm
 Hot
 No strong opinion

5. I prefer the current temperature at my desk to be

- Much colder
 Colder
 Slightly colder
 No change
 Slightly warmer
 Warmer
 Much warmer
 No strong opinion

6. Currently at my desk, the air is dry

- Strongly agree
 Agree
 Slightly agree
 Neutral
 Slightly disagree
 Disagree
 Strongly disagree
 No strong opinion

7. Currently at my desk, the following is

	Strongly adequate	Adequate	Slightly adequate	Neutral	Slightly inadequate	Inadequate	Strongly inadequate	No strong opinion
a. Air movement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
b. Fresh air	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
c. Light level	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

8. Currently this part of my body is

	Very cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot	No strong opinion
a. Feet	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
b. Hands	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
c. Face	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

9. Compared to normal, currently my productivity is

Much higher Higher Slightly higher The same Slightly lower Lower Much lower No strong opinion

10. During the last hour, I changed the followings
(select all that apply)

- Put on some clothes
- Take off some clothes
- Open a window
- Close a window
- Open a door
- Close a door
- Open a blind
- Close a blind
- Change the thermostat
- Informed the facilitator manager/the person in charge
- Moved to another space
- None of the above
- Other (please specify):

11. Currently at my desk, the overall environment makes me feel

Very satisfied Satisfied Slightly satisfied Neutral Slightly dissatisfied Dissatisfied Very dissatisfied No strong opinion

Continue >

Figure 70: Occupants' online questionnaire to record their instant comfort and satisfaction regarding their thermal environment

4 Times

1. Code

2. What is the date today

 (DD-MM-YYYY)

Time

If you selected Other, please specify:

3. Please fill in the blank

a. Temperature	<input type="text"/>
b. Humidity	<input type="text"/>
c. CO2	<input type="text"/>
d. Light	<input type="text"/>
e. Noise	<input type="text"/>

4. Wall Temperature

5. Window

	Open	Slightly open	Half open	Much open	Closed	Does NOT have this kind of window
a. Main window	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
b. Side window	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
c. Top window	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
d. Botton window	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

6. Blinds

	Open	Semi open	Closed	No blinds	Other (please specify)
a. Corridor blinds	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/> <input type="text"/>
b. Interior window blinds	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/> <input type="text"/>
c. Exterior window blinds	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/> <input type="text"/>

7. Cloths

Short Sleeves
 Long Sleeves
 Jumper
 Two Jumpers
 Other (please specify):

8. Measurements

a. Width	<input type="text"/>
b. Length	<input type="text"/>
c. Height	<input type="text"/>

9. Picture

Yes
 No
 Other (please specify):

10. How often do you have the following:

	Constantly	Very Often	Often	Occasionally	Rarely	Never	No Strong Opinion	Other (please specify)
a. Dry or Watery Eyes	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/> <input type="text"/>
b. Blocked or Runny Nose	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/> <input type="text"/>
c. Dry or Irritated Throat	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/> <input type="text"/>
d. Chest Tightness	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/> <input type="text"/>
e. Headaches	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/> <input type="text"/>
f. Tiredness	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Figure 71: Researcher's online questionnaire to record observations and measurements of the thermal environment

6.4. Measuring Equipment

Two different measurements are applied, constant and instant, which require two different sets of equipment. In addition, a laptop, iPad, and camera are required for this research. The presented equipment is compatible with ASHRAE Standard 55-2010.

6.4.1. Continuous Recording of Environmental Conditions

Dry bulb temperature and relative humidity are constantly monitored in the building by using a data logger, which includes both a thermocouple and hygrometer, as explained in section 6.3.3. Figure 72 illustrates the type of logger used, a Tinytag plus 2 TGP-4500 data logger. It contains a 10K NTC Thermistor, mounted internally. Dry bulb temperature readings ranges from -25°C to $+85^{\circ}\text{C}$ and relative humidity from 0% to 100% RH. Reading accuracy is 0.01°C for dry bulb temperature and $\pm 3.0\% \text{RH}$ for relative humidity. The equipment complies with FCC regulations, ISO 9001 and ISO 14001 (<http://www.geminidataloggers.com>). Eight of these data loggers were used simultaneously for thermal readings at different parts of the building, as explained in section 6.3.3. The equipment is expected to be re-calibrated every six months for humidity and once a year for temperature recordings. In this research, new equipment was used so re-calibration was not required.



Figure 72: Tinytag plus 2, Gemini data loggers, constant measurements of dry bulb temperature and relative humidity (image source: <http://www.geminidataloggers.com/>)

6.4.2. Instant Recordings

In order to record the instant environmental measurements of every workstation, different equipment is required. Environmental conditions include dry bulb temperature, relative humidity, carbon dioxide, light, and sound levels. The dry bulb temperature, relative humidity and carbon dioxide levels are recorded by the PCE-GA 70 air quality meter, which is illustrated in Figure 73. The equipment has a dual wavelength detector with a non-dispersed infrared (NDIR) sensor to measure carbon dioxide level up to 6000 ppm, the resolution is

1ppm and the accuracy is $\pm 3\%$ of reading or ± 50 ppm. Dry bulb temperature is recorded by a thermocouple (i.e. thermistor) that measures -20°C to 60°C , the resolution is 0.1°C and the accuracy is $\pm 0.5^{\circ}\text{C}$. Relative humidity is recorded using a hygrometer (i.e. precision capacitance sensor) that measures 10 to 95% RH, the resolution is 0.1% RH and the accuracy is $\pm 3\%$ RH. The instrument is precalibrated by the manufacturer (<http://www.industrial-needs.com>).



Figure 73: Air quality meter, instant measurement of carbon dioxide, temperature and humidity (image source: <http://www.industrial-needs.com/technical-data/air-quality-meter-pce-ga70.htm>)

Light levels are recorded by mini environmental quality meter – 850070, which is presented in Figure 74. This device measures light levels, dry bulb air temperature, relative humidity, and also air speed through a light meter, thermometer, hygrometer, and an anemometer. In this research, this instrument has been used only for recording light levels therefore information regarding other functions are not included. The instrument records light levels from 0 to 20000 Lux with a resolution of 1 Lux and accuracy of $\pm 3\%$ + 20ft/min (<http://www.sperdirect.com>).



Figure 74: Anemometer, mini environmental quality meter - 850070 (image source: <http://www.sperdirect.com/mini-environmental-quality-meter-410-prd1.htm>)

The noise level is measured by a sound level meter called a digital type 2 sound meter 840029, which is presented in Figure 75. This device is useful to measure continuous sound levels in the workplace. The equipment measures A and C frequency weighting ranging from 30-70 dB, 60 to 100 dB, and 90-130 dB, the resolution is 0.1 dB, the accuracy is ± 1.5 dB, and the frequency is 31.5 Hz to 8000 Hz. The calibration adjustment of the instrument is built-in using a button on the front panel and the internal calibration is 94 dB/1 kHz square wave generator. The instrument complies with IEC 61672 class 2, ANSI S1.4 type 2 frequency and time weighting specifications, DIN 45633 and JIS 1502 (<http://www.sperdirect.com>).



Figure 75: Sound level meter (image source: <http://www.sperdirect.com/digital-type-2-sound-meter-310-prd1.htm>)

6.5. Criteria

In this research, the selection of the case study buildings is based on different criteria, such as building layout and environmental control systems. However, complexities in accessing the buildings greatly influence and limit this selection, discussed later in section 10.4. Based on the literature review, Norwegian cellular and British open plan offices are selected for comparison with respectively high and low environmental control systems, explained in Chapter Four. In order to have a basis for comparison, at least two buildings of each office layout are studied. This research seeks to investigate successful and benchmarked practices of both types, which provide high standards of indoor environment. In this way, users' satisfaction, comfort, health, and productivity are less likely to be influenced by the quality of the indoor environment. Therefore their difference is more likely to be related to the great difference in the availability of individual environmental control systems. Further qualitative interviews are applied to clarify this matter.

Based on the experiences in the pilot studies and in order to avoid complication, old and refurbished office buildings have been avoided. Preferably selected offices had been built within the last ten years and they are based on the latest modern office regulations in the two countries, discussed in section 4.2.2. It is particularly essential that the cellular practices follow the Norwegian regulations, including natural light, ventilation and outside view, discussed in section 4.2.2.1. The availability of individual environmental control systems in the cellular plan offices is particularly important, including openable window, blind, door, light, and preferably temperature controls. Very deep open plan offices are avoided, as they are associated with low user satisfaction (Bordass et al., 1993). All case study buildings are required to have openable windows, as this is an important thermal control system. However, the main air supply is provided by mechanical ventilation. Therefore a combination of natural ventilation and mechanical ventilation is desirable.

In the cellular plan offices, single occupancy of the personal offices is desirable, since the occupant's decision to control the thermal environment is not affected by others. In addition, Van Meel reports lower satisfaction levels in personal offices with more than one or two occupants (Van Meel, 2000). Full time occupancy of the workstations is preferable, as the long period of occupancy increases knowledge of the impact of the thermal environment, such as building related symptoms. Administrative occupations and similar activities are preferable, due to long hours of working at the workstation and similarity in activity and metabolic rate.

Due to the depth of data that is being collected in this study, the sample size is relatively small. In total, over three hundred responses are included in this research. Therefore, approximately thirty respondents are selected in every building, as every participant is surveyed three times in a particular day and overall four buildings are studied. Related studies include a similar sample size, which is between thirty to hundred respondents per building (de Dear and Brager, 2001, Leaman and Bordass, 2004, Arens et al., 2006, Wagner et al., 2007, Newsham et al., 2009, Bos and Love, 2013). Generalising the results of a small sample size is difficult. However, this research is based on in-depth and qualitative methods and analysis, which require time. Therefore a large sample size is avoided. In addition, Fisk reports that studies with a large sample size are more likely to have lower variance in regression analysis, thus extra consideration is required (Fisk et al., 2009). The sample does not require to represent the building as a whole, but to demonstrate various individuals in that particular office layout (Schiller et al., 1988). Participation in the research is mainly based on occupants' willingness (Schiller et al., 1988). A balance in participants' age and gender is required.

In order to specify a suitable season to apply the survey of the case study buildings, the two extremes of the year, summer and winter, were researched in the pilot studies, as explained in section 6.1.6. This is based on the fact that if the internal environment of a building is comfortable during the extremes of the year, most likely it is comfortable in the milder outdoor conditions in spring and autumn. CIBSE TM37 presents guidelines for overheating in the summer (CIBSE, 2006a). Due to climate change, increased electric equipment and body heat in an office in addition to the fact that majority of newly built offices are highly glazed, over heating in summertime is becoming an important problem in offices in the UK and similar countries (Nicol and Humphreys, 2005, Tuohy et al., 2007). Therefore summer is selected for the fieldwork in this thesis.

6.6. Summary

This chapter discussed the pilot studies, methods and analysis, research objectives, research plan, and finally criteria in selecting the case study buildings. The pilot studies are carried out according to the grounded theory in order to develop the research objectives, methods and analysis. Based on these findings, research objectives are finalised, including challenging the ‘comfort zone’ and investigating the ‘individual thermal control’. In addition, the research plan is finalised. It mainly includes recording the building performance through environmental measurements, the occupants’ perception of their thermal environment through a questionnaire, and in-depth investigation of environmental control through a semi-structured interview. Research equipment is presented and finally criteria for selecting the case study buildings are discussed, including building layout, environmental control, construction conditions, the number of buildings and participants, and the suitable season to conduct the research.

CHAPTER 7

BUILDING PERFORMANCE

7. Building Performance

Two Norwegian cellular plan offices with high levels of individual environmental control are compared to two British open plan offices with limited opportunity for individual control. This chapter includes an introduction to these case study buildings as well as a comparison of their performance. The introduction is a general overview of each building, including its location, measurements and layout, while the building performance section is a more detailed analysis of the ventilation system, energy performance, individual and central environmental control systems. This comparison is followed by qualitative observations and interviews in every section if applicable.

7.1. Overview of the Case Study Buildings

This thesis compares thermal comfort in two settings: cellular and open plan offices. The Norwegian practice provides high levels of thermal control for every individual, based on the regulations as presented in section 4.2.2.1. In contrast, the British practice provides limited thermal control as it is not required in the regulations, presented in section 4.2.2.2. Therefore two cellular plan offices in Norway are compared to two open plan offices in the UK.

The climatic analysis of Oslo, Aberdeen and Inverness, presented in this section shows that Oslo has colder winters (i.e. approximately 5°C) and warmer summers (i.e. approximately 23°C) compared to Aberdeen and Inverness. Aberdeen has lower precipitation rate compared to Oslo and Inverness (i.e. approximately 20mm). Although in August it rains a lot in Oslo, the precipitation rate is similar to Inverness the rest of the year. The average wind speed is stronger in Aberdeen and Inverness compared to Oslo (i.e. approximately 5 kts). Oslo is 60N latitude and Aberdeen and Inverness 57N latitude. Summer days in Oslo (i.e. approximately 2:50 am to 9:10 pm) are longer (i.e. approximately one hour) than Aberdeen and Inverness (i.e. approximately 3:30 am to 8:30 pm). Winter days in Oslo (i.e. approximately 9:20 am to 2:40 pm) are shorter (i.e. approximately one hour) than Aberdeen and Inverness (i.e. approximately 8:50 am to 3:20 pm). Figure 76 and Figure 77 demonstrate yearly climatic information of Oslo that applies to both Building A and Building B. Figure 78 and Figure 79 present yearly climatic condition in Inverness that applies to Building C and Figure 80 and Figure 81 in Aberdeen that applies to Building D.

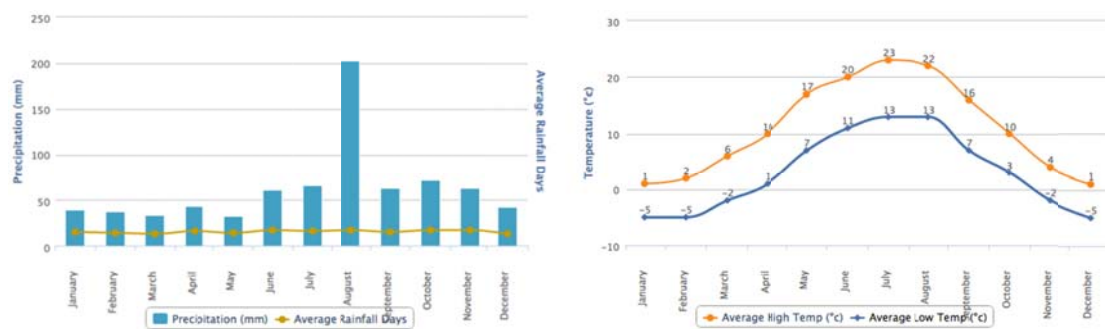


Figure 76: Yearly average precipitation and temperature: Oslo (source: www.worldweatheronline.com)

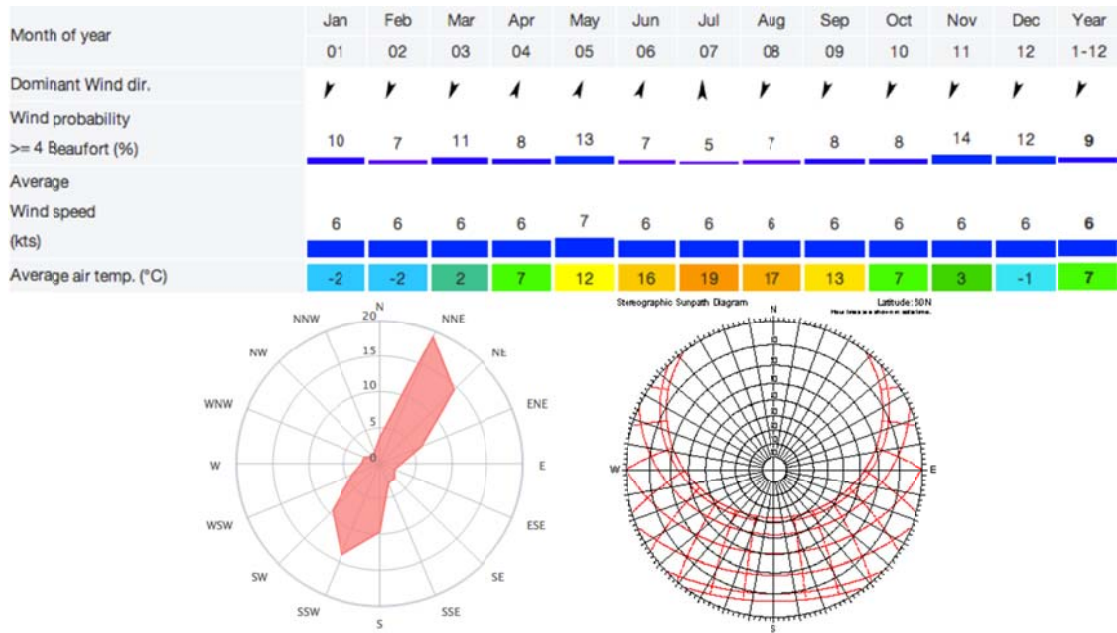


Figure 77: Wind direction distribution and sunpath diagram: Oslo (sources: www.windfinder.com and <http://www.jaloxa.eu/>)

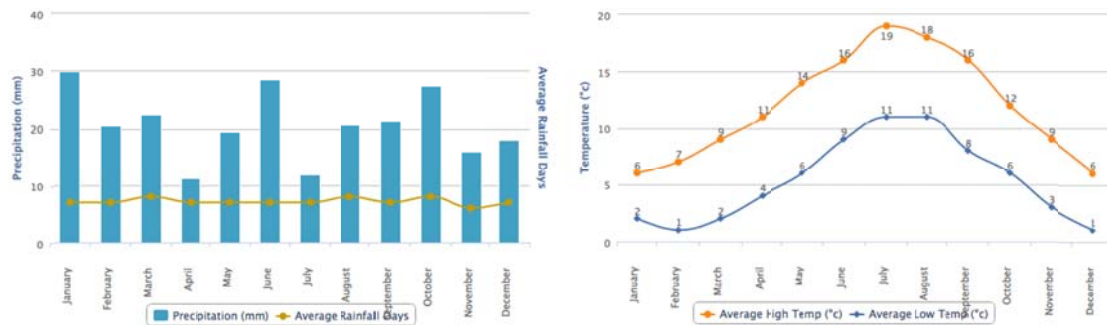


Figure 78: Yearly average precipitation and temperature: Inverness (source: www.worldweatheronline.com)

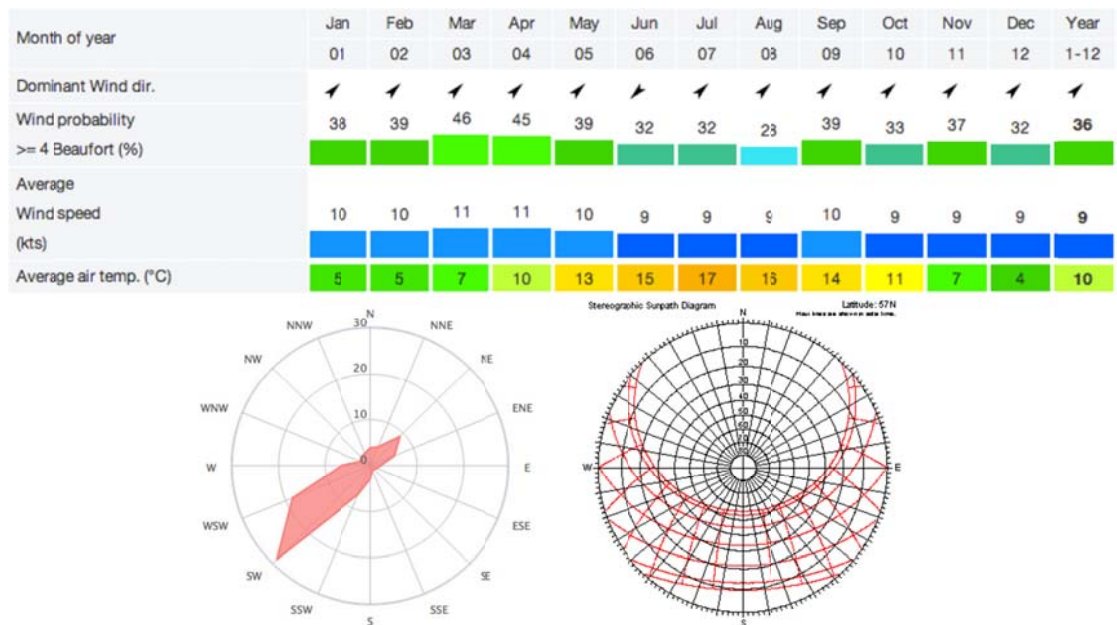


Figure 79: Wind direction distribution and sunpath diagram: Inverness (sources: www.windfinder.com and <http://www.jaloxa.eu/>)

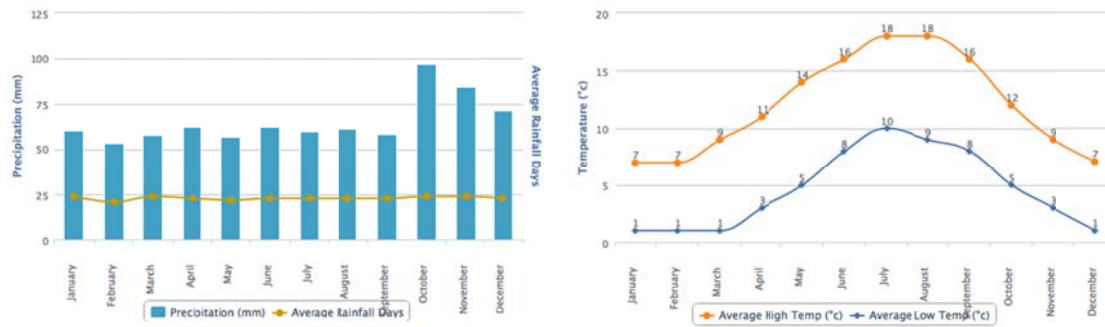


Figure 80: Yearly average precipitation and temperature: Aberdeen (source: www.worldweatheronline.com)

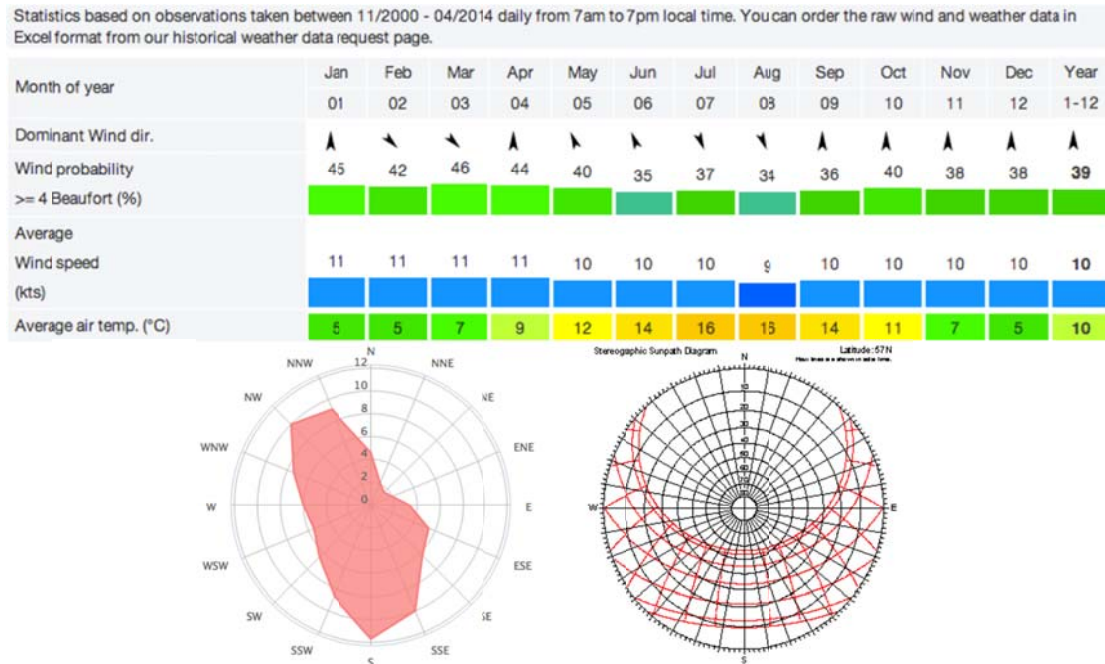


Figure 81: Wind direction distribution and sunpath diagram: Aberdeen (sources: www.windfinder.com and <http://www.jaloxa.eu/>)

7.1.1. Cellular Plan Offices in Norway

Buildings A and B are selected as the Scandinavian cellular plan offices with high levels of individual thermal control in this research, as discussed in sections 2.2.4.6 and 4.1.1. Building A is a commercial office and Building B is an academic department. Natural ventilation and air conditioning are in operation in the buildings. The design of these buildings provides every user with a high level of environmental control, such as a window, blind and thermostat, to adapt their thermal environment to their needs, which is based on the Norwegian work regulations, as discussed in section 4.2.2.1.

7.1.1.1. Building A



Figure 82: Building A: North facade

Building A is anonymised by the request of the office management. Built in 2000, it is a Scandinavian cellular plan workplace in Oslo, at the suburban ten kilometres away from the centre of Oslo. Train and bus provide public transport access to the building. It is a four-storey office building that is rented to different companies. The third floor, comprising mainly offices and service area, is part of this research. A company with research and administrative activities rent this floor as well as the top floor, which also includes several meeting rooms and a canteen. The plan of the third floor is 2000 m² overall (i.e. 20 m² per person), includes 100 offices, and every office is 10 m², presented in Figure 86.

The personal offices are located around the perimeter of the building, while the service areas, such as copy rooms, toilets and pantries, are in the middle. Every office has natural ventilation, air conditioning (i.e. 4 ach⁻¹), cooling and heating, are explained in detail in section 7.2.1. In each office, the window allows sufficient amount of light, which can be controlled by a blind, and the artificial florescent light is adjusted via a light switch. The openable window allows the occupant to control the natural ventilation and the thermostat provides control over the temperature. According to the interviews, occupants are well aware of these control opportunities and they use them extensively to adjust the thermal condition in their personal offices. Each office is connected to the corridor through a wooden door and a large glass wall. This provides every office with a visual connection to the rest of the floor and indirectly lights the central spaces, presented in Figure 87. In order to encourage communication between staff, the company has an open door policy and the arrangement of the desk and computer in each office is in such a way that the occupant faces the door, presented in Figure 88. According to the interviews, occupants close the door as a signal to

other staff not to be interrupted when they want to concentrate on their work, have a confidential conversation, or further regulate the climatic condition in their office. In order to increase users' comfort, everything in the office is adjustable, including desks and chairs to meet individual requirements.

The climatic analysis of Oslo is presented in section 7.1: Figure 76 and Figure 77. The wind and shadow pattern analysis of Building A are illustrated in Figure 83 and Figure 84. Figure 85 to Figure 94 present plans, sections and photos of Building A, on which important information are highlighted to illustrate the office context.

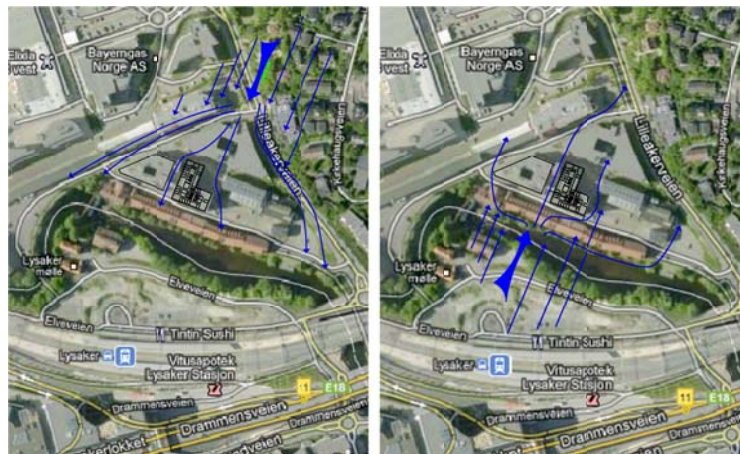


Figure 83: Building A: Predominant wind direction and analysis in summer (left) and winter (right)

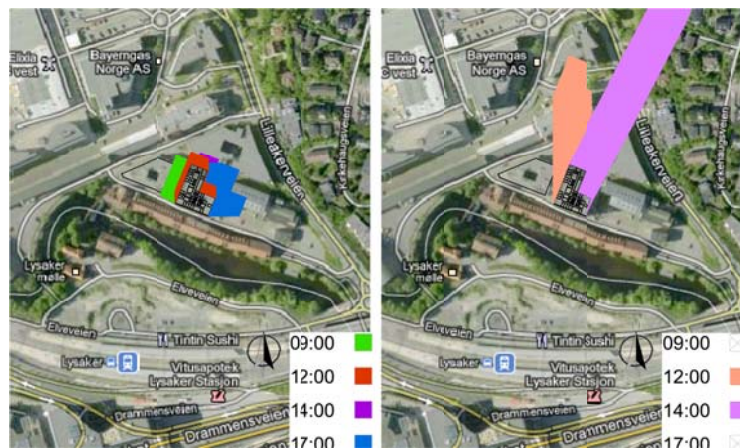


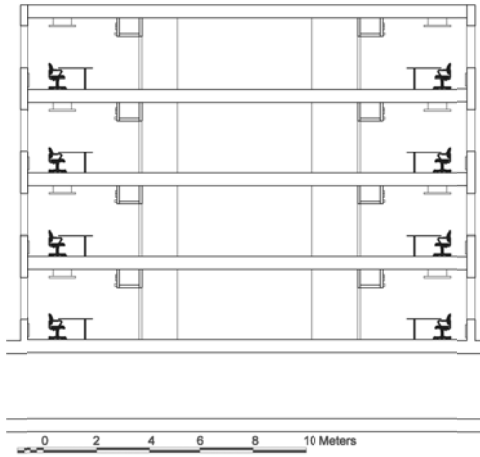
Figure 84: Building A: shadow pattern analysis in summer (left) and winter (right)



Figure 85: Building A: South façade and the main entrance



Figure 86: Building A: Third floor plan: researched area is highlighted by a black frame



Building A: Section

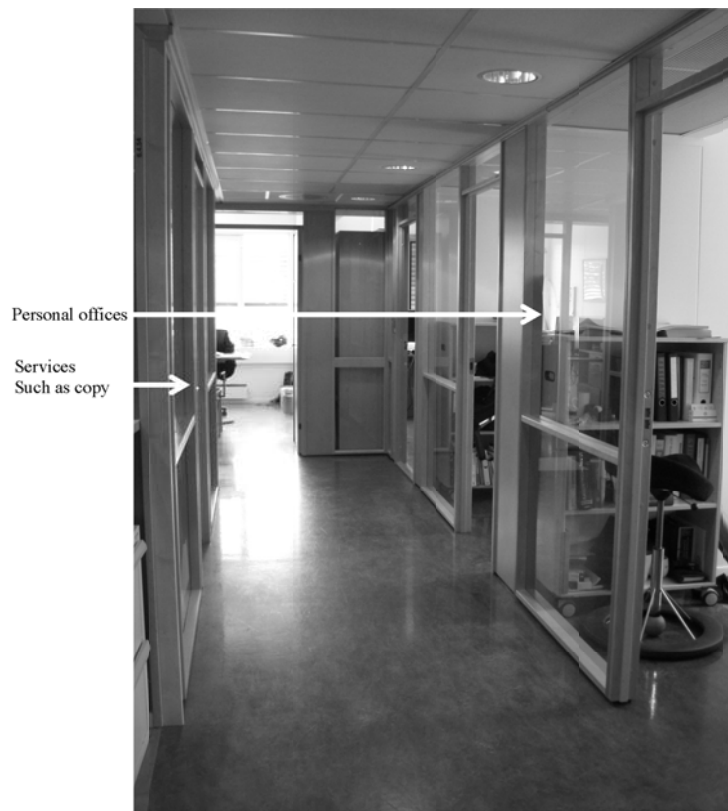


Figure 87: Building A: Personal offices, corridor and services



Figure 88: Building A: A typical personal office, third floor

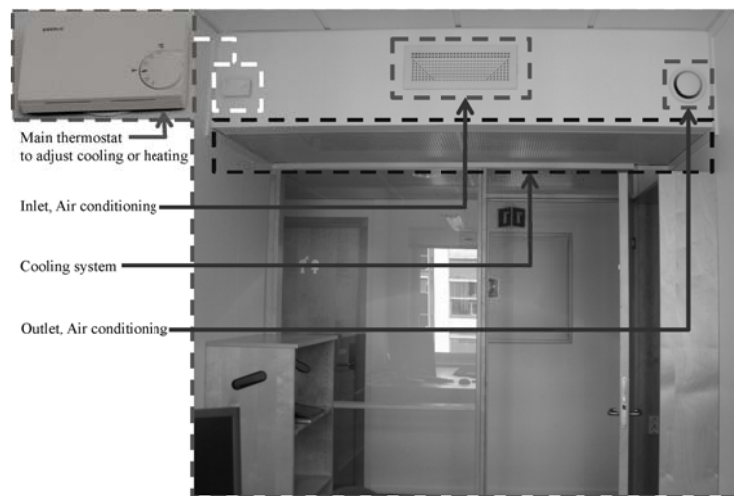


Figure 89: Building A: Ventilation system and thermal control

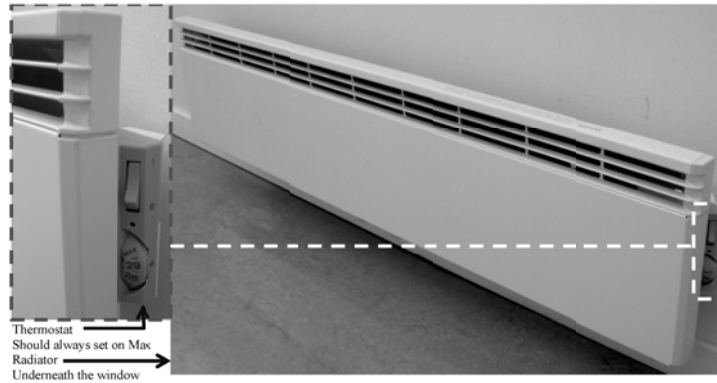


Figure 90: Building A: Radiator and its thermostat (i.e. not to be used)

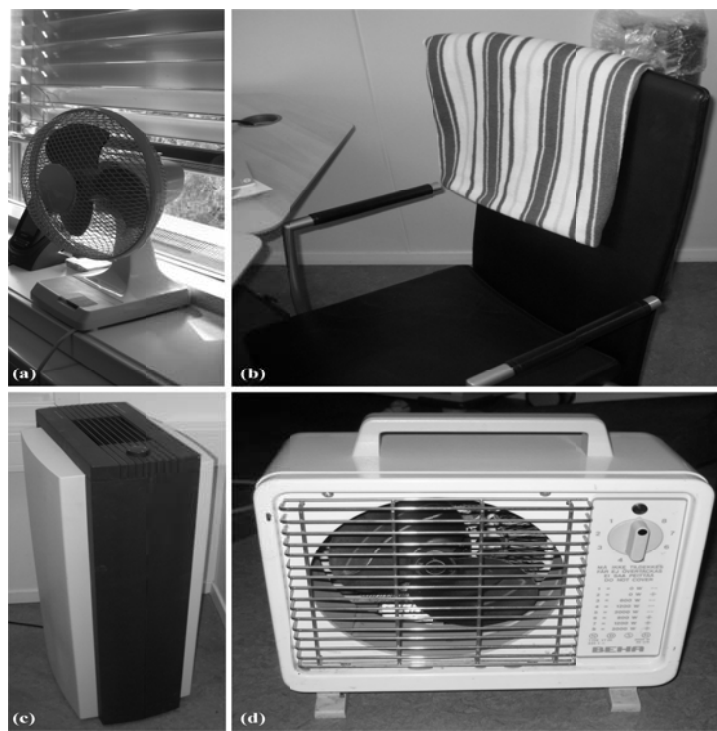


Figure 91: Building A: Additional individual thermal control, such as a fan, blanket, cooler, and heater



Figure 92: Building A: Service areas, including break areas and pantry



Figure 93: Building A: Service areas, such as canteen



Figure 94: Building A: Air handling unit with heat recovery, located in the basement

7.1.1.2. Building B



Figure 95: Building B: East façade

Building B is a Scandinavian cellular plan office in Oslo. It is located in the university campus away from the centre of the city (i.e. over 3 km away towards North). Tram and bus are public transport systems to the building, and there is a bike shed to encourage cycling. The building has three different parts. The old part was originally a paper industry research institute, built in 1953. Later this old building refurbished and an extended in 2006 by L2 Arkitekter AS. This new part is a separate building with connections to the old section and the new part is the case study Building B. Mainly academic and administrative activities take place in the new building. Although the façade of the new and old parts are similar, they are very different regarding the design of their plans. The new part is constructed based on modern regulations and comfort criteria, as described in section 4.2.2.1. This is a four-storey building, every floor is 840 m² (i.e. 35 m² per person) and includes 24 cellular offices with 14m² per office. Although this building has a separate entrance, it is connected to the old building on the fourth floor through a door at the end of the corridor. The fourth floor is researched as part of this thesis.

The cellular offices are located around the perimeter of the building and services, such as copy room, pantry, break areas, and toilets are in the centre, presented in Figure 99 and Figure 101. Every individual has a personal office with an outside view, natural light and natural ventilation, which can be controlled through two openable windows, external, internal and corridor blinds, light switches, door, and a thermal control device on the wall. The personal offices are connected to a wide corridor via a wooden door and a glass wall. The door and the blind on the glass wall allow the occupant to control their visual connection and privacy. The windows provide sufficient quantities of natural light, while two blinds, interior and exterior,

provide control over natural light for the occupant. An additional artificial florescent light is positioned hanging from the ceiling over the desk. Light switches are provided to adjust light. Every office has natural ventilation as well as air conditioning with 4 ach⁻¹, which are discussed in detail in section 7.2.1. The windows are openable to enable control over natural ventilation, while the main ventilation system is air conditioning, with an inlet close to the window, an outlet close to the door, and cooling system between these two parts, explained in detail in section 7.2.1. A radiator is placed underneath the window in every office for heating purposes in the cold season. A control device is placed on the wall close to the door of every office to provide control over the heating and cooling.

The climatic analysis of Oslo is presented in section 7.1: Figure 76 and Figure 77. The wind and shadow pattern analysis of Building B are presented in Figure 96 and Figure 97. Figure 95 to Figure 109 present plans, sections and photos of Building B, on which important information are highlighted to illustrate the building context.

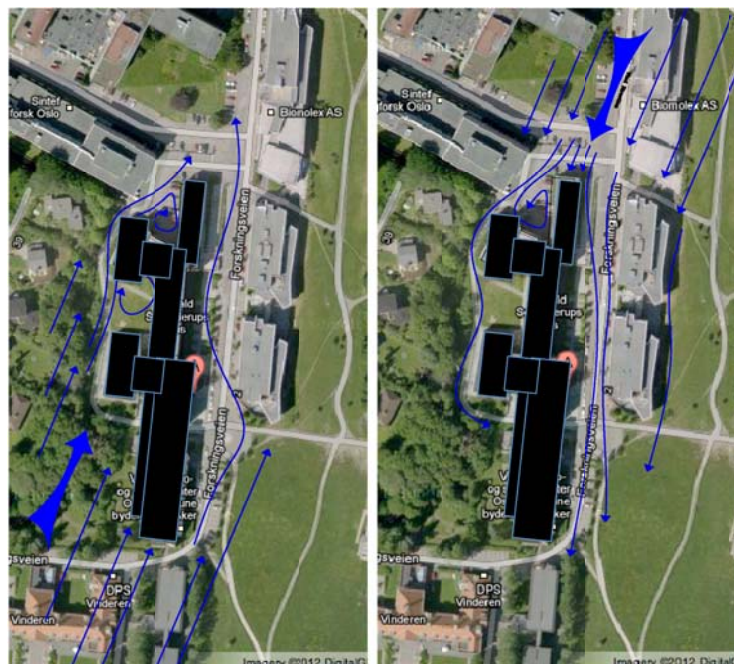


Figure 96: Building B: Predominant wind direction and analysis in summer (left) and winter (right)

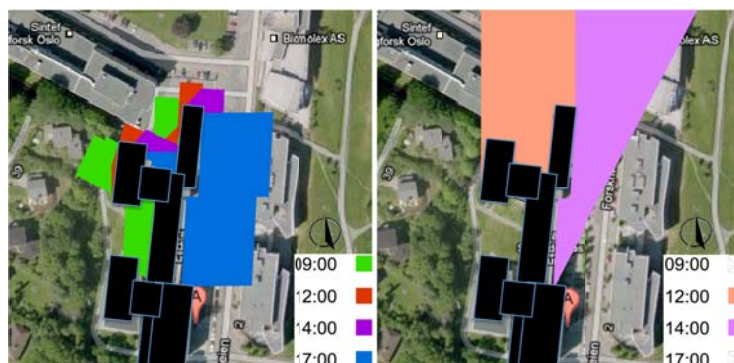


Figure 97: Building B: shadow pattern analysis in summer (left) and winter (right)



Figure 98: Building B: West façade

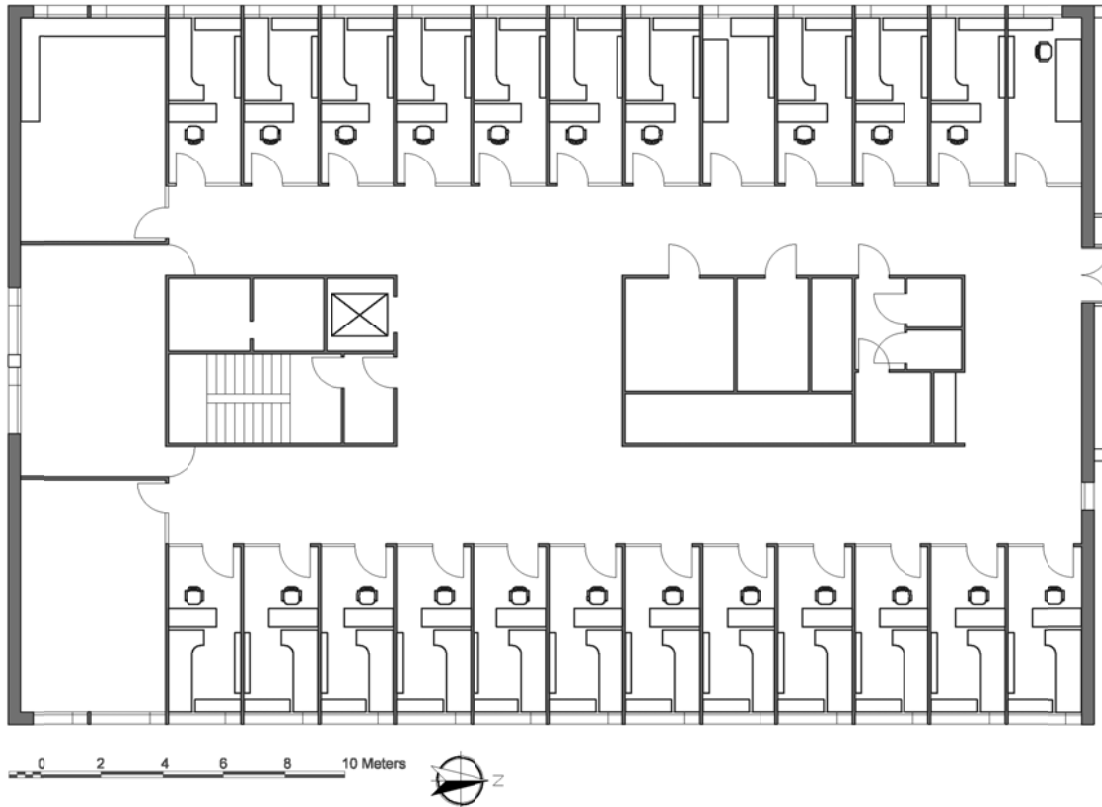


Figure 99: Building B: Typical floor plan, the fourth floor is researched and the connection doors with the old section are usually closed and not much activity takes place through them



Figure 100: Building B: East-West Section



Figure 101: Building B: Personal offices, corridor and service areas



Figure 102: Building B: Visual connection between the personal offices and corridor



Figure 103: Building B: A personal office

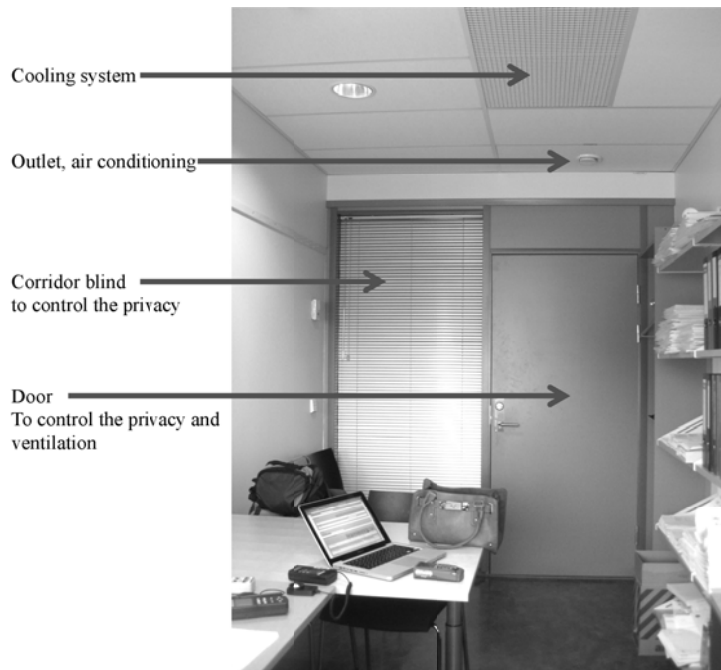


Figure 104: Building B: Ventilation system and privacy in a personal office



Figure 105: Building B: Control device, blind and light switch

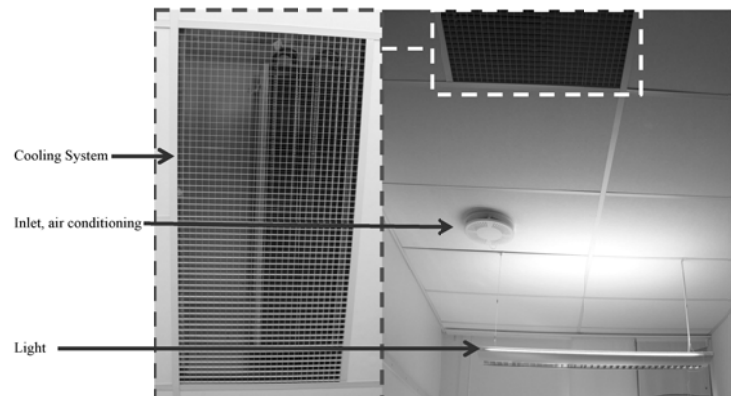


Figure 106: Building B: Cooling system, inlet and light

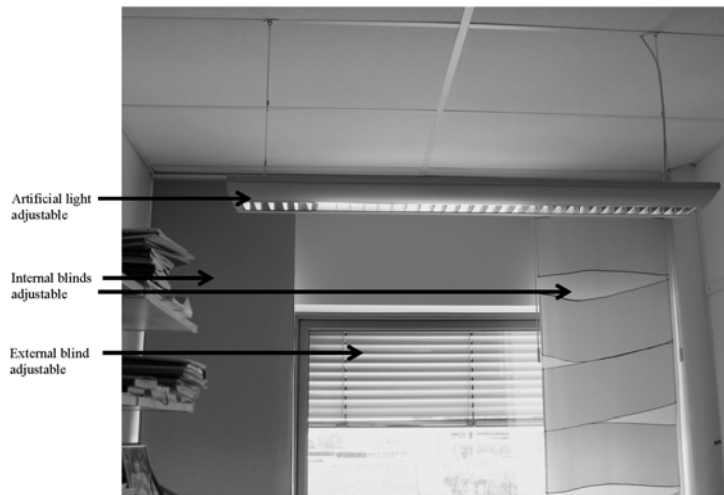


Figure 107: Building B: Light and blinds



Figure 108: Building B: Air handling units and central control system



Figure 109: Building B: Copy room

7.1.2. Open Plan Offices in Scotland

Building C in Inverness and Building D in Aberdeen are selected as the British open plan offices in this research, as discussed in sections 2.2.4.4 and 4.1.2. Both buildings have

achieved high environmental ratings, discussed in sections 7.1.2.1 and 7.2.4. Building C is a naturally and mechanically ventilated building. Limited users sitting around the perimeter of the building have access to openable windows and blinds to adjust the thermal environment, as discussed in sections 4.1.2 and 4.6. Displacement ventilation and limited natural ventilation are operating in Building D. Nevertheless, the majority of occupants sit close to the centre away from windows due to the depth of the open plan office and they are not provided with any environmental control opportunity, which is compatible with the British work regulations as discussed in sections 4.2.2 and 4.2.2.2.

7.1.2.1. Building C



Figure 110: Building C: West façade

Building C in Inverness, UK is one of the British open plan case studies in this research. This is the most sustainable building in this study with an ‘excellent’ BREEAM rating, 84% score, which was the highest score at the time. It also achieved 10 out of 10 Environmental Performance Indicator (EPI) rating. It also won the British Council for Offices award in 2006. This building is the headquarters for the Scottish Natural Heritage (SNH) and the Deer Commission for Scotland (DCS) in 2006 By Keppie Design and Mr Donald Canavan as the main architect. Mainly administrative activities take place in the building. It is located on a hill with a stunning view and far from the city centre. Bus is the main public transport, while a large bike shed and cycle paths encourage the staff to cycle to work. The building includes a canteen, library and a large atrium as an entrance. It is a three storey building and the office area of every floor is 1000 m² (i.e. 18 m² per person), including 125 workstations, and each workstation is allocated approximately 5 m², presented in Figure 115 to Figure 119.

This is a total open plan office even for senior management. Large windows and the glass atrium allow every occupant an outside view and natural light. Natural ventilation is the main ventilation system, although mechanical ventilation ensures indoor air quality, which is discussed in detail in section 7.2.1. Occupants sitting around the perimeter of the eastern part of the building have access to openable windows and blinds. Occupants sitting around the perimeter of the atrium have access to a blind to control natural light and prevent draughts from the atrium in the cold season, as the blind and its material are designed to separate the atrium and the office space. Thermal mass and body heat are the main source of the heat in the building and the perimeter radiators decrease the radiation effect from body to the cold surface of the window. Solar water heating and rainwater collection systems are in use.

The climatic analysis of Inverness is presented in section 7.1: Figure 78 and Figure 79. The wind and shadow pattern analysis of Building C are presented in Figure 111 and Figure 112. Figure 110 to Figure 131 demonstrate plans, sections and photos of Building C, on which important information are highlighted to illustrate the office context.

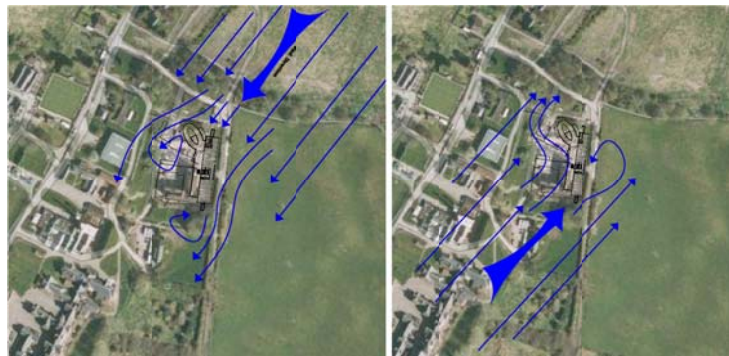


Figure 111: Building C: Predominant wind direction and analysis in summer (left) and winter (right)

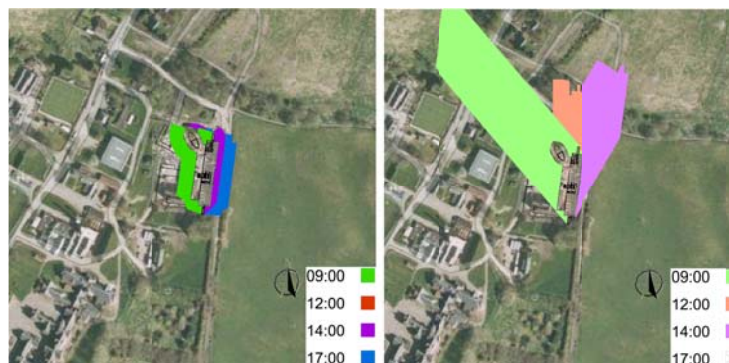


Figure 112: Building C: shadow pattern analysis in summer (left) and winter (right)



Figure 113: Building C: East façade



Figure 114: Building C: Atrium

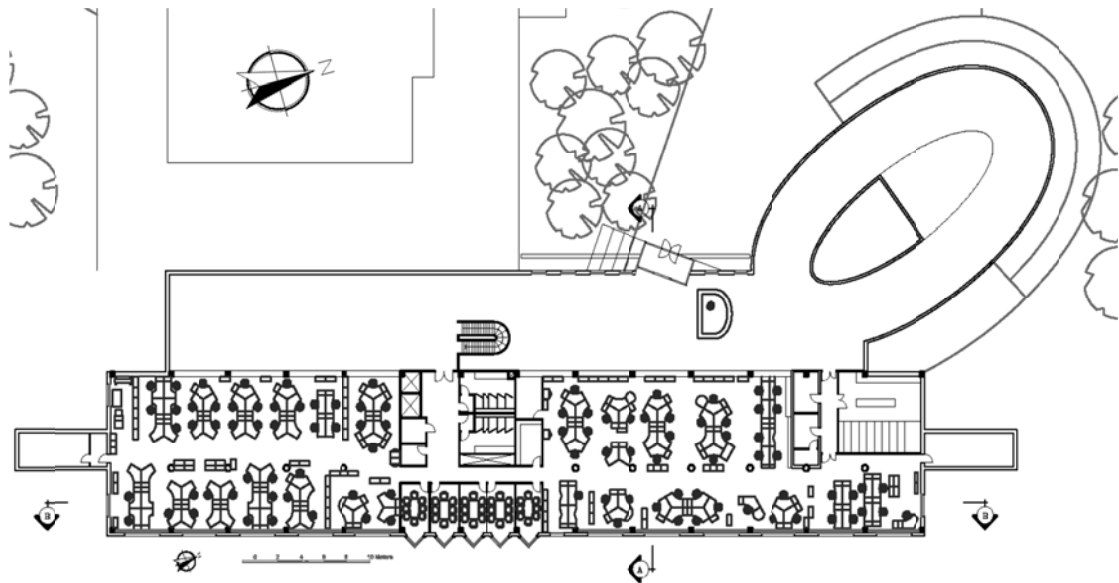


Figure 115: Building C: Ground floor plan

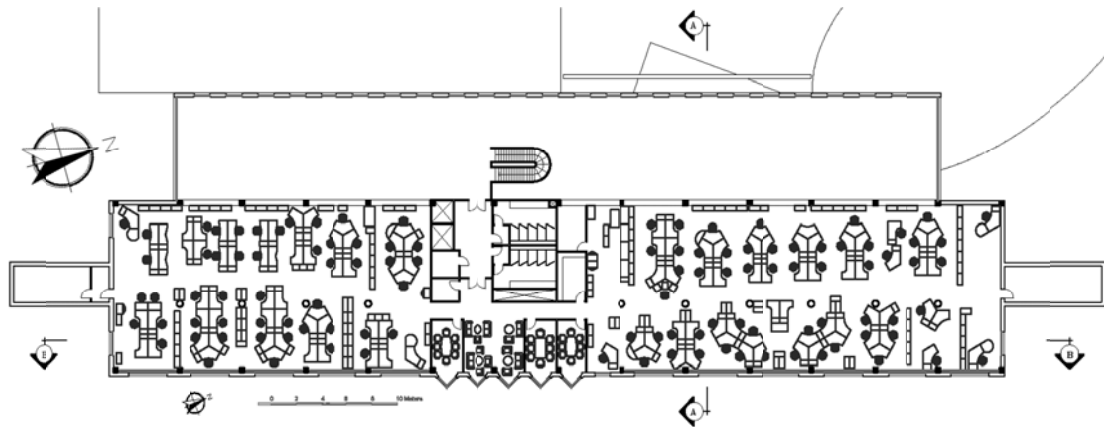


Figure 116: Building C: First floor plan

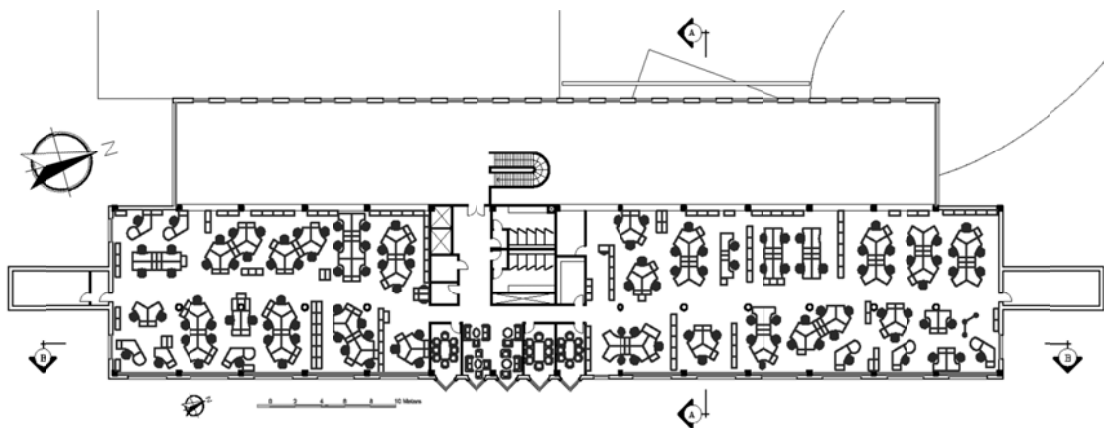


Figure 117: Building C: Second floor plan

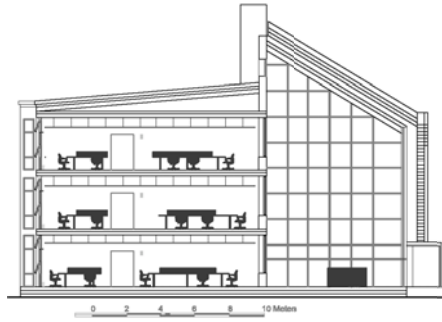


Figure 118: Building C: East-West Section

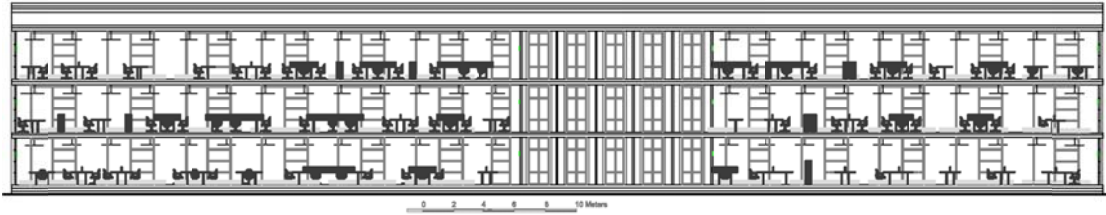


Figure 119: Building C: North-South Section



Figure 120: Building C: Open Plan office



Figure 121: Building C: View from the windows, window seat and far from the windows



Figure 122: Building C: Mechanically controlled windows

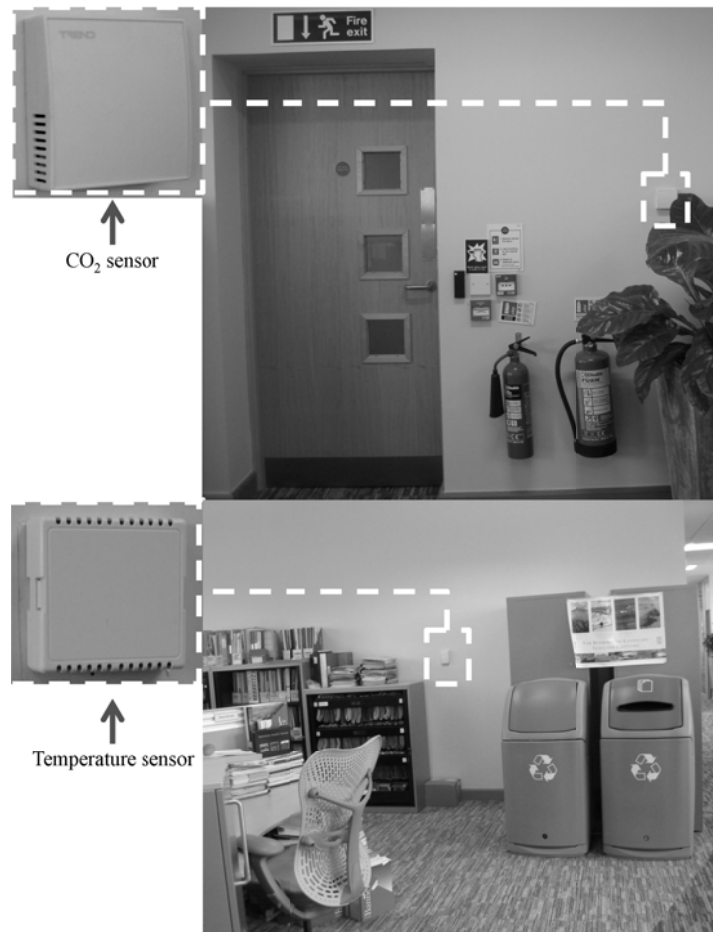


Figure 123: Building C: CO₂ and temperature sensors, two per office



Figure 124: Building C: Blinds toward the atrium to prevent glare, solar gain and draughts

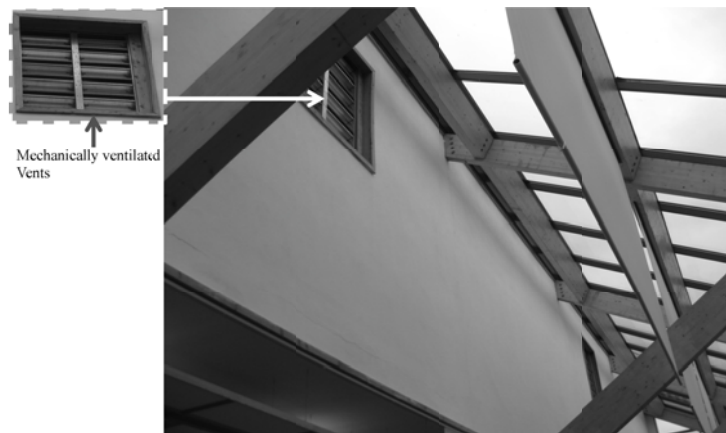


Figure 125: Building C: Vents above the atrium as part of the mechanical ventilation to help the flow of natural ventilation

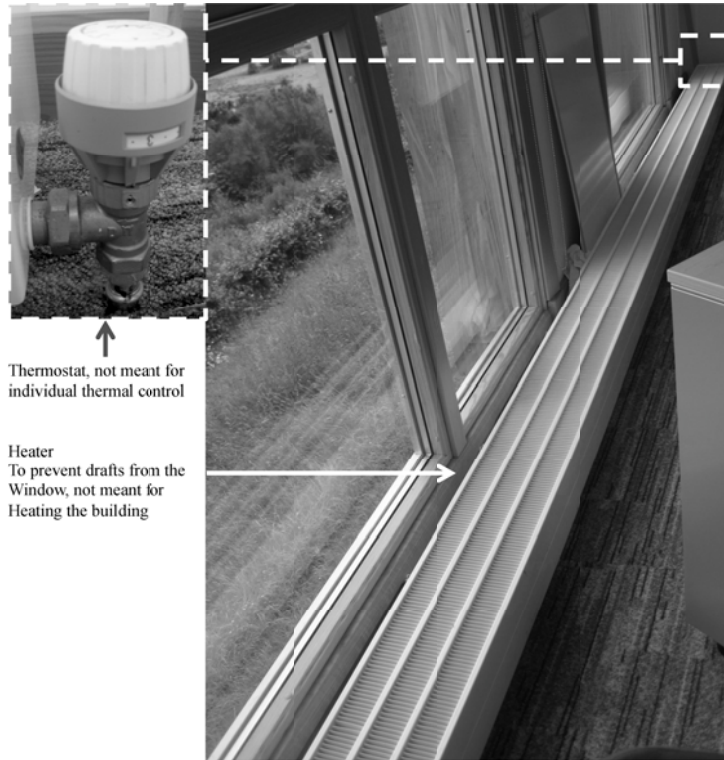


Figure 126: Building C: Radiator to reduce the radiation effect of the body loosing heat to the cold surface of the window



Figure 127: Building C: Passive thermal adaptation, hot water bottle and clothing layers



Figure 128: Building C: Services, including a meeting room, informal break area, pantry, and canteen

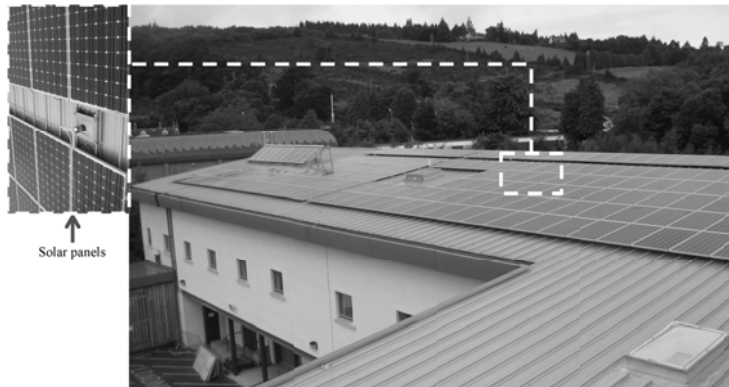


Figure 129: Building C: PV solar panels



Figure 130: Building C: Boilers



Figure 131: Building C: Copy machine in the open plan and separated copy room

7.1.2.2. Building D



Figure 132: Building D: North façade

Building D in Aberdeen, Scotland is an open plan workplace. It is located in the centre of Aberdeen, although the surrounding streets are not particularly busy. Bus is the main public access to the building, although a bike shed encourages staff to cycle to work. It was designed by Richard Murphy Architects and built in 2011. It won three different awards including the British Council for Offices award in 2012. It achieved the 'Very Good' BREEAM rating, and a 'B' score regarding the energy use. The office building is a six-storey building and its flexible design provides an opportunity to be let to a single occupier as well as up to four occupiers per floor. An oil company occupied three floors of this office building since it was built in 2011. The first two floors are completely open plan, while third floor includes mainly personal offices for senior management, meeting rooms and limited open plan areas. There is a significant difference between the management personal offices in this building compared to personal offices in the two Norwegian workplaces, presented in Figure 143. The former has no window and consequently no natural light or ventilation. Except for a door and a light switch there is no environmental control available for the occupant. The main focus of this study is the open plan settings with administrative activities, the first two floors of Building D. The office area of every floor is 1680 m^2 , and (i.e. 12 m^2 per person), including overall 525 workstations in all three floors. Each workstation in the open plan is approximately 3.5 m^2 , while each management personal office is about 10 m^2 .

Displacement ventilation (i.e. 4 ach^{-1}) is the main ventilation system in Building D. The raised floor (i.e. 0.35 meter depth) works as a duct for the treated air, presented in Figure 141, and

provides a high degree of flexibility to change the location of inlets according to the furniture settings. Very limited and small openable windows and blinds are provided for occupants around the perimeter of the building. However, the majority of the users sit close to the centre of the open plan away from windows without any access to environmental control. Few occupants use small fans on their desks. Building D is quite a deep open plan so that natural light does not reach the centre, as daylight is not evenly distributed and artificial florescent lights are required. The exposed concrete ceiling functions as a thermal mass to reduce the internal temperature fluctuations.

The climatic analysis of Aberdeen is presented in section 7.1: Figure 80 and Figure 81. The wind and shadow pattern analysis of Building D are presented in Figure 133 and Figure 134. Figure 132 to Figure 146 demonstrate plans, sections and photos of Building D, on which important information are highlighted to illustrate the office context.



Figure 133: Building D: Predominant wind direction and analysis in summer (left) and winter (right)

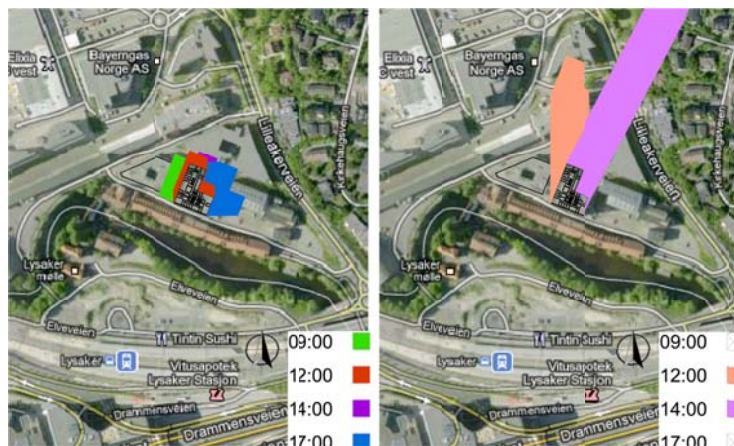


Figure 134: Building D: shadow pattern analysis in summer (left) and winter (right)



Figure 135: Building D: South façade and the main entrance

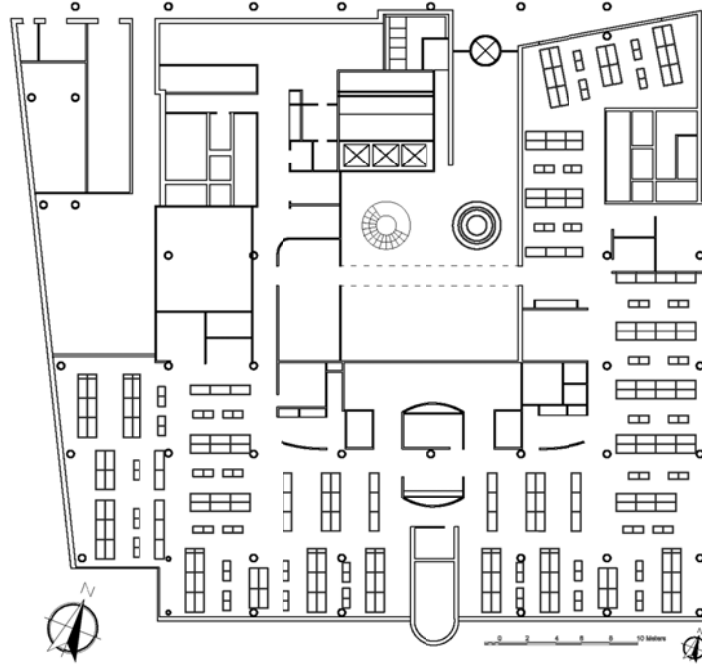


Figure 136: Building D: Ground floor plan

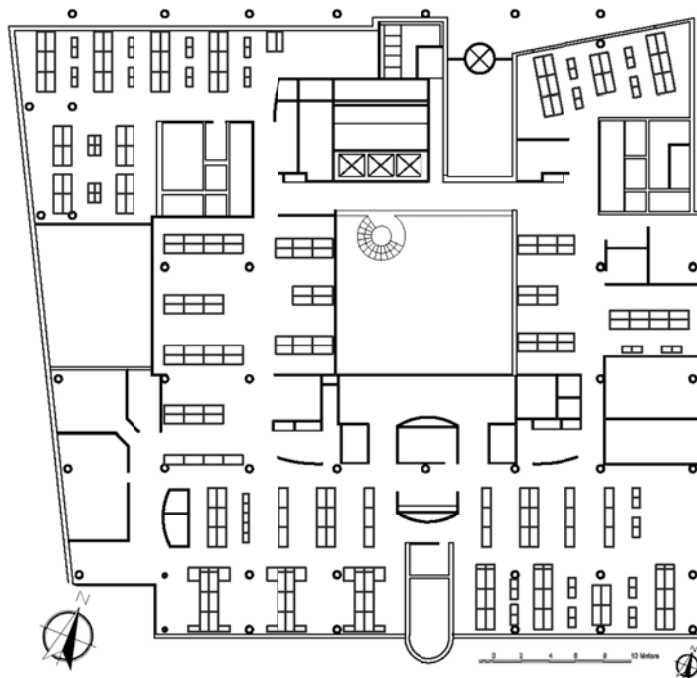


Figure 137: Building D: First floor plan

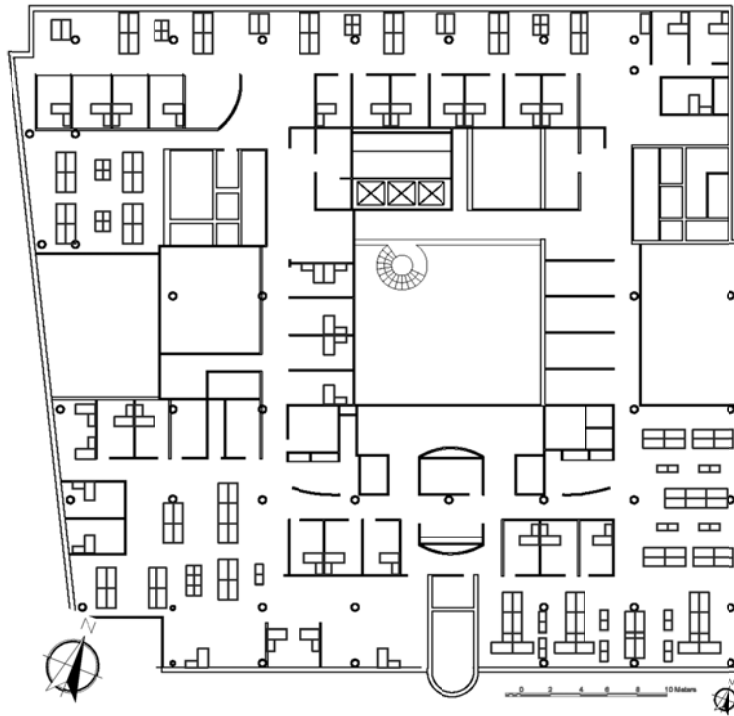


Figure 138: Building D: Second floor plan

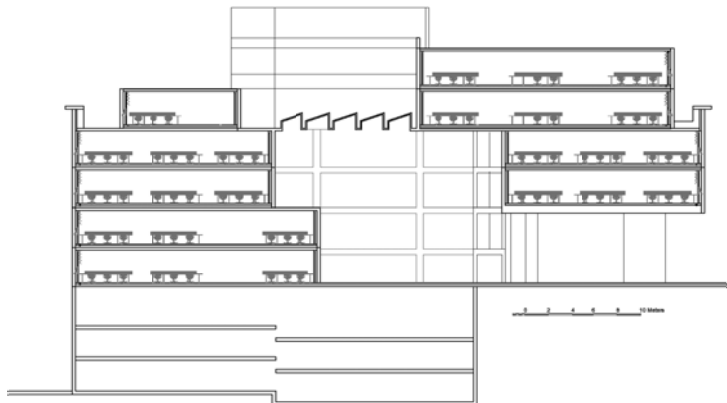


Figure 139: Building D: North-South Section



Figure 140: Building D: The open plan office



Figure 141: Building D: Displacement ventilation



Figure 142: Building D: Trench radiator and a floor box for Internet and power sockets



Figure 143: Building D: A focus room and management office



Figure 144: Service areas, including a break area, meeting room, café, and pantry



Figure 145: Building D: Copy room and a copy machine in the open plan office



Figure 146: Building D: Boiler and personal fan as an adaptive opportunity provided based on occupants' request

7.2. Building Performance

Environmental performance of the four buildings is measured and analysed in this section, including the ventilation system, environmental control, thermal zones, the ASHRAE comfort predictions, energy performance, carbon dioxide, light and sound levels. Climatic analysis of the buildings is briefly included in this section. The case study buildings in this thesis are selected from good practice examples of workplaces. They are expected to provide a good quality standard of indoor thermal environment, which is examined in this section.

7.2.1. Ventilation System

The two cellular plan offices have air conditioning in addition to the ability to open a window and adjust the temperature for individual offices. Building C is a naturally ventilated building that provides occupants, who sit around the perimeter of the building, with openable windows. Mechanical ventilation is also in operation to ensure the required ventilation in the building as well as regulating the temperature and CO₂ levels. Building D has displacement ventilation in operation with limited openable windows around its perimeter. It is a deep open plan office and dependant on the mechanical ventilation compared to Building C, which mainly relies on natural ventilation. All four case studies in this research rely on mechanical ventilation as well as openable windows as part of their ventilation system. In the cellular plan offices every individual has access to an openable window, while in the open plan offices only people sitting around the perimeter of the building have limited access to the openable windows. Figure 147 to Figure 152 present the ventilation systems, including centrally and individually controlled ventilation systems in addition to a seasonal ventilation performance.

7.2.1.1. Centrally Controlled Ventilation System

Figure 147 shows the centrally controlled ventilation systems in the four case study buildings, which occupants cannot control. In Building A, the air conditioning is centrally controlled and both inlet and outlet are located above the door in every personal office. In Building B, also centrally controlled air conditioning is in operation. Nevertheless, the inlet and outlet are separated and located in a more effective way as the inlet is above the person's seat and the outlet is close to the door in each personal office. In Building C, mechanical ventilation is in use. Few sensors are placed on the wall to measure the temperature and CO₂ levels. The top windows are mechanically adjusted according to these readings. In addition, several mechanically controlled vents are located above the atrium to increase the stack ventilation in the building. These vents as well as radiators are centrally controlled and programmed. In Building D, displacement ventilation is used, which is centrally controlled and programmed.

Several sensors are located on the walls to measure the temperature and CO₂ level. The mechanical ventilations in Building A, Building B and Building D provide 4 ach⁻¹ with heat recovery.

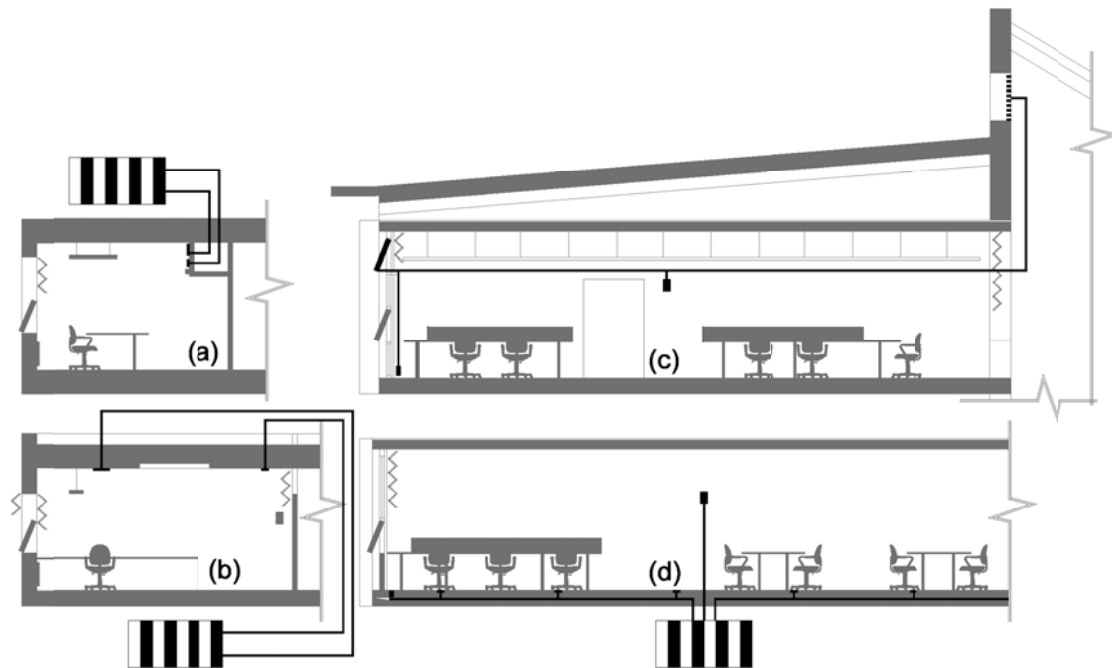


Figure 147: Sections, centrally controlled ventilation systems in (a) Building A, (b) B, (c) C, and (d) Building D

7.2.1.2. Individual Environmental Control

The two cellular plan offices provide a much higher level of environmental control for every individual compared to the two open plan offices. Figure 148 shows the individual environmental control in the four case study buildings. In Building A, every occupant has access to an openable window, blind, light switches, door, and thermostat to adjust cooling or heating. In Building B, every individual has access to two openable windows, internal, external and corridor blinds, light switches, door, and a control device to adjust heating or cooling. In contrast, the two open plan offices provide limited adaptive opportunity for the occupants. In Building C, only few people sitting around the perimeter of the building have access to openable windows or internal blinds. Occupants sitting close to the atrium have access to blinds to block the sun in summer or prevent a draught in winter. Occupants who sit in the middle of the open plan are not provided with any means to adjust the thermal environment. Individual heaters and fans are not allowed due to energy consumption. In Building D, occupants sitting around the perimeter of the building have access to internal blinds to adjust the light level, however very limited openable windows are provided. This building has a deep open plan and majority of occupants are allocated to the seats closer to

the middle of the open plan with no opportunity to adjust the thermal environment. Few users have small fans on their desks in the summer.

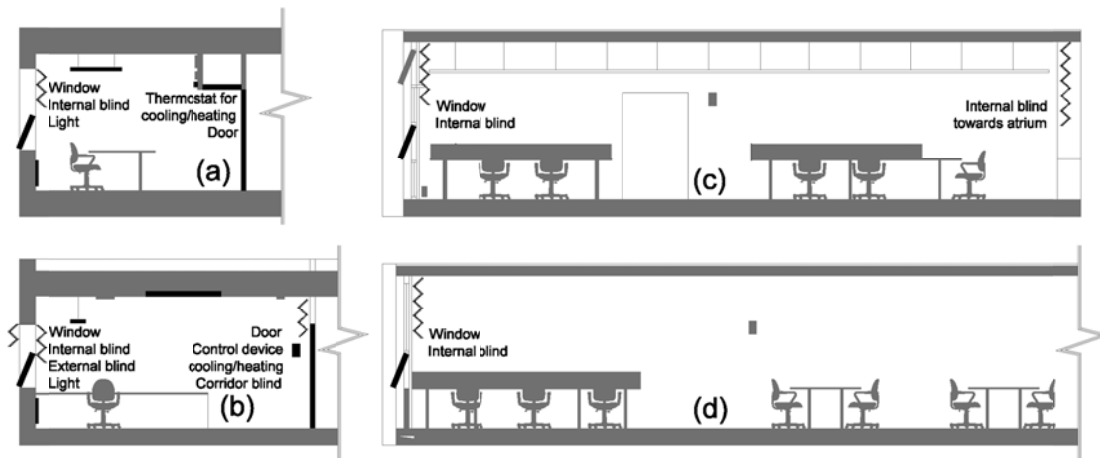


Figure 148: Sections, individual environmental control in (a) Building A, (b) Building B, (c) Building C, and (d) Building D building

7.2.1.3. Summer and Winter Ventilation

The summer and winter ventilation performance of the case study buildings on working days are analysed in this part. Figure 149 shows the ventilation systems of the buildings in the summer during the day. In Building A, air conditioning, cooling, natural ventilation and heating are in operation. The air conditioning cannot be adjusted manually in the personal offices, therefore to adjust the temperature in summer either cooling or heating will be turned on. When the occupant adjusts the thermostat above 20 degrees, the radiator starts operating, and below 20 degrees the cooling system starts. The occupant has access to two thermostats, one is on the radiator and the other above the door. Based on the building manual, the former thermostat should be always set on the maximum during winter and summer, while the latter thermostat is to be adjusted according to occupant's requirements. This thermostat includes a sensor and adjusts the heating or cooling system in the room. Radiators are electric and their set point is centrally set. The occupant can adjust the radiator up to that set point via the thermostat above the door. So the radiator is always running even during the summer in case the occupant felt too cool and needed to warm up since the air conditioning cannot be individually adjusted. In addition, the occupant can open the window for natural ventilation, and the door for a cross ventilation in the room. Overall, in order to satisfy individuals in Building A, air conditioning, natural ventilation and either cooling or heating systems are all in operation during the summer days. This may be the main reason for the high energy consumption of the building, which is presented in section 7.2.4.

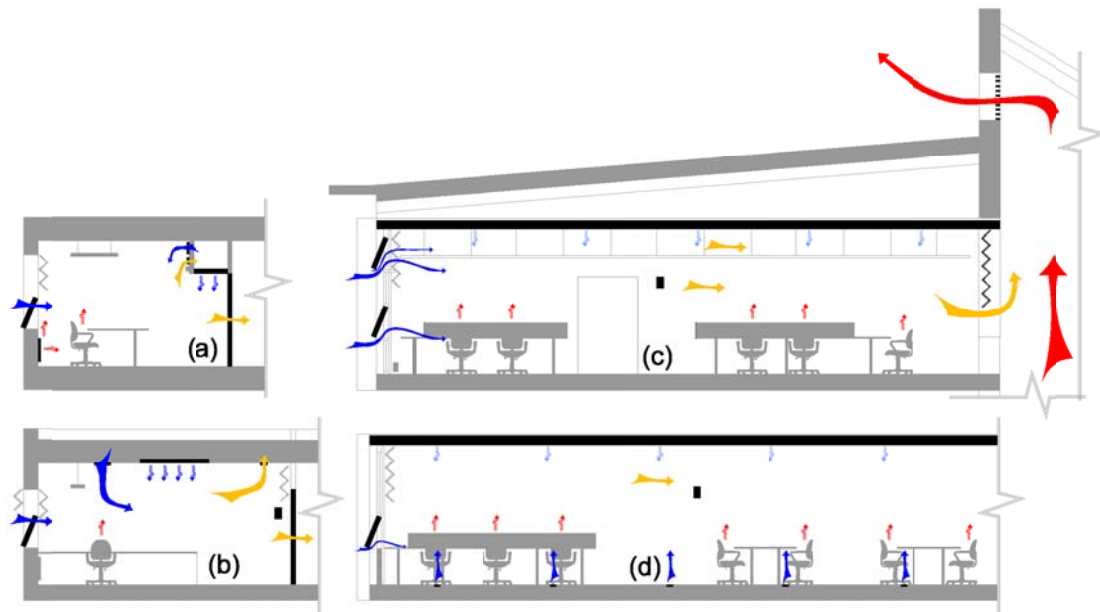


Figure 149: Summer day ventilation sections (a) Building A, (b) Building B, (c) Building C, and (d) Building D

In Building B, air conditioning, cooling and natural ventilation are applied during the summer days. The air conditioning is constantly in operation and centrally controlled, it cannot be adjusted manually in the individual rooms. A control device on the wall allows users to regulate the temperature. This device has two programs including heating and cooling. In the winter only the heating system can be set, while cooling in the summer. Based on the interviews, users find this control device quite complicated as they may try to adjust the heating in the summer, which does not work as only the cooling program should be adjusted in summer. Every occupant can control the natural ventilation by opening two windows and a door.

In Building C, natural and mechanical ventilations are in operation during the summer days. The occupants with a window seat can adjust the windows, which are at the desk level. The top windows and the outlet above the atrium are mechanically ventilated to control the airflow in the office. The thermal mass absorbs heat from the office space during the day. In Building D, natural and mechanical ventilations are in operation during the summer day. Thermal mass absorbs heat from the office space and limited openable windows allow the users to have limited natural ventilation. Nevertheless, displacement ventilation is the main source of fresh air and the main system to adjust the temperature. In all these buildings, internal gains (e.g. computer heat and metabolic rate) influence the temperature as well.

Figure 150 presents the ventilation system in the buildings in summer at night. In all four buildings mechanical systems are off during the night. In Building A and B, if the windows

are left open, night cooling takes place. The mechanical system starts operating two hours prior to arrival of the users and goes off two hours after the normal working hours. In Building C and D, thermal mass releases heat. The mechanical ventilation starts two hours prior to staff arrival. In Building C, there is limited ventilation through the top windows. The security closes the manual windows and opens the corridor blinds at the end of the working day.

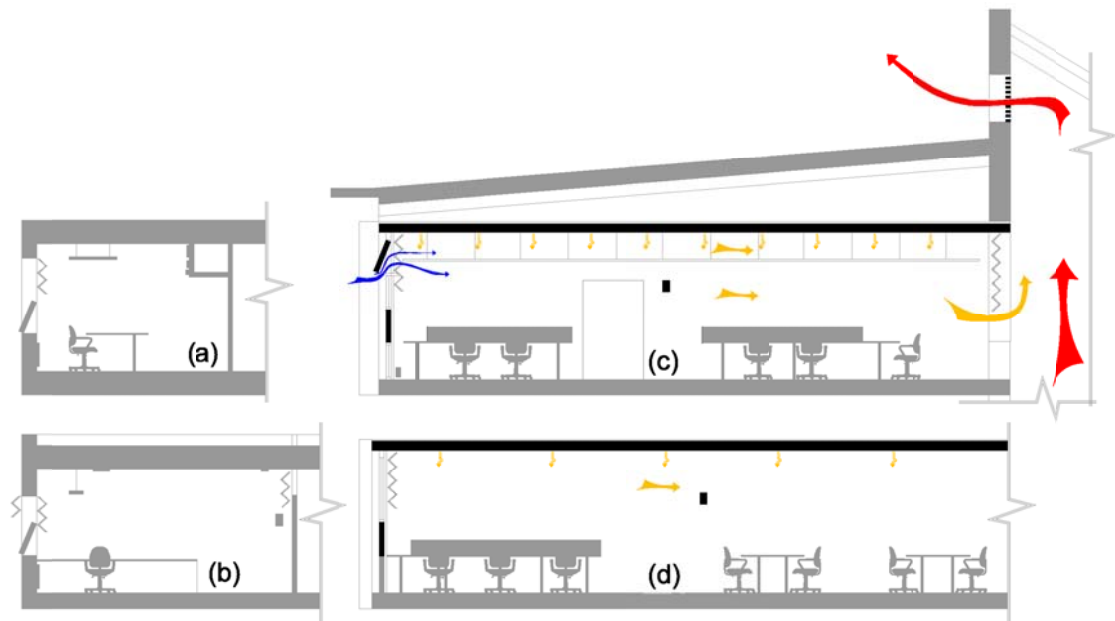


Figure 150: Summer night ventilation sections (a) Building A, (b) Building B, (c) Building C, and (d) Building D

Figure 151 shows the ventilation system in the buildings in winter during the day. The two cellular plan offices have heating and air conditioning in operation. The latter provides fresh air, which is slightly warmed. Occupants can regulate the temperature through heating, and they can open or close the door. According to the interviews, the users hardly open any windows in winter in all four buildings. In the two open plan offices, internal gains (e.g. computer heat and metabolic rate) are the main sources of heat. The radiators mainly reduce the radiation effect of the body losing heat to the cold surface of a window. The mechanically controlled top windows in Building C provide fresh air based on the CO₂ readings. In Building D, the displacement ventilation provides slightly warmed fresh air.

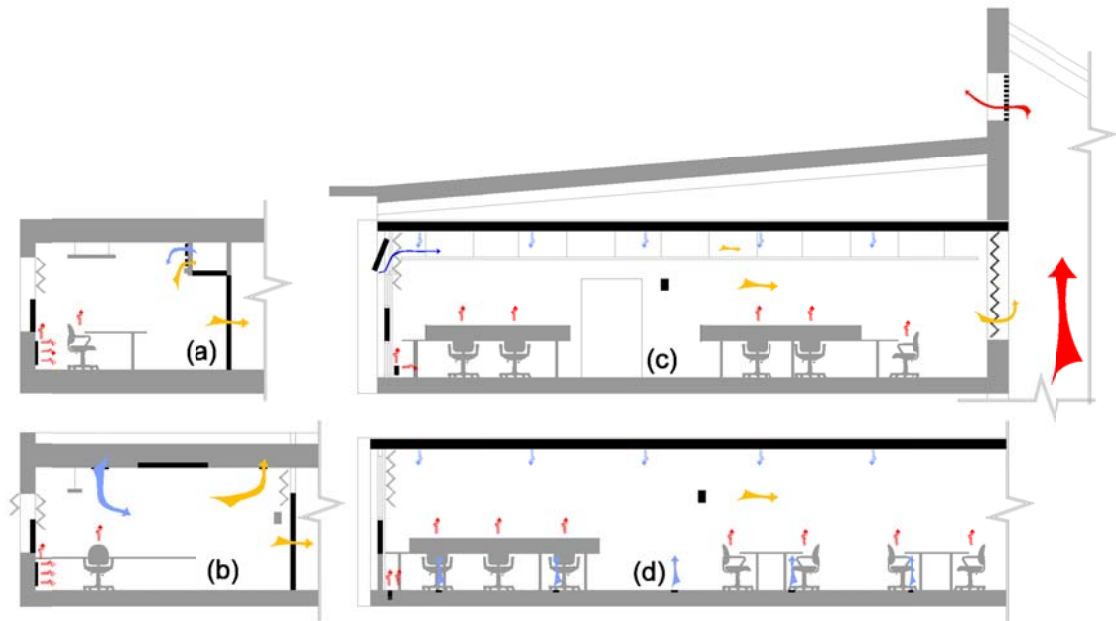


Figure 151: Winter day ventilation sections (a) Building A, (b) Building B, (c) Building C, and (d) Building D

Figure 152 presents the winter night ventilation system. The mechanical ventilations in all four buildings do not operate and the windows are closed. Thermal mass in the two open plan offices releases heat during the night. Although the mechanical ventilation in Building C is off, slight ventilation takes place through the designed gap in the windows to provide some fresh air for the office.

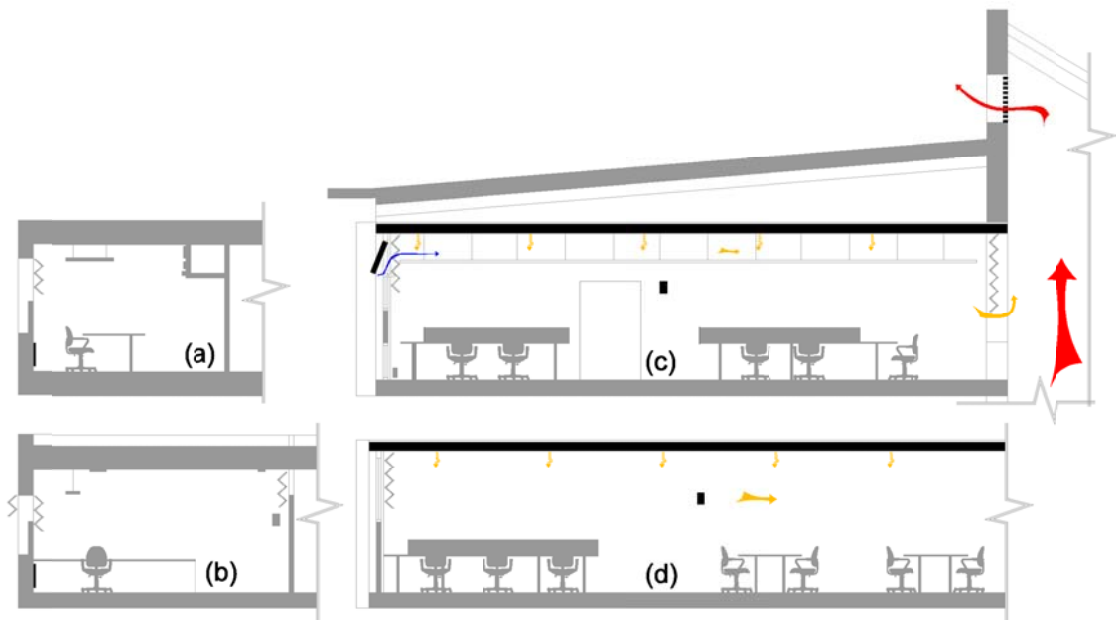


Figure 152: Winter night ventilation sections (a) Building A, (b) Building B, (c) Building C, and (d) Building D

7.2.2. Thermal Performance

Figure 153 to Figure 157 show the temperature changes in every building during 24 hours (i.e. one day) in summertime. Temperature measurements are recorded at three levels, floor, desk and ceiling levels in every building, in addition to the corridor and outside, explained in section 6.3.3. Based on the ASHRAE Standard 55-2010, temperatures between 20 to 26°C are acceptable, which are highlighted in Figure 153.

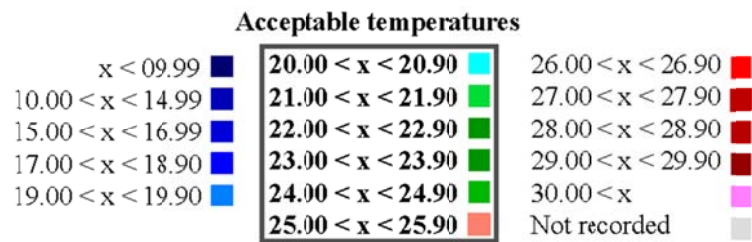


Figure 153: Temperature colour code

Figure 154 shows the thermal analysis of Building A and it indicates that during the working hours (i.e. in these case studies, approximately 9:00 to 17:00 in the UK and 8:00 to 16:00 in Norway) the thermal environment of the building is within the comfort zone. The measuring points are explained in section 6.3.3. The outdoor temperature during this day does not fluctuate much and stays below 19°C. During the early hours in the morning the indoor temperature drops below the comfort zone.

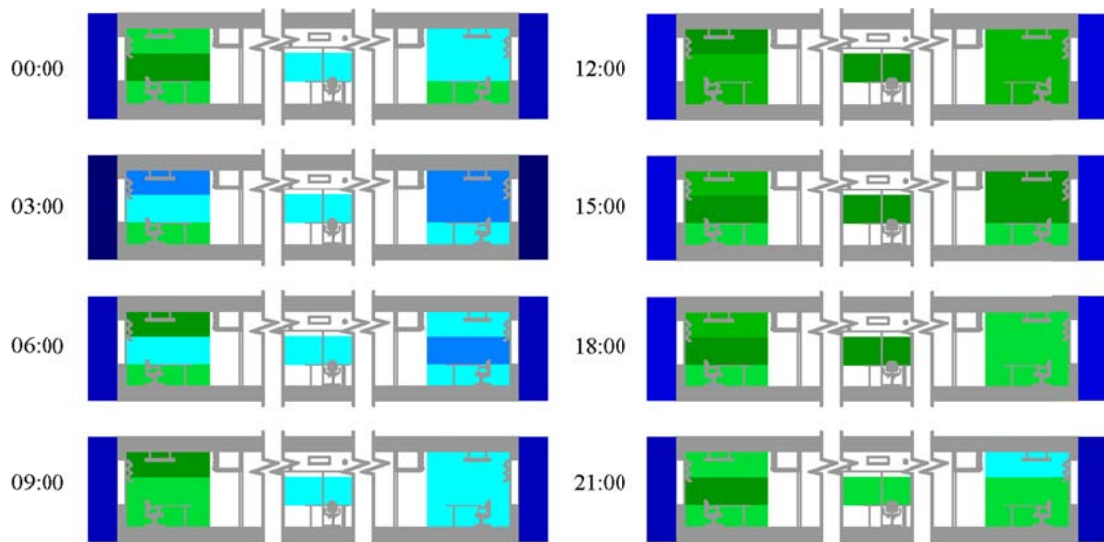


Figure 154: Building A: thermal sections of 31 May 2012

Figure 155 presents the thermal analysis of Building B. It shows that the air temperature around a seated person is within the comfort zone during the working hours, however at the end of the working day (i.e. 18:00) due to solar gain the temperature of the western part of the

building rises at the desk and ceiling levels and falls out of the comfort zone. The outdoor temperature fluctuates during this day from 20 to 26°C.

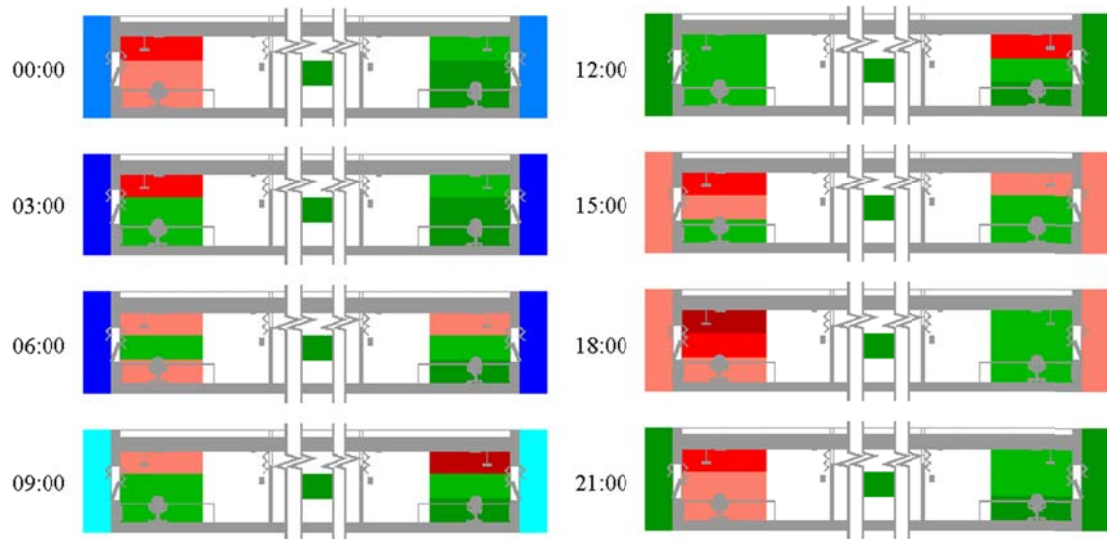


Figure 155: Building B: thermal sections of 23 May 2012

Figure 156 demonstrates the thermal analysis of Building C. It indicates that during the working hours, the temperature stays well within the comfort zone. The outdoor temperature does not fluctuate much and stays below 19°C. In the early hours of the morning the indoor temperature drops below the comfort zone.

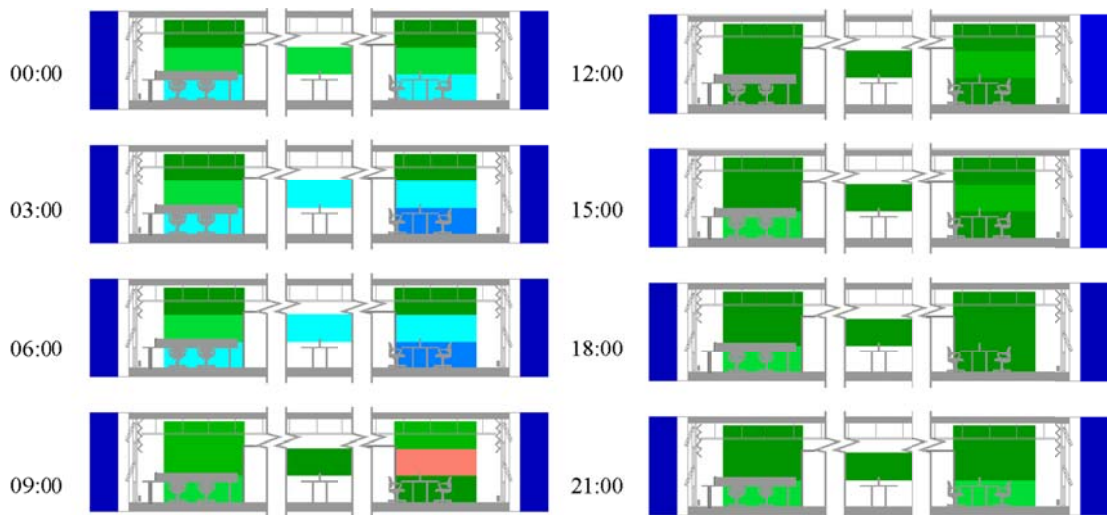


Figure 156: Building C: thermal sections of 23 August 2012

Figure 157 presents the thermal analysis of Building D. The thermal environment of this building is well within the comfort zone as well, and the outdoor temperature remains below 15 degrees. Even during the night time the indoor temperature is within the comfort zone.

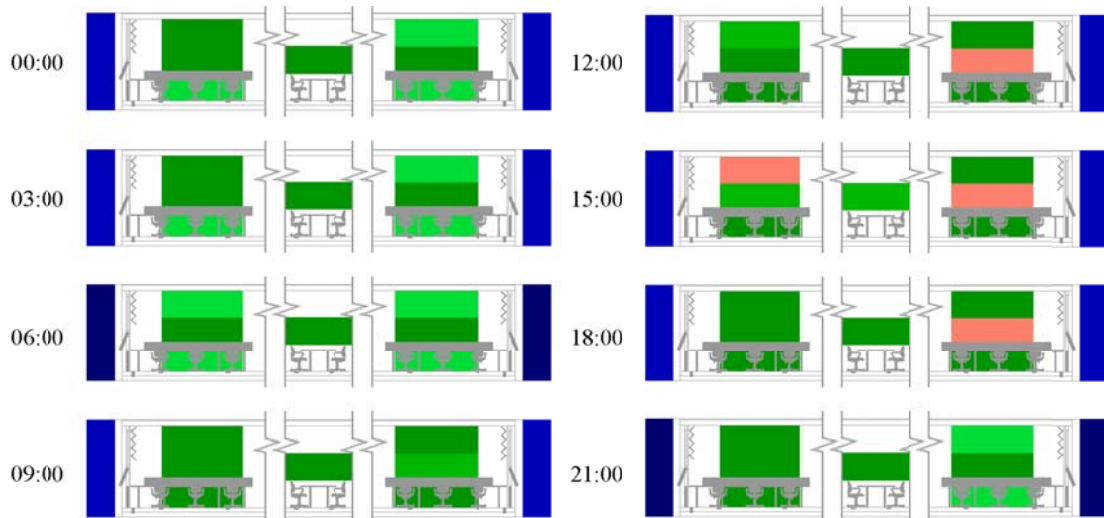


Figure 157: Building D: thermal sections of 30 August 2012

These analyses indicate that all four case study buildings provide thermal environments within the comfort zone during the working hours, regardless of the outdoor temperature fluctuations and indoor night temperatures.

7.2.2.1. Thermal Zones

Figure 158 and Figure 159 show the thermal conditions of every workstation in the morning, early and late afternoon based on the ASHRAE Standard 55-2010, which is presented in detail in section 3.2.2.1 and Figure 24. Each workstation is presented with a dot on the graphs according to humidity and operative temperature, which is the mean of dry bulb temperature and mean radiant temperature (MRT), the latter is explained in section 7.2.3. Figure 158 shows that with a few exceptions, all of the workstations in Building A are within the general comfort zone. However, they are predicted to be slightly cool, as they fall into the accepted winter zone rather than the summer one. Figure 158 demonstrates the thermal readings of Building B and it indicates that all of them are within the overall comfort zone. Nevertheless, one third of them fall into the winter comfort zone, which are expected to be slightly cool in summer.

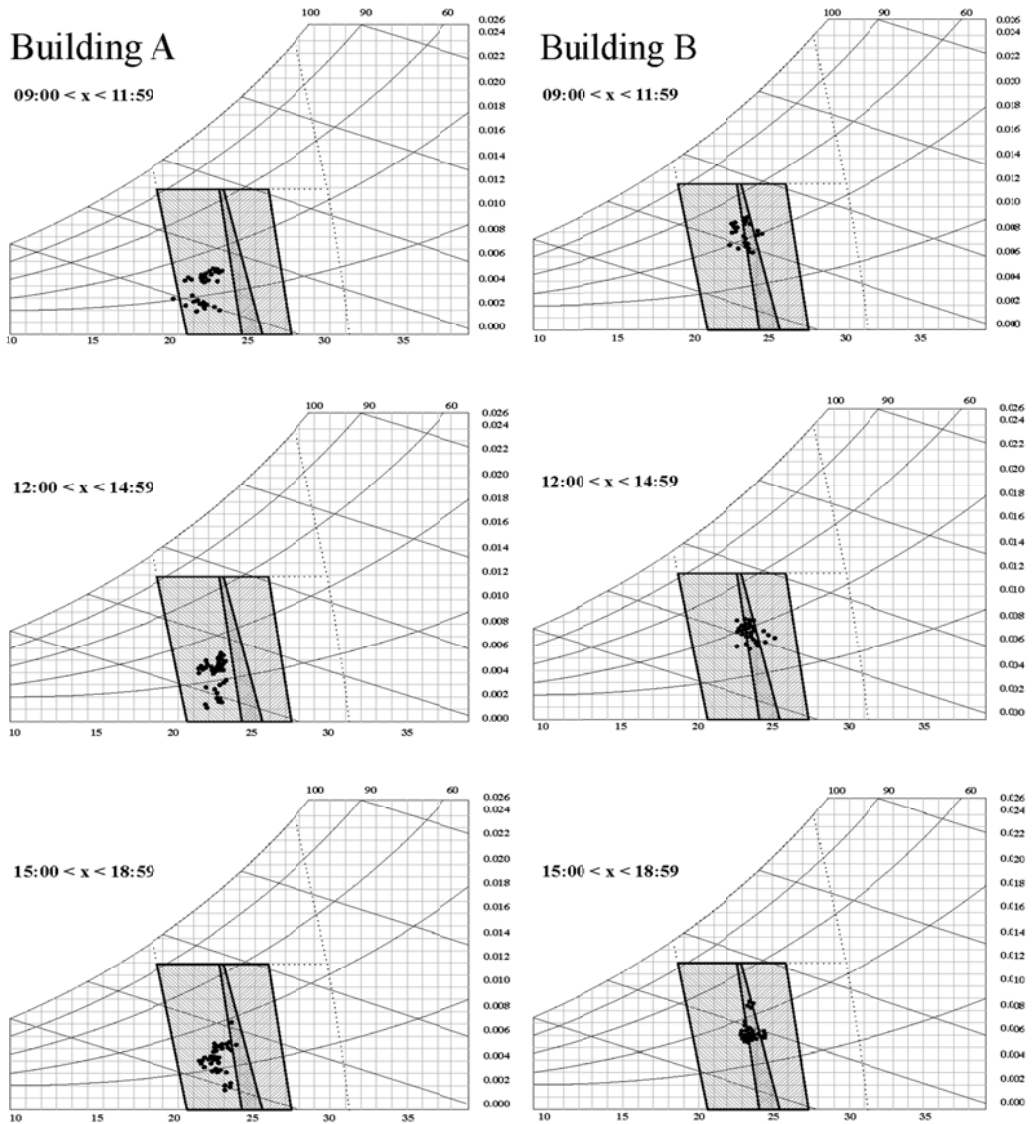


Figure 158: Building A (on the left) and Building B (on the right): Thermal conditions of individual workstations, morning, early and late afternoon

Figure 159 is the thermal readings of Building C, which are all within the general comfort zone, although over half of them are within the winter zone and they are expected to be slightly cool. Figure 159 is the thermal readings of Building D and it indicates that all of them are within the general comfort zone. However, majority of them fall into the winter comfort zone and they are expected to be slightly cool.

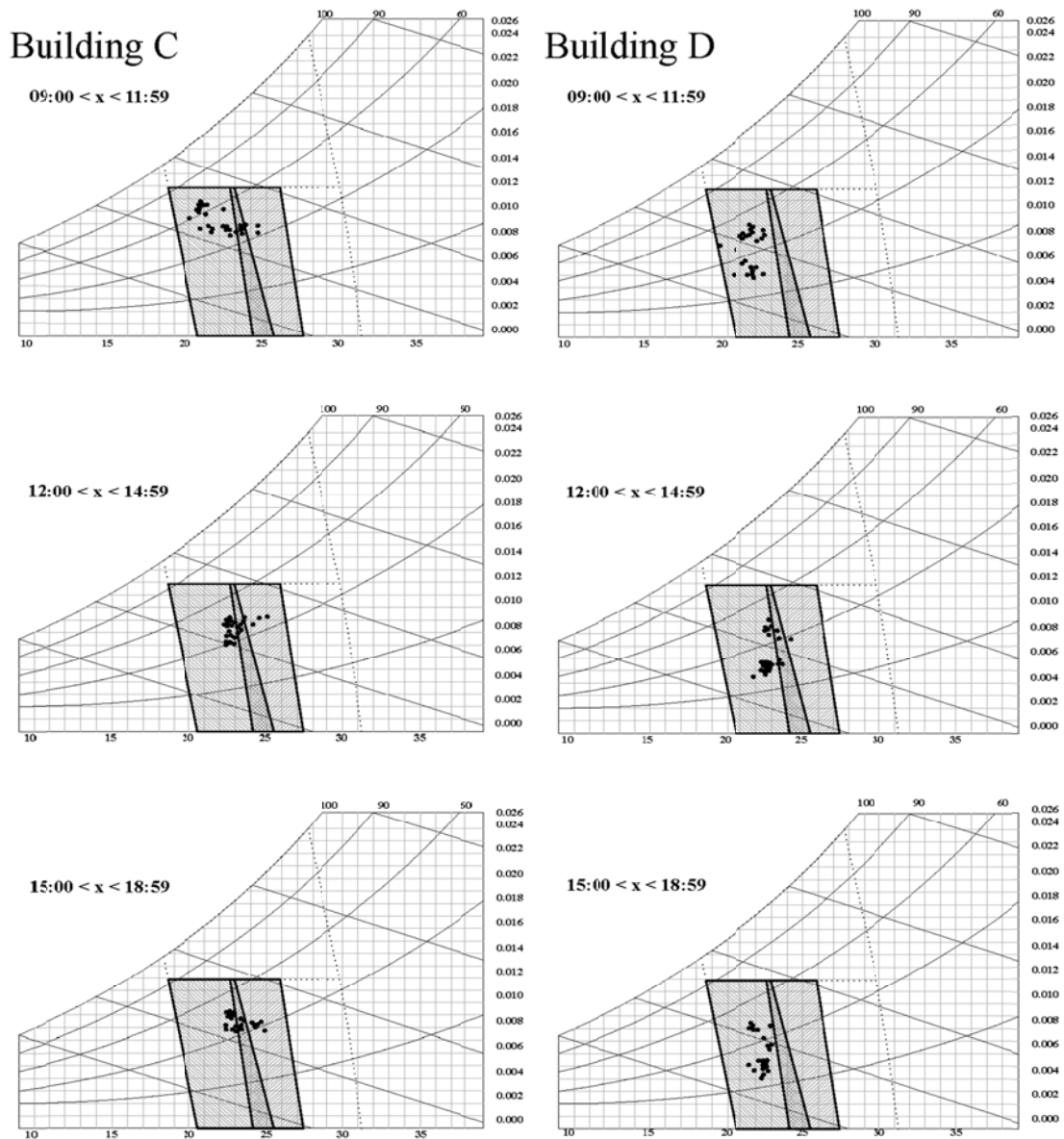


Figure 159: Building C (on the left) and Building D (on the right): Thermal conditions of individual workstations, morning, early and late afternoon

Overall, the thermal conditions of all four case study buildings are similar and within the general comfort zone. However, most of them are within the winter comfort zone and they are expected to be slightly cool for summertime.

7.2.3. ASHRAE Thermal Predictions

The ASHRAE PMV and adaptive comfort prediction models are based on thermal readings and observations of every workstation three times a day, including morning, early and late afternoon. These measurements are analysed using the second version of the ASHRAE Thermal Comfort Tool, which is a software designed by ASHRAE and based on the

ASHRAE Standard 55-2010 to predict thermal comfort. The recorded dry bulb temperature and relative humidity of every workstation, temperature of surrounding wall surfaces, outdoor temperature as well as observations regarding the occupant's clothing, activity, location of their seat in the room, and size and location of windows are the data entry in the software. Then the software calculates the mean radiant temperature, PMV and adaptive comfort predictions, which are respectively presented in Figure 160, Figure 161 and Figure 162, regarding the particular workstation at a particular time and context.

The screenshot shows the 'MRT Calculator' window. It includes input fields for room dimensions (width: 5.000 m, length: 5.000 m, height: 2.600 m) and occupant data (x: 1.000 m, y: 1.000 m, Facing: Average, Azimuth: Average, Seated/Standing). A diagram shows a square room with walls labeled Wall 1 to Wall 4 and an occupant icon. Below is a table for 'Glass/panel data' and a summary of MRT.

	Temperature °C	Emis	Wall view factor	Temperature °C	Emis	Width m	Height m	Centered	Sill m	L. Jamb* m	Window view factor
Wall 1	21.0	0.90	0.207	20	0.84	1.000	1.000	<input checked="" type="checkbox"/>	0.80	2.00	0.0125
Wall 2	21.0	0.90	0.049								
Wall 3	21.0	0.90	0.049								
Wall 4	21.0	0.90	0.220								
Ceiling	21.0	0.90	0.138								
Floor	21.0	0.90	0.317								
View factor total	1.0										
MRT	21.0 °C										

*distance from left edge of wall to left jamb when viewed from inside the room
View factors are calculated based on Fanger, P.O., "Thermal Comfort", McGraw-Hill, 1972

Figure 160: Mean radiant temperature calculations using ASHRAE Thermal Comfort Tool

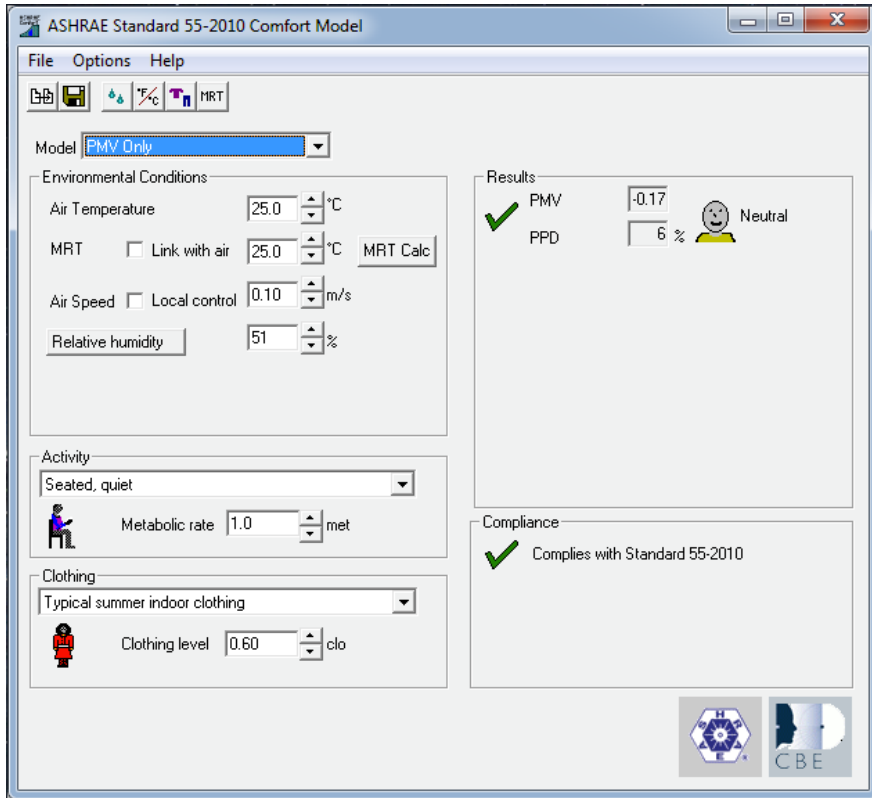


Figure 161: PMV prediction using ASHRAE Thermal Comfort Tool

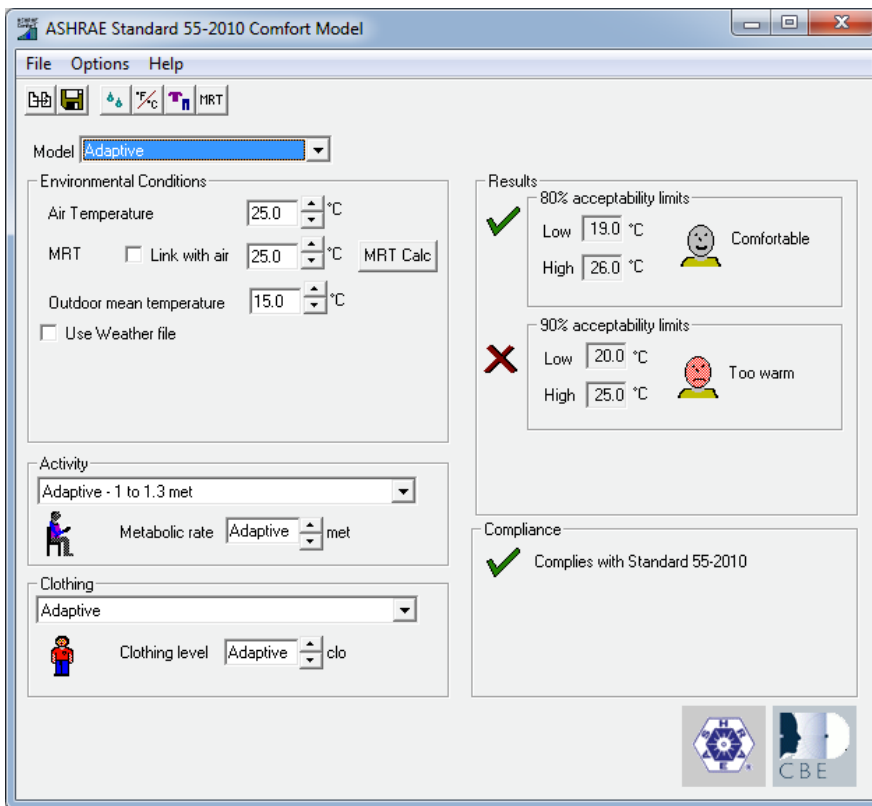


Figure 162: Adaptive comfort prediction using ASHRAE Thermal Comfort Tool

7.2.3.1. ASHRAE PMV Prediction Model

In this section, the PMV predictions of the four case study buildings are compared. Firstly, the thermal comfort of every workstation is calculated based on the ASHRAE PMV prediction model three times a day, including morning, early and late afternoon, as explained in section 7.2.3. Secondly, the PMV predictions of the four buildings are compared using SPSS frequency analysis, as presented in Figure 163.

Ventilation System and Typology of Plan		Frequency	Percent	Valid Percent	Cumulative Percent
Building A: Air Conditioned, Openable Window and Heating in Cellular Plan	Valid	Cool	5	3.2	3.2
		Slightly cool	90	94.7	97.9
		Neutral	2	2.1	100.0
		Total	95	100.0	100.0
Building B: Air Conditioned & Openable Window in Cellular Plan	Valid	Slightly cool	35	45.5	45.5
		Neutral	42	54.5	100.0
		Total	77	100.0	100.0
		Slightly cool	47	64.4	64.4
Building C: Natural Ventilation in Open Plan	Valid	Neutral	26	35.6	100.0
		Total	73	100.0	100.0
		Cool	2	2.9	2.9
		Slightly cool	61	89.7	92.6
Building D: Displacement Ventilation in Open Plan	Valid	Neutral	5	7.4	100.0
		Total	68	100.0	100.0
		Cool	2	2.9	2.9
		Slightly cool	61	89.7	92.6

Figure 163: SPSS frequency analysis of the ASHRAE PMV model in the four case study buildings

Based on this table, the highest to lowest PMV neutral predictions are as follows:

- Building B: 54.5% neutral predictions
- Building C: 35.6% neutral predictions
- Building D: 7.4% neutral predictions
- Building A: 2.1 % neutral predictions

Approximately over half of the workstations in each building are expected to be slightly cool. This is very high in Building A (i.e. 95%) and Building D (i.e. 88%). This comparison is more visible on the graph in Figure 164.

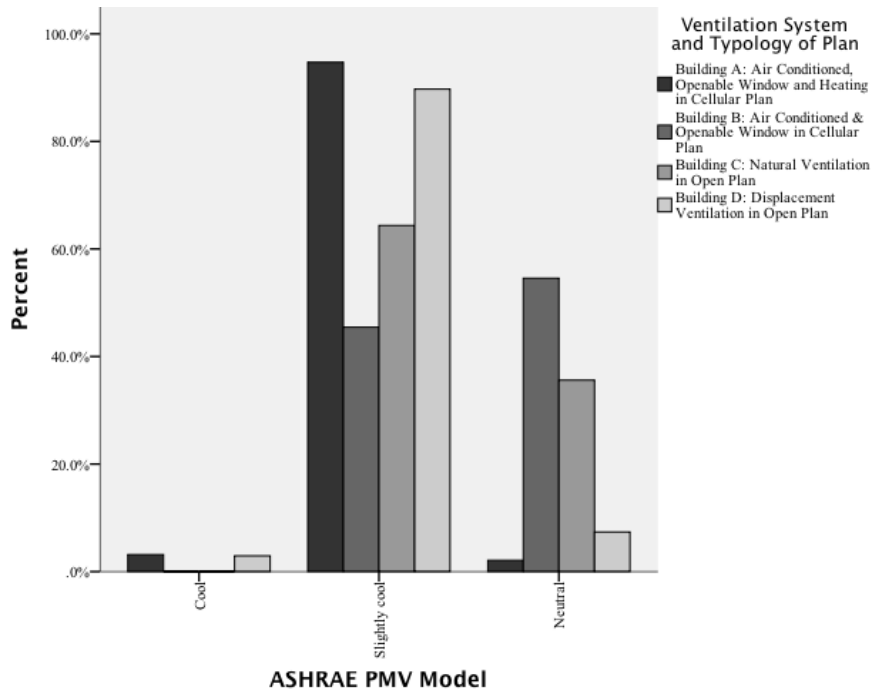


Figure 164: SPSS bar chart, frequency analysis of the ASHRAE PMV model in the four office buildings

Overall, the ASHRAE PMV model predicts that the thermal environments of the workstations in all four buildings are between slightly cool to neutral, with majority of them predicted as slightly cool.

7.2.3.2. ASHRAE Adaptive Prediction Model

The ASHRAE adaptive prediction of the four case study buildings are compared in this section. The process is very similar to section 7.2.3.1, using the ASHRAE Thermal Comfort Tool to calculate and SPSS frequency analysis to compare the adaptive comfort predictions between the buildings. The latter is presented in Figure 165.

Ventilation System and Typology of Plan	Frequency	Percent	Valid Percent	Cumulative Percent
Building A: Air Conditioned, Openable Window and Heating in Cellular Plan	95	100.0	100.0	100.0
Building B: Air Conditioned & Openable Window in Cellular Plan	76	98.7	98.7	98.7
Too warm	1	1.3	1.3	100.0
Total	77	100.0	100.0	
Building C: Natural Ventilation in Open Plan	66	90.4	90.4	90.4
Too warm	7	9.6	9.6	100.0
Total	73	100.0	100.0	
Too cool	2	2.9	2.9	2.9
Building D: Displacement Ventilation in Open Plan	65	95.6	95.6	98.5
Too warm	1	1.5	1.5	100.0
Total	68	100.0	100.0	

Figure 165: SPSS frequency analysis of the ASHRAE adaptive model in the four case study buildings

Based on Figure 165, the adaptive comfort ranking of the buildings are as follows:

- Building A: 100% comfortable prediction
- Building B: 99% comfortable prediction
- Building D: 96% comfortable prediction
- Building C: 90% comfortable prediction

Figure 166 shows this comparison better on a bar chart.

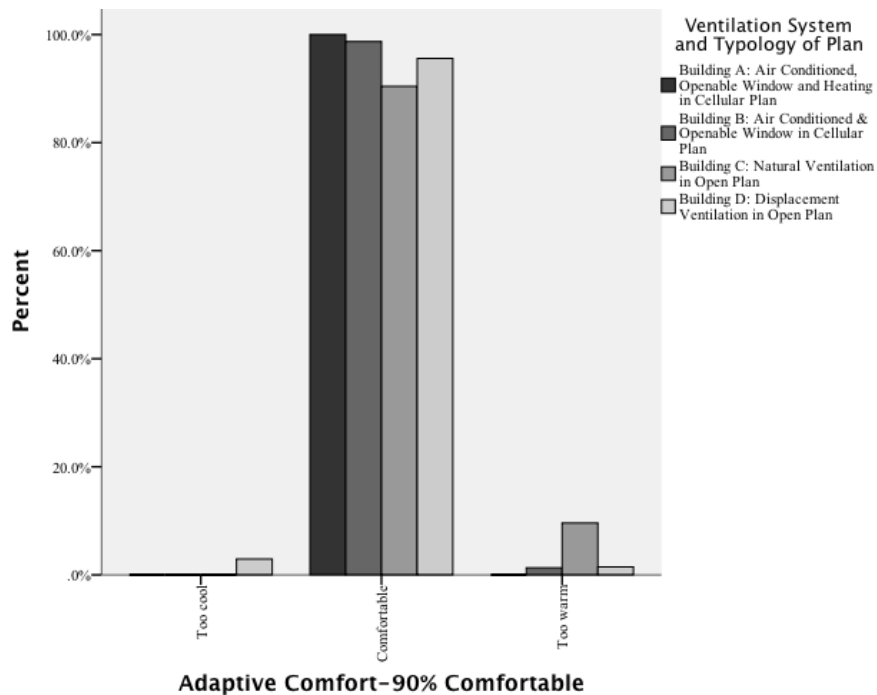


Figure 166: SPSS bar chart, frequency analysis of the ASHRAE adaptive model in the four office buildings

Overall, the comparison of adaptive comfort prediction between the four case study buildings shows very similar results indicating that over 90% of the studied workstations are predicted to be comfortable. Although the ASHRAE PMV and adaptive comfort predictions of the four buildings show different results, overall the buildings provide a high standard of thermal comfort.

7.2.4. Energy Consumption

Energy consumption of the four buildings is compared with the CIBSE energy use in offices (CIBSE, 2003). This energy benchmark provides the energy use in detail, such as heating, cooling and lighting, presented in Figure 167.

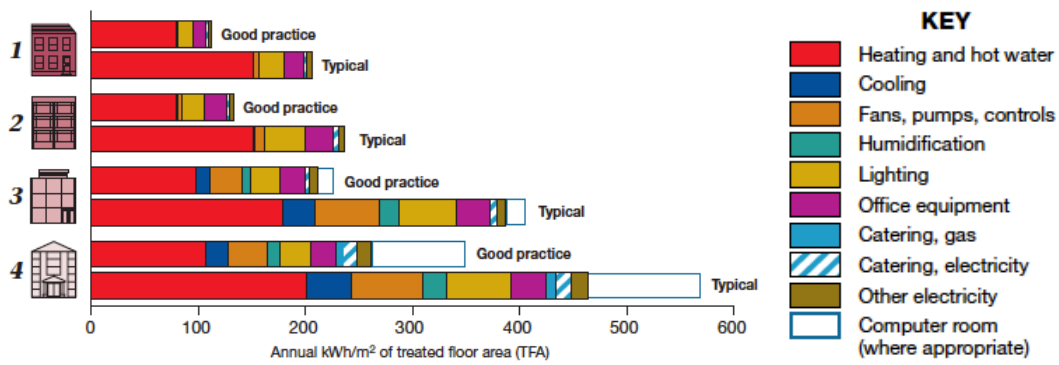


Figure 167: Energy benchmark based on the CIBSE energy use in offices (CIBSE, 2003)

In this research, the energy performance of every building is based on their monthly energy use, which is provided by the facilities management. Most of the buildings only provide the overall energy use of every month rather than specific details of energy consumption that is mentioned in the benchmark. Therefore the energy benchmark is simplified in order to compare to the energy performance of the four case study buildings, which is as follows:

- Building A: 1568 KWh/m² per year
- Building B: 552.8 KWh/m² per year
- Building C: 155.45 KWh/m² per year
- Building D: 159.38 KWh/m² per year

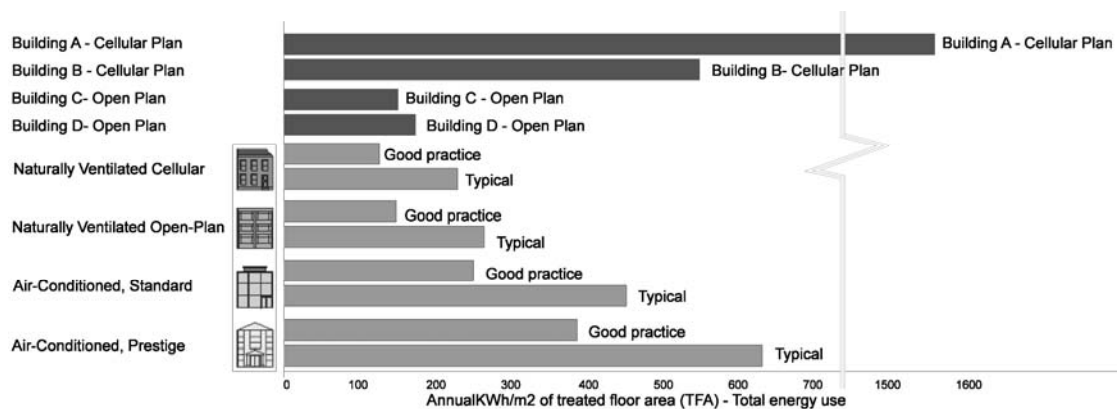


Figure 168: Energy consumption of the four case study buildings KWh/m² per year

Overall, the two open plan offices have much lower energy consumption compared to the two cellular plan offices. The energy consumption of Building A is very high, while the other three buildings are within an acceptable range. In terms of energy use, the open plan offices are much more sustainable compared to the cellular plan offices. Particularly Building A has an excessive use of energy. It concerns issues of individual freedom in relation to broader environmental perspectives.

7.2.5. CO₂ Level

In this section, the indoor air quality based on the carbon dioxide levels are evaluated and compared in the four case study buildings. The measuring points are on the desk level at every workstation, discussed in section 6.4.2. According to the ASHRAE Handbook 2001 (Bemisderfer et al., 2001), carbon dioxide in the workplace ‘ranges between 400 to 1500 depending on occupant density, ventilation distribution, and amount of outside air supplied to the occupied spaces’ (Bemisderfer et al., 2001). Different standards allow different ranges for carbon dioxide (Bemisderfer et al., 2001), for instance OSHA standard accepts up to 10000 ppm (OSHA, 1985). When carbon dioxide concentration exceeds 35,000 ppm, it is a danger to health (Bemisderfer et al., 2001). Outdoor air pollution does not influence any of the four case study buildings in this research, as three of them are located away from the city centre and polluted areas of the city. Although Building D is located in the centre of the city, the indoor air quality is mainly less than 600 ppm, which is very low. In this section, the indoor carbon dioxide concentration in the four case study buildings are compared according to the ASHRAE Standard, which are presented in Figure 169 and Figure 170.

Ventilation System and Typology of Plan	Frequency	Percent	Valid Percent	Cumulative Percent
Building A: Air Conditioned, Valid Openable Window and Heating in Cellular Plan	600-799	1	1.1	1.1
	400-599	45	47.4	48.4
	0-399	49	51.6	100.0
	Total	95	100.0	100.0
Building B: Air Conditioned & Valid Openable Window in Cellular Plan	600-799	3	3.9	3.9
	400-599	22	28.6	32.5
	0-399	52	67.5	100.0
	Total	77	100.0	100.0
Building C: Natural Ventilation Valid in Open Plan	800-999	1	1.4	1.4
	600-799	1	1.4	2.8
	400-599	22	30.6	33.3
	0-399	48	66.7	100.0
Total	72	100.0	100.0	
Building D: Displacement Valid Ventilation in Open Plan	600-799	7	10.1	10.1
	400-599	51	73.9	84.1
	0-399	11	15.9	100.0
	Total	69	100.0	100.0

Figure 169: SPSS Frequency analysis of comparing the CO₂ level between the four case study buildings

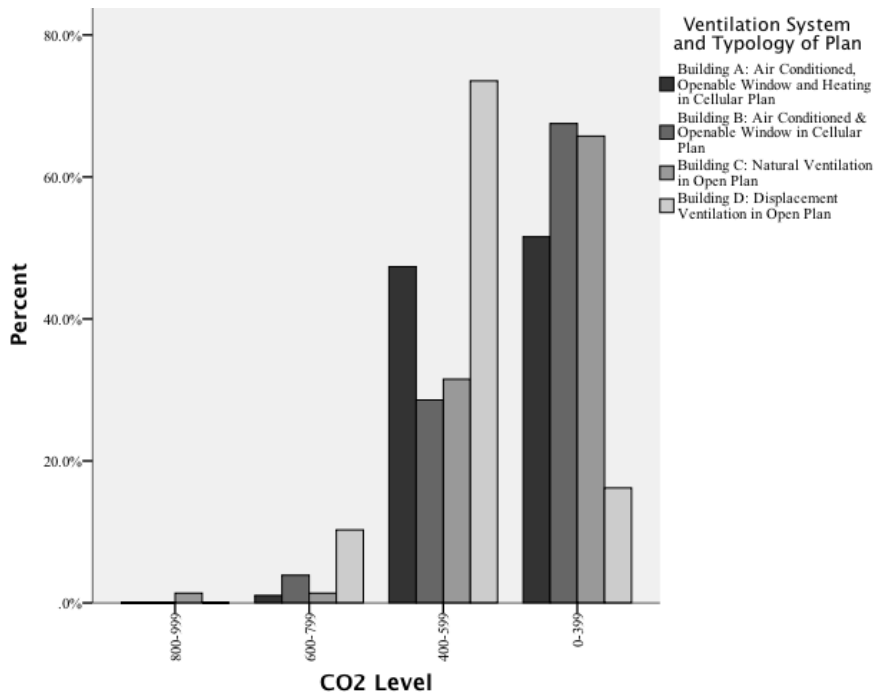


Figure 170: Frequency bar chart, comparing the CO₂ levels between the four case study buildings

Based on these statistics, the carbon dioxide levels in all four case study buildings are measured below 1000 ppm, which are well within the ASHRAE’s acceptable range. Building C and Building B have the best rate of carbon dioxide level. This is closely followed by Building A, while Building D has slightly higher levels of carbon dioxide but still within the acceptable range. All four offices have separate print rooms, however except Building B, most of these print areas are not separated with a door. Most personal rooms in the Building A are equipped with a printer. In the Building C also some printers are placed within the open plan office. Overall, the CO₂ levels in all four case study buildings are within the acceptable range and quite low. Users’ view of the indoor air quality is analysed in section 9.1.

7.2.6. Light Level

According to CIBSE Code for Lighting (CIBSE, 2002) the acceptable light level for workplaces, where moderately difficult visual tasks such as writing, typing, reading, and data processing take place, is 500 Lux. Figure 171 and Figure 172 present the comparison between the four case study buildings regarding their light level, both natural and artificial light. 300 to 500 Lux is considered the acceptable range. The measuring points are on the desk level at every workstation, discussed in section 6.4.2.

Ventilation System and Typology of Plan	Frequency	Percent	Valid Percent	Cumulative Percent
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Building A: Air Conditioned, Openable Window and Heating in Cellular Plan	Valid	100<x<199 Lux (Low)	2	2.1	2.1	2.1
		200<x<299 Lux (Slightly high)	9	9.5	9.5	11.6
		300-500 Lux (Acceptable)	25	26.3	26.3	37.9
		501-699 Lux (Slightly high)	29	30.5	30.5	68.4
		700<x<899 Lux (High)	9	9.5	9.5	77.9
		900<x Lux (Very high)	21	22.1	22.1	100.0
		Total	95	100.0	100.0	
Building B: Air Conditioned & Openable Window in Cellular Plan	Valid	0<x<99 Lux (Very low)	1	1.3	1.3	1.3
		100<x<199 Lux (Low)	6	7.8	7.8	9.1
		200<x<299 Lux (Slightly high)	3	3.9	3.9	13.0
		300-500 Lux (Acceptable)	13	16.9	16.9	29.9
		501-699 Lux (Slightly high)	5	6.5	6.5	36.4
		700<x<899 Lux (High)	18	23.4	23.4	59.7
		900<x Lux (Very high)	31	40.3	40.3	100.0
Total	77	100.0	100.0			
Building C: Natural Ventilation in Open Plan	Valid	100<x<199 Lux (Low)	1	1.4	1.4	1.4
		200<x<299 Lux (Slightly high)	11	15.1	15.1	16.4
		300-500 Lux (Acceptable)	33	45.2	45.2	61.6
		501-699 Lux (Slightly high)	12	16.4	16.4	78.1
		700<x<899 Lux (High)	4	5.5	5.5	83.6
		900<x Lux (Very high)	12	16.4	16.4	100.0
		Total	73	100.0	100.0	
Building D: Displacement Ventilation in Open Plan	Valid	200<x<299 Lux (Slightly high)	4	5.9	5.9	5.9
		300-500 Lux (Acceptable)	31	45.6	45.6	51.5
		501-699 Lux (Slightly high)	25	36.8	36.8	88.2
		700<x<899 Lux (High)	5	7.4	7.4	95.6
		900<x Lux (Very high)	3	4.4	4.4	100.0
		Total	68	100.0	100.0	

Figure 171: SPSS Frequency analysis of comparing the light level between the four case study buildings

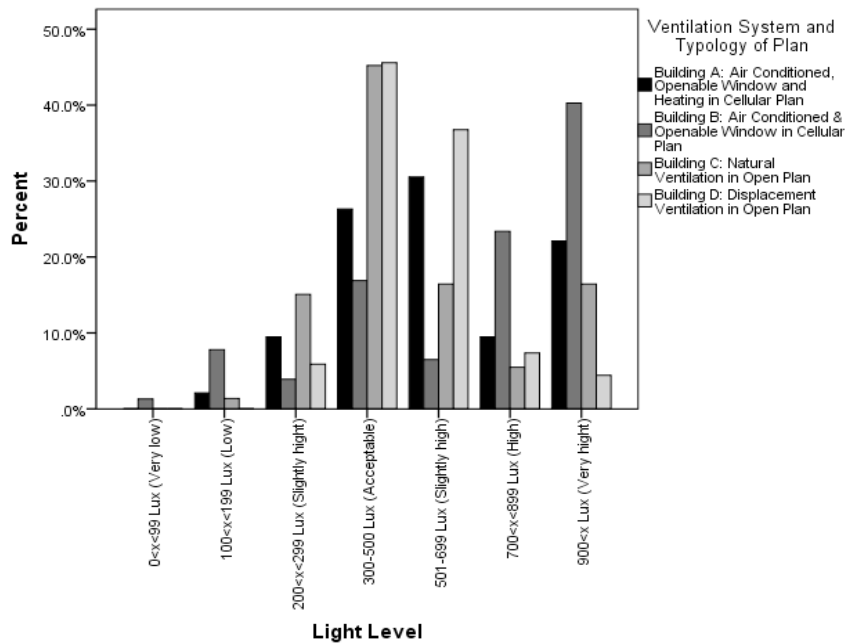


Figure 172: Frequency bar chart, comparing the light levels between the four case study buildings

Based on the analysis of light level between the four case study buildings, the light levels of the two open plan offices are closer to the accepted range. The light level is consistent and does not fluctuate much in the two open plan offices as artificial light the main source. Particularly lack of natural light in the middle of the open plan and the constant use of florescent lights provides a consistency and acceptable range of light level. In contrast, the cellular plan offices have more variety of light levels, which do not fit in the acceptable range most of the time as they exceed 500 Lux. This is mainly due to natural light as the main source, which is not consistent and changes according to the outdoor climatic conditions, season and time of the day. This is part of the Scandinavian regulations as every individual has the right to access the natural light (Van Meel, 2000), discussed in sections 2.2.4.6 and 4.1.1. Although the natural light greatly influences the light level of the cellular plan offices, every individual is provided with an internal blind to control the natural light level in their personal office. In building B an additional external blind is provided to completely block the natural light. Furthermore, the occupants of these two Norwegian buildings are provided with light switches to control the artificial light level in their offices.

According to the survey questionnaires, users' satisfaction with the light level is quite high in all of the four case study buildings, as it ranges between neutral to strongly adequate, presented in Figure 173. However, occupants' satisfaction with the light level is much higher where natural light is provided. As displayed in Figure 173, three of the buildings have similar satisfaction levels, while light satisfaction in the deep open plan office, Building D, is not as high. Although Building C is also an open plan office, most of the workstations are provided with both natural as well as artificial light. The design of the building, large windows and atrium, allows natural light to cover most of the workstations. In the interviews, occupants mentioned 'light and airy' to describe their building. This building has a steady light level, high satisfaction with lighting and good use of natural light. The occupants of the personal offices often use blinds to block the direct sunlight or allow more natural light. Their satisfaction with the light level is quite high.

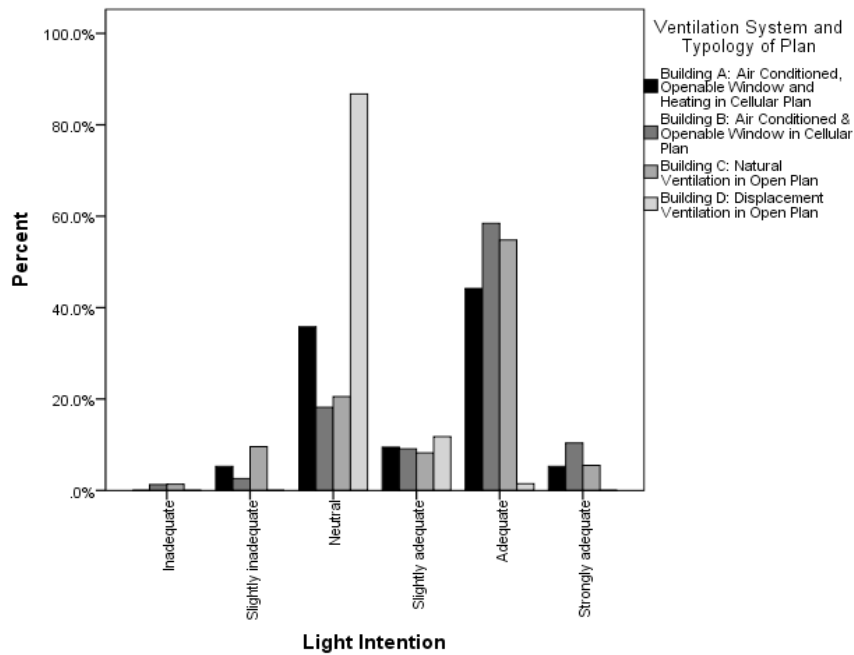


Figure 173: Users' satisfaction with the light level in the four case study buildings

Overall, occupants' satisfaction with the light level in all four buildings is within a good range. In addition, the interviews confirm these results as occupants of the two cellular plan offices and Building C mentioned their high satisfaction level with the natural light. However, the 'glare' was mentioned as the only negative aspect. The occupants controlled the direct sunlight through the provided blinds.

7.2.7. Sound Level

'Loud noise at work can damage people's hearing and lead to risks to safety' like difficulty in hearing warnings (HSE, 2012). According to different standards such as the ASHRAE (ASHRAE, 2007) and British standards (BS8233, 1999), the satisfactory level varies between 25 to 40 dB, while the maximum background noise level is up to 50 dB.

Occupancy Type	BS8233		ASHRAE	
	Satisfactory	Maximum	Satisfactory	Maximum
Private office	35	40	25	35
Open plan office	40	45	30	40

Figure 174: Recommended background noise limits for unoccupied mechanically ventilated spaces (Field, 2010)

However, the background sound level mentioned in the standards is in regard to mechanical ventilation (ASHRAE, 2007) when there is no occupant in the room. According to the Control of Noise at Work Regulations 2005, it is required to ensure health and safety by reducing noise risks and maintaining the noise level under the legal limits. The ‘lower exposure action value’ for ‘daily or weekly personal noise exposure’ is 80 decibels, while for ‘peak sound pressure’ is 135 decibels (HSE, 2012).

The measuring points are on the desk level at every workstation, discussed in section 6.4.2. Except Building D, the other case study buildings are located in quiet areas away from noise pollution. Although Building D is located in the city centre in Aberdeen, no particular outdoor noise pollution was observed or mentioned in the interviews. This building has no openable windows on the ground floor and limited openable windows on the other floors towards the main street. Overall none of the buildings suffer from outdoor noise pollution. The observation of the workstations and users’ view of the noise level during the interviews indicate that the sound level of all four case study buildings is within an acceptable range. In the sound measurements of the workstations due to a calibration mistake, C-weighting is applied rather than A-weighting, which is suitable for human ear at low sound levels (Bies, 2009). Therefore, the results cannot be compared against the standards. However, Figure 175 and Figure 176 show similar noise levels in all four case study buildings.

Ventilation System and Typology of Plan		Frequency	Percent	Valid Percent	Cumulative Percent
Building A: Air Conditioned, Openable Window and Heating in Cellular Plan	Valid	36-40	3	3.2	3.2
		41-80	56	58.9	62.1
		81-135	36	37.9	100.0
		Total	95	100.0	100.0
Building B: Air Conditioned & Openable Window in Cellular Plan	Valid	41-80	35	45.5	45.5
		81-135	41	53.2	98.7
		136<x	1	1.3	100.0
		Total	77	100.0	100.0
Building C: Natural Ventilation in Open Plan	Valid	25-35	2	2.7	2.7
		41-80	30	41.1	43.8
		81-135	41	56.2	100.0
		Total	73	100.0	100.0
Building D: Displacement Ventilation in Open Plan	Valid	41-80	23	33.8	33.8
		81-135	45	66.2	100.0
		Total	68	100.0	100.0

Figure 175: SPSS Frequency analysis of the noise level (dB) in the four case study buildings

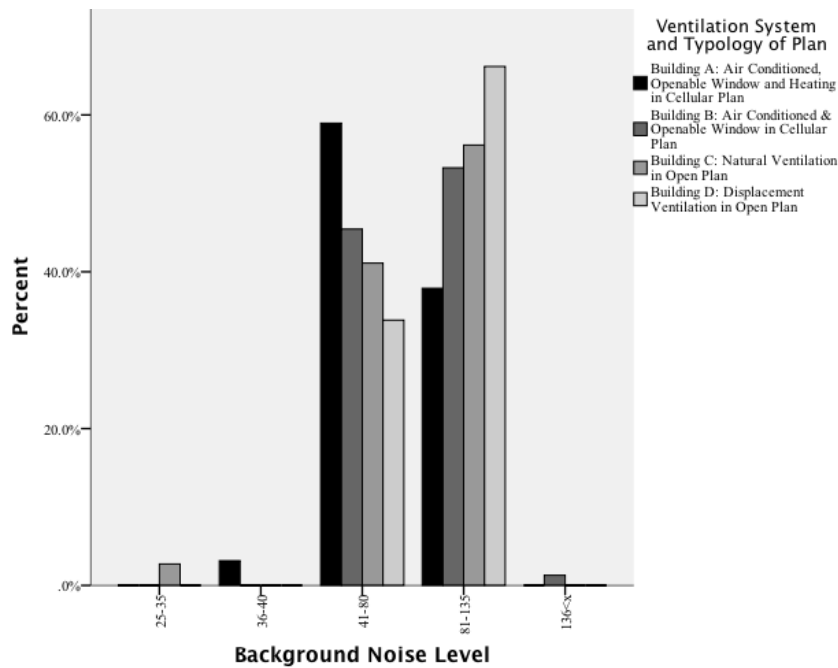


Figure 176: Frequency bar chart, comparing the noise levels (dB) between the four case study buildings

In many personal offices, occupants were listening to radio or the sound of river could be heard through the open window. Only one respondent was concerned about the sound of water. Occupants of the personal rooms close to the break areas, such as pantries, complained about the noise and colleagues talking loudly. Generally, occupants expressed high satisfaction levels with the control over the noise level through openable windows as well as the door. They use the door both to block the noise and as a signal to their colleagues not to be disturbed when they need to concentrate on their work.

In the open plan offices, the majority of occupants were fine with the background sound level. However, the main complaint was in regard to immediate colleagues chatting loudly with one another or over the telephone. Most of them did not use headphones as this was regarded as ‘anti-social’, and ‘not a solution’. Although noise is a disadvantage in the open plan offices, it did not trouble the majority of respondents. Many occupants expressed their satisfaction with the ease of communication with colleagues and the flow of information they receive with no effort. An occupant in Building D mentioned ‘twice I was able to prevent a disaster, because I heard my colleague’s conversation on the phone regarding our shared project’.

7.3. Summary

The four office buildings in this thesis were selected for their high and low levels of environmental control: Two cellular plan offices in Norway with high levels of individual thermal control and two open plan offices in Scotland with limited thermal control. All these buildings have openable windows and a sort of mechanical ventilation. In the cellular plan offices, air conditioning is in operation and every user is provided with an opportunity to adjust a window, blind, door, and thermostat. In Building C, natural ventilation is the main system although mechanically ventilated windows adjust the temperature and CO₂ level in the office. Occupants with a window seat have access to openable windows and blinds to adjust the thermal environment. In Building D, displacement ventilation is the main ventilation system and limited openable windows and blinds are provided for occupants, who sit next to them, to adjust the thermal environment. The building performances of these four buildings are compared against the ASHRAE Standard 55-2010 as well as the benchmarks.

The analysis of building performance indicate:

- All four case study buildings provide similar thermal environments within the comfort zone during the working hours. Over 90% of the workstations are expected to be comfortable based on the ASHRAE adaptive prediction model.
- The two open plan offices have much lower energy consumption compared to the two cellular plan offices. The energy consumption of Building A is very high, while the other three buildings are within an acceptable range. Although the cellular plan offices provide more thermal control opportunities through the architectural layout and building facilities, this comes with a price as they use much more energy and therefore they are less sustainable in this matter. The question is do cellular plan offices provide more comfort at the cost of energy they consume? This leads to a broader question: which measure is more important: user comfort or sustainability? Discussed in section 10.1.3.
- The carbon dioxide levels in all four case study buildings are within the acceptable range and quite low.
- The light levels are varied, however the open plan offices have closer to the acceptable range because mainly artificial light is operating, which is more uniform.

In contrast, the cellular plan offices mainly rely on the natural light, which is according to Norwegian work legislations.

- The noise levels in all the case studies are within the acceptable range.

Overall, according to the analysis, all these buildings are expected to provide a comfortable and good quality standard of thermal environment for their occupants.

CHAPTER 8

STAGE I: COMFORT ZONE

8. Stage I: Comfort Zone

This thesis is based on the challenge in the field of thermal comfort between the steady state and adaptive comfort theories, which are followed by distinct approaches, respectively ‘comfort zone’ and ‘adaptive opportunity’, discussed in Chapter Three. This chapter will challenge the view of ‘comfort zone’, while Chapter Nine will examine the application of the ‘adaptive opportunity’ in the Norwegian and British workplace contexts.

Chapter Seven evaluated all four case study buildings in this research. It revealed that they have a high quality standard of indoor environment, according to building standards, such as ASHRAE, and benchmarks, such as CIBSE. The purpose of this chapter is to challenge the ASHRAE thermal comfort zone as the basis of the steady state theory given the research undertaken by the author. It reflects the complexity found in addressing thermal comfort, control systems and spatial layout in the workplace. This chapter will suggest that thermal environmental conditions that are predicted to be comfortable based on the ASHRAE Standard 55-2010 do not guarantee user comfort. The ASHRAE predictions based on the measurements in the field are compared against the comfort surveys. We also ask whether the concept of ‘neutral thermal sensation’, which is the basis of thermal comfort standards, guarantee thermal comfort, as many occupants prefer sensations other than ‘neutral’ when working. This is followed by examining the consistency of thermal preference of the user throughout the day. This chapter will propose that thermal comfort is dynamic rather than fixed, which is in contrast with the standard ‘comfort zone’ in providing a uniform thermal environment for occupants in the workplace. The chapter will conclude by suggesting that a standard ‘comfort zone’ that satisfies everyone is less likely to apply to the real world context of the workplace.

Quantitative and qualitative methods are applied to analyse these objectives. These analyses are based on over 300 responses, the total number of respondents to the survey questionnaire, which is followed by simultaneous thermal measurements at every workstation. These 300 responses include approximately 30 participants in each of the four buildings, who responded to the survey questionnaire three times a day. The survey questionnaire was collected over three days in each building, approximately ten participants per day.

8.1. The ASHRAE Comfort Predictions

This section investigates the accuracy of the comfort zone in the ASHRAE Standard 55-2010, as the most widely used comfort standard, explained in section 3.2.2.1. Using the ASHRAE Thermal Comfort Tool, which is according to the ASHRAE Standard 55-2010, the PMV and adaptive comfort of every workstation is evaluated based on the thermal measurements of the workstations at the time of the survey, explained in section 7.2.3. When the prediction indicates ‘neutral’, it means that the occupant of the particular workstation at the time of the survey is expected to be comfortable (ASHRAE, 2009, ASHRAE, 2010). Then this prediction is compared against the actual survey questionnaire regarding thermal sensation, comfort and satisfaction of the occupant.

Quantitative and qualitative analysis methods are applied. Based on the traditional quantitative analysis in the field of thermal comfort, mainly linear regression analysis is used (Jaakkola et al., 1989, Busch, 1992, de Dear and Brager, 1998, Brager and De Dear, 2000, Raja et al., 2001, de Dear and Brager, 2002, Wong et al., 2002, Feriadi and Wong, 2004, Bouden and Ghrab, 2005) to investigate the relationship between the ASHRAE prediction models and the variables of the survey questionnaires. A similar process is used for all the quantitative analysis sections, therefore a sample of the SPSS regression analysis is presented in section 8.1.1.1.1 and the remaining tables and analysis are presented in Appendix D. Descriptive analysis and boxplot are also used to show the results in detail. In addition, qualitative analysis is applied for a more intensive investigation using the visual recording technique. Calculations using the ASHRAE adaptive and PMV models are explained in section 7.2.3.

8.1.1. Adaptive Model

In this section, the accuracy of the ASHRAE adaptive prediction model is examined against the thermal sensation, comfort and satisfaction responses of the survey questionnaires. The detailed descriptive analysis of the ASHRAE adaptive model is presented in section 8.2.1. This model is based on a five point scale and ‘neutral’ is considered as a thermally comfortable condition:

- +2 = Too warm
- +1 = Warm
- **0 = Neutral**
- -1 = Cool
- -2 = Too cool

8.1.1.1. Quantitative Analysis

This section investigates the accuracy of the adaptive prediction using the SPSS linear regression analysis and a boxplot to compare the prediction against the actual survey results.

8.1.1.1.1. Thermal Sensation

According to the ASHRAE Standard 55-2010, the adaptive model is able to predict the comfort condition for up to 90% of the occupants. Therefore the prediction based on the environmental measurements is compared to the actual surveyed questionnaire regarding the thermal sensation of the user in all four case study buildings. The detailed descriptive analysis of the ASHRAE adaptive comfort prediction model and the surveyed thermal sensation is presented in section 8.1.1.2. Figure 177 to Figure 179 represent the SPSS regression analysis of the two variables. Figure 177 shows the SPSS Descriptive Statistics analysis of the ASHRAE adaptive model and thermal sensation based on 313 responses overall.

	Mean	Std. Deviation	N
Adaptive Analysis-5 Point Scale	.76	1.300	313
Thermal Sensation-7 Point Scale ASHRAE	.09	.994	313

Figure 177: Descriptive Statistics, SPSS linear regression analysis of the ASHRAE adaptive comfort prediction model and thermal sensation

The ANOVA analysis is presented in Figure 178. It shows that thermal sensation can be predicted based on the ASHRAE adaptive comfort prediction model, since the P value is 0.008, which is less than 0.05.

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	11.657	1	11.657	7.034	.008^a
	Residual	515.372	311	1.657		
	Total	527.029	312			

a. Predictors: (Constant), Thermal Sensation-7 Point Scale ASHRAE

b. Dependent Variable: Adaptive Analysis-5 Point Scale

Figure 178: ANOVA, SPSS linear regression analysis of the ASHRAE adaptive comfort prediction model and thermal sensation

The R Square in the SPSS Model Summary, Figure 179, shows that 2.2% of variance in thermal sensation can be explained by ASHRAE adaptive comfort prediction model. Although the P value suggests a strong relationship between the variables, 2.2% is not so significant.

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.149 ^a	.022	.019	1.287	.022	7.034	1	311	.008

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1.	.149 ^a	.022	.019	1.287	.022	7.034	1	311	.008

a. Predictors: (Constant), Thermal Sensation-7 Point Scale ASHRAE

Figure 179: Model Summary, SPSS linear regression analysis of the ASHRAE adaptive comfort prediction model and thermal sensation

Figure 180 presents the boxplot of the ASHRAE adaptive model and thermal sensation. It shows that the majority of the participants, who are predicted to be comfortable, have a thermal sensation between slightly cool and slightly warm; here ‘neutral’ is their mean. The majority of the occupants, who are expected to feel warm, have a thermal sensation between neutral and hot; while ‘slightly warm’ is their mean. The majority of the occupants, who are expected to feel too warm, have a thermal sensation between neutral and slightly warm; here ‘neutral’ is their mean. A slight bias is visible in the boxplot as the prediction does not completely match the actual users’ responses, presented in Figure 181. Figure 182 presents separate offices on the boxplot and it shows similar results to Figure 180. It reveals that when the ASHRAE predicts the thermal environment of the workstation as ‘comfortable’ for over 90% of the occupants: many respondents in Building A feel ‘slightly cool’, in Buildings B and D feel ‘slightly warm’, and in Building C the majority of respondents rate between ‘slightly cool’ to ‘slightly warm’. When the ASHRAE predicts a ‘warm’ environment, respondents in Buildings B and D perceive the environment as ‘neutral’, in Building A as ‘slightly warm’, and in Building C majority of them rate between ‘neutral’ to ‘warm’. This shows the differences between the buildings and variations in each building, as in Building C respondents have a wider range of thermal sensation than is predicted. It also exposes the difficulty in predicting the thermal environment. The prediction of the thermal environment of the workstations based on the ASHRAE adaptive model does not match what respondents actually perceive the thermal environment.

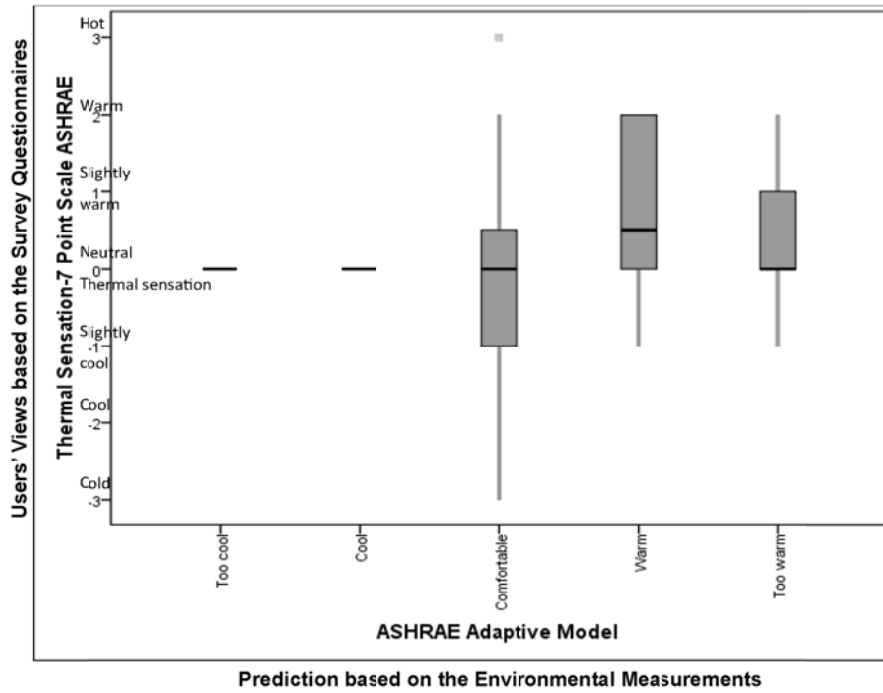


Figure 180: SPSS, boxplot of the ASHRAE adaptive prediction model and surveyed seven point scale thermal sensation

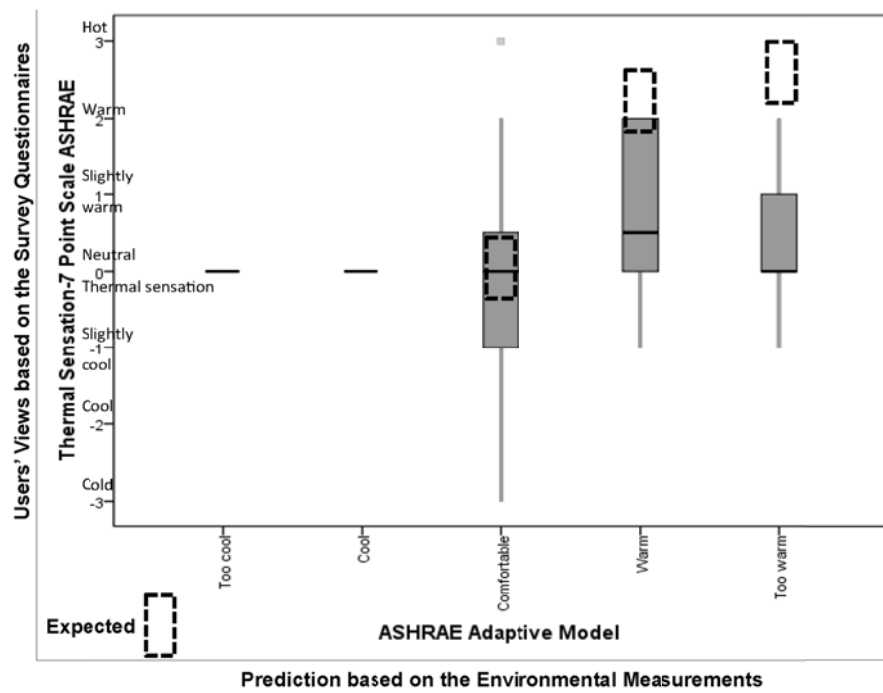


Figure 181: Boxplot presenting what was expected in Figure 180

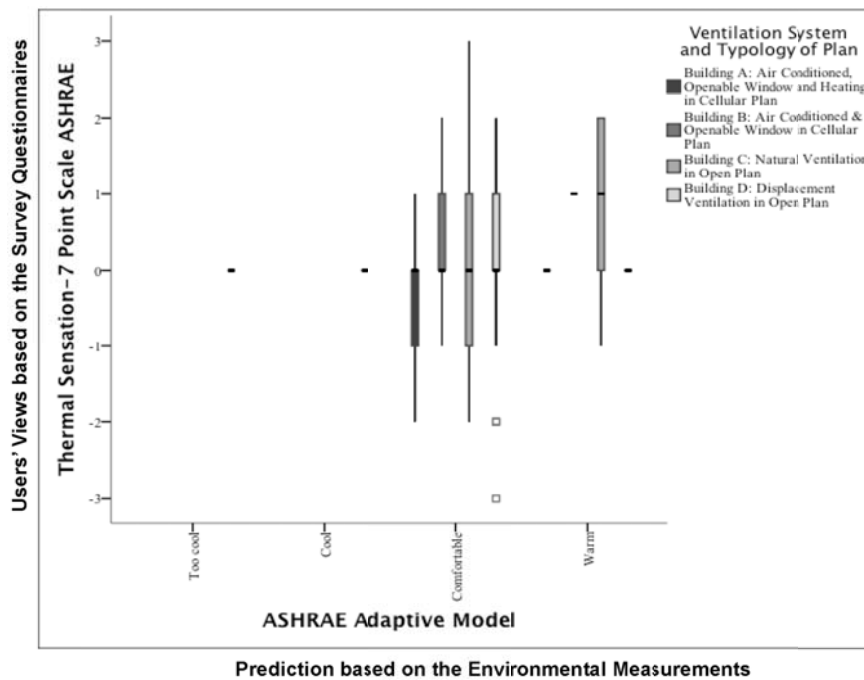


Figure 182: SPSS, boxplot of the ASHRAE adaptive prediction model and surveyed thermal sensation for each building

8.1.1.1.2. Comfort

In this section, the SPSS linear regression analysis has been applied to compare the accuracy of the ASHRAE adaptive prediction model against the surveyed comfort results. Comfort survey is based on the ASHRAE seven point scale question, presented in section 3.2.2.1:

- +3 = **Very comfortable**
- +2 = Comfortable
- +1 = Slightly comfortable
- 0 = Neutral
- -1 = Slightly uncomfortable
- -2 = Uncomfortable
- -3 = Very uncomfortable

Here the best possible result is +3, and the worst is -3. This is different from the ASHRAE adaptive five point scale, in which the best possible result is 0, which is comfortable. In the regression analysis, the comparison starts from the ends of the two variables. In this analysis the end of one variable cannot be compared to the midpoint of the other variable. Therefore the variables should be arranged so that their top ends can be compared. In other words, 'comfortable' response is the top ends of both variables. Therefore in order to compare these two variables using the SPSS regression analysis a three point scale has been used for the

adaptive model. In this case both variables have one end as the best and the other end as the worst possible result:

- **+2 = Comfortable**
- +1 = Warm/cool
- 0 = Too Warm/too cool

The SPSS regression analysis, which is similar to section 8.1.1.1.1 and presented in Appendix D, suggests no significant relationship between surveyed comfort and the ASHRAE adaptive prediction model (i.e. P value is $0.711 > 0.05$). Figure 183 is the boxplot of the surveyed comfort and the ASHRAE adaptive prediction model. It also shows a contradiction between the two variables: occupants who are expected to be warm and therefore not comfortable actually report being comfortable, presented in Figure 184 and separate offices presented in Figure 185. The latter shows similarities between the perceptions of the respondents in the two cellular plan offices and also in the two open plan offices when the ASHRAE predicts a 'comfortable' thermal environment. In the cellular plan offices, participants report between 'slightly uncomfortable' to 'very comfortable'. In the open plan offices, majority of participants report between 'neutral' (i.e. neither comfortable nor uncomfortable) to 'comfortable'. When the model predicts a 'warm' environment for over 90% of the occupants based on the environmental measurements, respondents of the cellular plan offices feel 'very comfortable' and majority of the respondents in the open plan offices feel 'slightly comfortable' or 'comfortable'. This shows the difficulty in predicting the thermal environment based on the environmental measurements as well as similarities between the buildings of each typology.

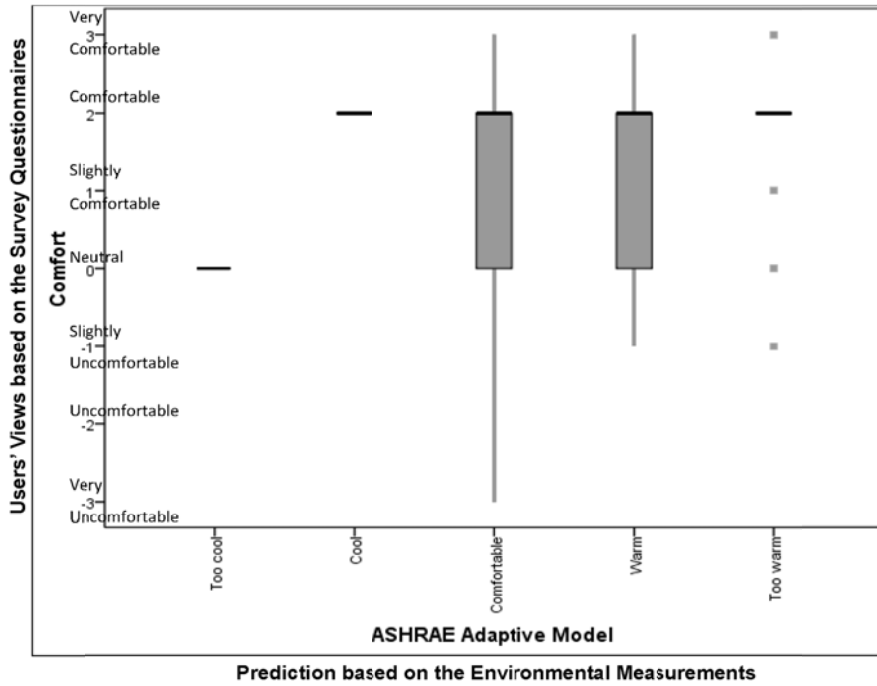


Figure 183: SPSS, Boxplot of the ASHRAE adaptive prediction model and the surveyed comfort

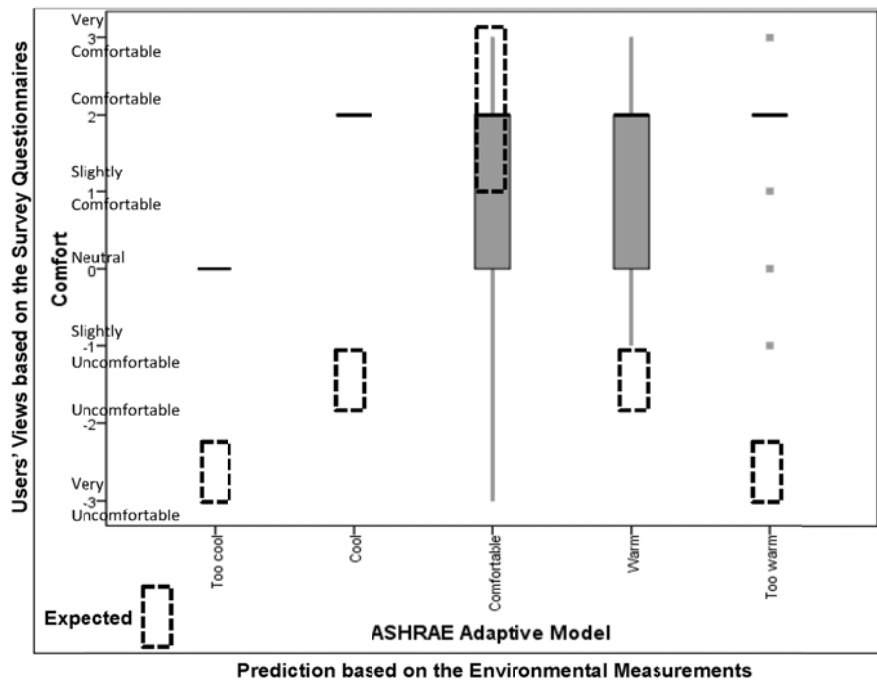


Figure 184: Boxplot presenting what was expected in Figure 183

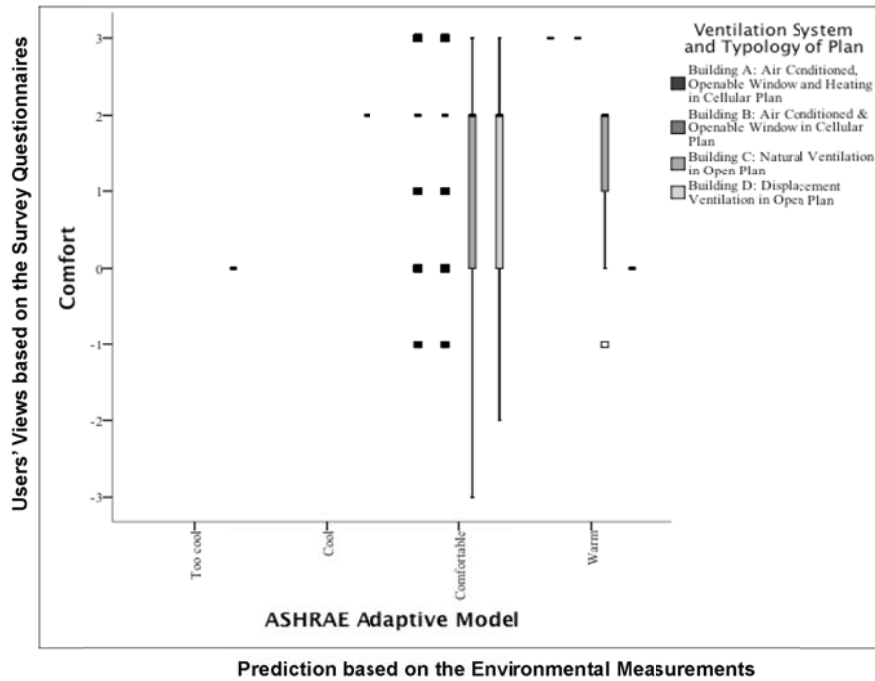


Figure 185: SPSS, Boxplot of the ASHRAE adaptive prediction model and the surveyed comfort for each building

8.1.1.1.3. Satisfaction

In this section, the accuracy of the ASHRAE adaptive prediction model is compared against the surveyed satisfaction results. Satisfaction survey is based on the ASHRAE seven point scale question, presented in section 3.2.2.1:

- +3 = Very satisfied
- +2 = Satisfied
- +1 = Slightly satisfied
- 0 = Neutral
- -1 = Slightly dissatisfied
- -2 = Dissatisfied
- -3 = Very dissatisfied

Here the best possible result is +3, and the worst is -3. This is different from the ASHRAE adaptive five point scale, in which the best possible result is 0, which is comfortable. Therefore in order to compare these two variables using the SPSS regression analysis, a three point scale has been used for the adaptive model, presented in section 8.1.1.1.2. The SPSS regression analysis, presented in Appendix D, suggests no significant relationship between surveyed satisfaction and the ASHRAE adaptive prediction model (i.e. P value is $0.462 > 0.05$). Figure 186 is the boxplot of satisfaction and the ASHRAE adaptive prediction model.

This graph also shows an inconsistency between the two variables. Participants, who are predicted to feel warm or too warm and therefore not comfortable, in the actual survey report feeling satisfied. This is particularly noticeable in ‘too warm’ prediction, as the mean is ‘satisfied’ on the survey questionnaire, which indicates that the majority of the participants who were predicted to feel too warm were actually satisfied at the time of the survey. Overall, many participants report against what would be expected according to the prediction model, presented in Figure 187. Figure 188 shows the information for separate offices and it shows that the adaptive model is more successful in predicting comfortable respondents in the cellular plan offices rather than the naturally ventilated open plan office (i.e. Building C). It shows that respondents of the cellular plan offices are mainly feel satisfied regardless of the prediction model, while many respondents in the open plan offices do not feel satisfied and this is also regardless of the prediction. Building C shows wider variation of perceived satisfaction level (i.e. ranging from ‘slightly dissatisfied’ to ‘satisfied’) both when the ASHRAE predicts ‘comfortable’ and ‘warm’ conditions.

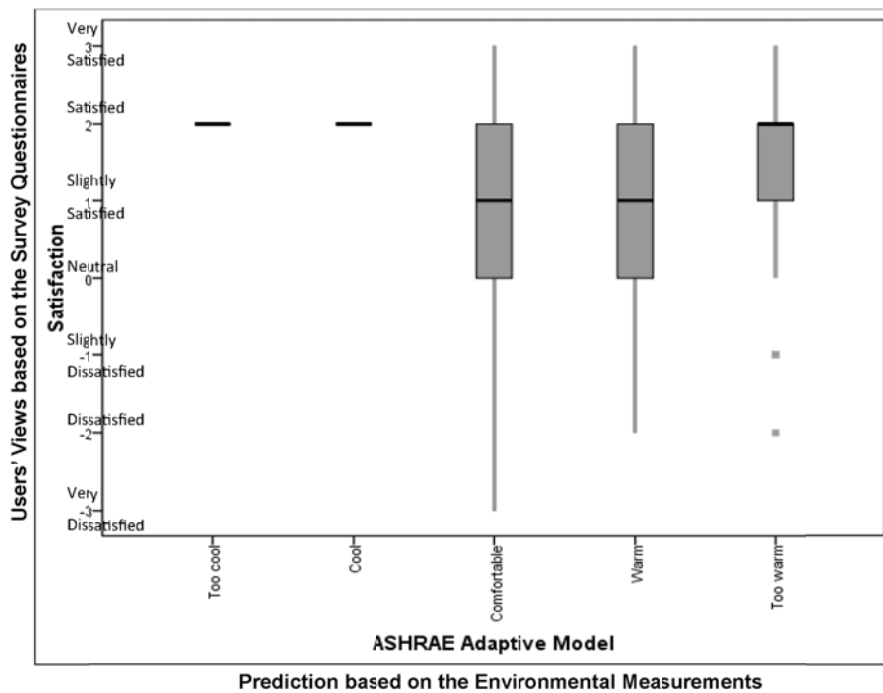


Figure 186: SPSS, boxplot of the ASHRAE adaptive prediction model and surveyed satisfaction

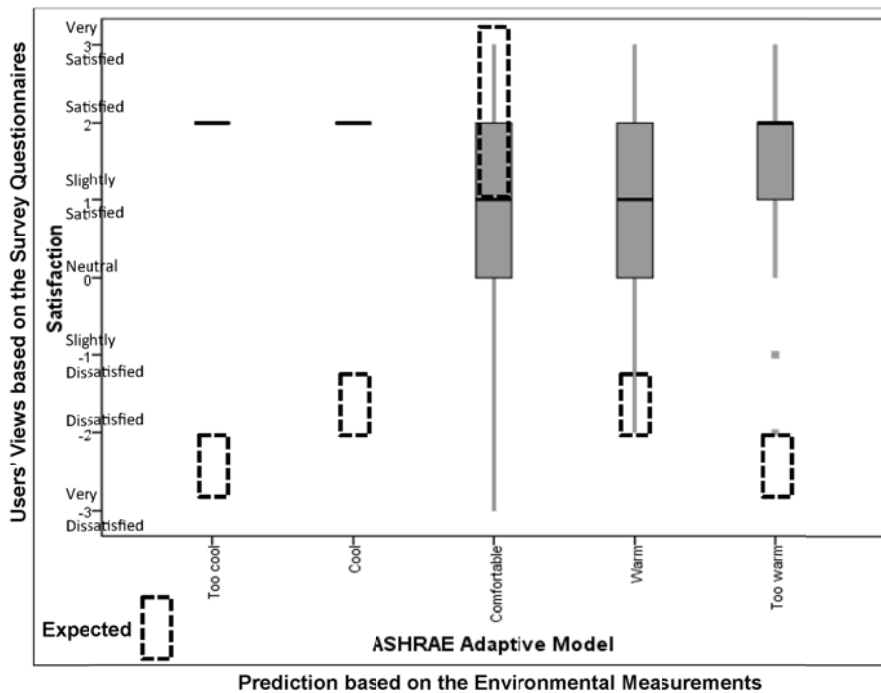


Figure 187: Boxplot presenting what was expected in Figure 188

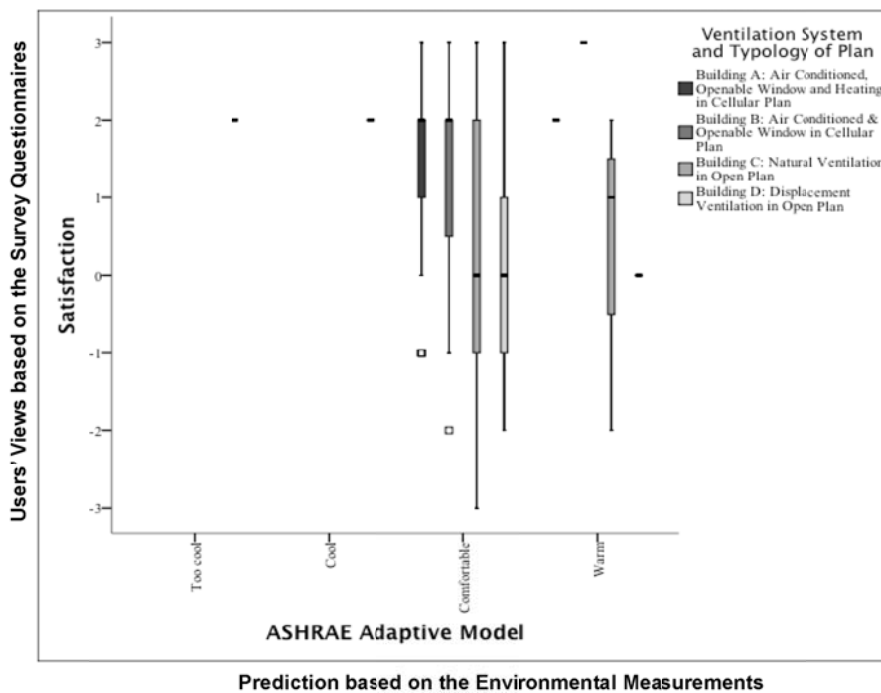
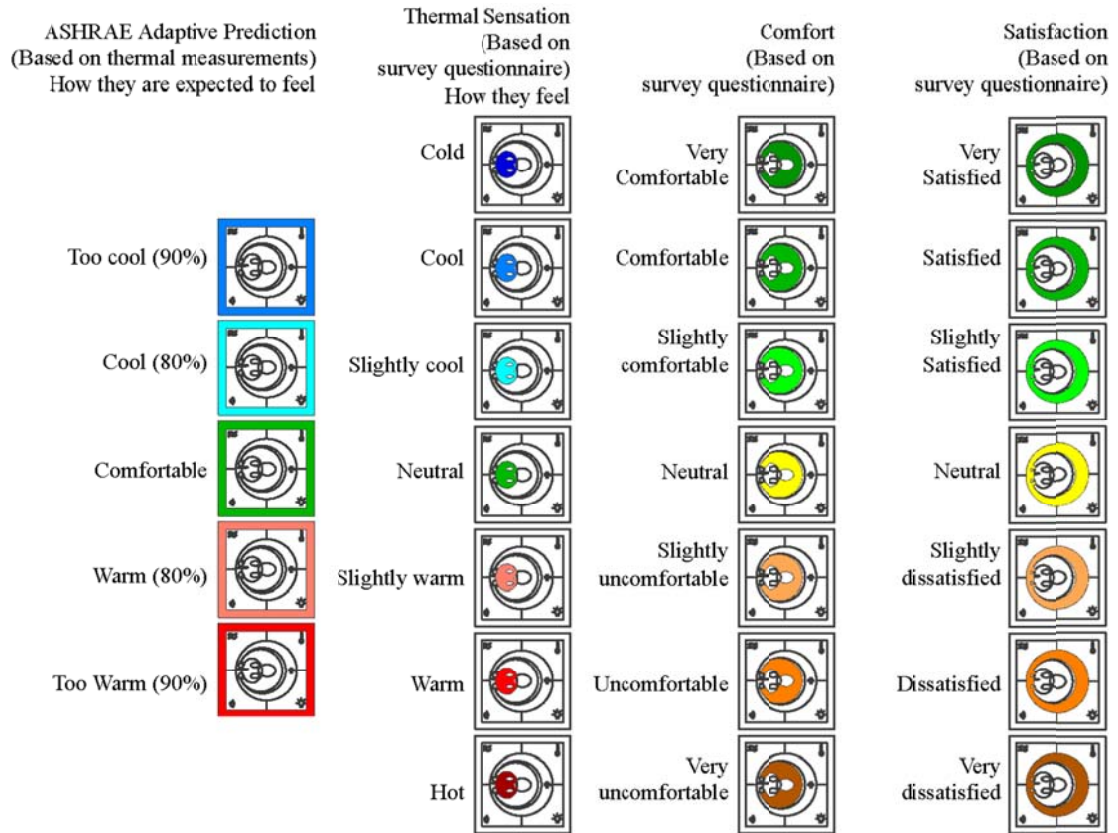


Figure 188: SPSS, boxplot of the ASHRAE adaptive prediction model and surveyed satisfaction in each building

Quantitative analysis of the ASHRAE adaptive comfort prediction model against comfort and satisfaction reveals no particular relationship between this model and any of the variables. There is a weak relationship between adaptive comfort model and thermal sensation, as only 2.2% of the responses can be explained by the model. Overall, these statistics suggest that the ASHRAE adaptive comfort prediction model is not as accurate as expected when it is applied to the actual context of the four case study buildings in this study.

8.1.1.2. Qualitative Analysis



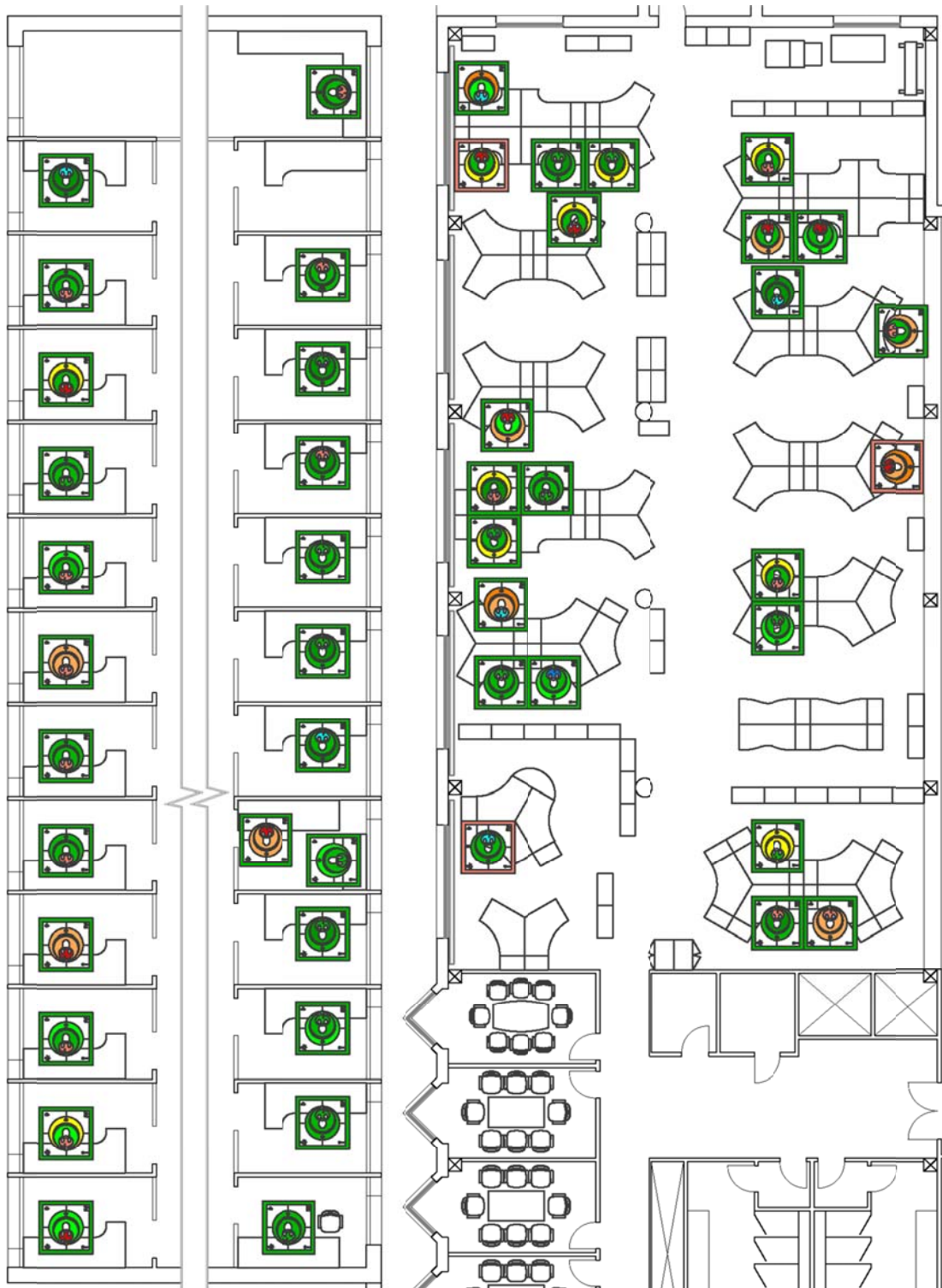


Figure 189: Building A and C: A sample of the qualitative analysis of the adaptive model and thermal sensation, comfort and satisfaction, presented properly in Appendix A

Figure 190 shows the analysis of the ASHRAE adaptive prediction model and the surveyed thermal sensation of all four case study buildings based on the qualitative visual analysis technique. A sample of this analysis is presented in Figure 189, and the proper pictograms in Appendix A. The ASHRAE adaptive model predicts that 308 out of 319 occupants of

workstations are considered neutral, which means that the occupants of those 308 workstations are expected feel comfortable. According to the survey questionnaire results, 144 out of those 308 respondents (i.e. 47%) report feeling neutral. However, 162 respondents (i.e. 53%) challenge the neutral prediction of the adaptive model, as they do not have a neutral thermal sensation. In addition, seven respondents, who are not predicted to feel neutral using the ASHRAE adaptive model, reported feeling neutral on their survey questionnaire. Overall, 174 out of 319 respondents (i.e. 55%) challenge the adaptive prediction.

All 4 Buildings							
Thermal Sensation Survey Questionnaire	ASHRAE Adaptive Prediction Model						
	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
Hot				2			
Warm				24	3		
Slightly warm				65	1		
Neutral		1	2	144	4		
Slightly cool				58	2		
Cool				11			
Cold				2			

Figure 190: Qualitative analysis of the ASHRAE prediction adaptive comfort model and thermal sensation survey results, based on the qualitative visual analysis

The following pictograms demonstrate the relationship between the ASHRAE adaptive prediction and the actual users' responses regarding their thermal sensation and thermal intention. They are based on the qualitative visual analysis for an intensive evaluation. Figure 191 and Figure 192 explain how to analyse the pictograms.

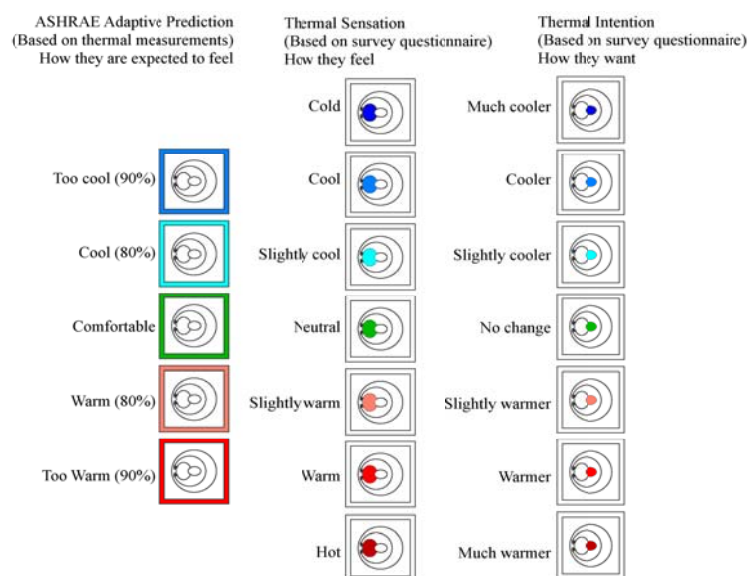


Figure 191: Explaining how to analyse the pictograms

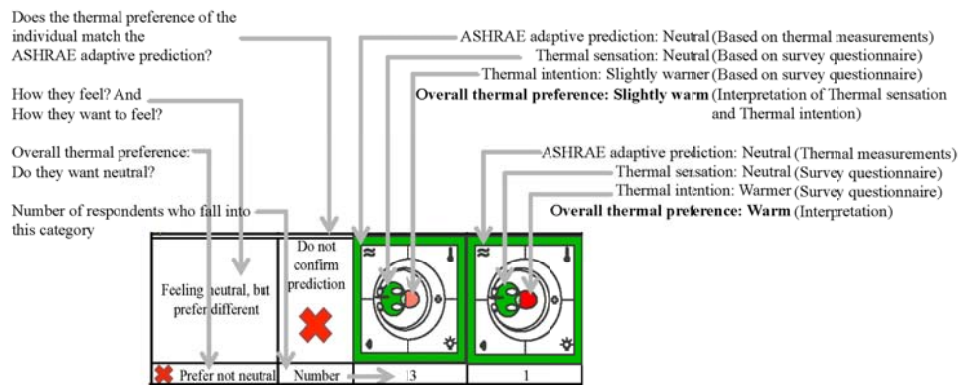


Figure 192: Explaining how to analyse the pictograms

Figure 193 shows that 144 participants are predicted to be neutral and report having a neutral thermal sensation. However, 26 of them prefer to have a different thermal sensation, such as slightly warm, slightly cool or hot, rather than a neutral thermal sensation. In addition, the table reveals that although 47 occupants, who are predicted to have a neutral thermal sensation, have reported not feeling neutral, but in fact they are fine and do not want any change in the temperature. This suggests that these occupants also do not want to have a neutral thermal sensation. Overall, in 119 out of 319 of the responses there is a consistency between the ASHRAE adaptive prediction model and surveyed thermal sensation and thermal intention. Therefore the model has been successful in predicting 37% of the thermal comfort conditions in the four case study buildings overall, rather than the expected 90% (Huizenga, 2011).

Warm	Feeling not neutral and prefer neutral	Confirm prediction																		
	✓ Prefer neutral	Number	1																	
	Feeling neutral, but prefer different or feeling not neutral jnuit want no change	Do not confirm prediction																		
	✗ Prefer not neutral	Number	1	1	1															
Neutral	Feeling neutral, and prefer no change	Confirm prediction																		
	✓ Prefer neutral	Number	118																	
	Feeling neutral, but prefer different	Do not confirm prediction																		
	✗ Prefer not neutral	Number	13	1	1	11														
Cool and Too cool	Feeling not neutral, but prefer no change	Do not confirm prediction																		
	✗ Prefer not neutral	Number	16	3	26	1	1													
	Feeling not neutral and prefer neutral	Do not confirm prediction																		
	✓ Prefer neutral	Number	42	6	25	6														
Cool and Too cool	Feeling not neutral, and prefer different	Do not confirm prediction																		
	✗ Prefer not neutral	Number	5	15	2	4	3	2	1	1										
	Feeling not neutral, and prefer even more different	Do not confirm prediction																		
	✗ Prefer not neutral	Number	1	2	1															
Cool and Too cool	Feeling neutral, and prefer no change	Do not confirm prediction																		
	✓ Prefer neutral	Number	1	1																

Figure 193: Qualitative comparison between the ASHRAE adaptive prediction, thermal sensation and thermal intention survey results

ASHRAE Adaptive Prediction	Thermal Sensation of Individual	Overall Thermal Preference of Individual	Number of Respondents	Prediction Matches Preference?	Number of Respondents
(How they are expected to feel?)	(How they feel?)	(How they want to feel?)			
Based on Thermal Measurements	Based on Survey Questionnaire	Based on Survey Questionnaire			
Warm	Warm	Neutral	1	✓	1
	Not warm	Not Neutral	4	✗	9
	Not warm	Neutral	5	✗	
Neutral	Neutral	Neutral	113	✓	113
	Neutral	Not Neutral	26	✗	189
	Not neutral	Not Neutral	47	✗	
	Not neutral	Neutral	79	✗	
	Not neutral	Not Neutral	33	✗	
	Not neutral	Not Neutral	4	✗	
Cool	Neutral	Neutral	1	✗	1
Too cool	Neutral	Neutral	1	✗	1

Figure 194: Based on Figure 193: Qualitative comparison between the ASHRAE adaptive prediction, thermal sensation and thermal intention survey results

Furthermore, this analysis suggests that 114 out of 319 respondents (i.e. 36%) in this research prefer not to have a neutral thermal sensation. They fall into the following categories:

- 25% already have a neutral thermal sensation, but prefer to have other sensations, such as Figure 195.





Feeling neutral, but prefer different	Do not confirm prediction ✗				
✗ Prefer not neutral	Number	13	1	1	11

Figure 195: Sample: Have a neutral thermal sensation, but prefer a different temperature setting

- 41% have sensations other than neutral, but prefer to have no change, Figure 196 shows some examples of this category.

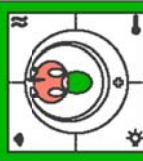

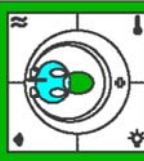
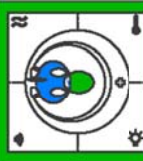
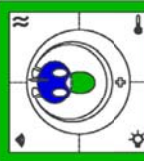
Feeling not neutral, but prefer no change	Do not confirm prediction ✗					
✗ Prefer not neutral	Number	16	3	26	1	1

Figure 196: Sample: Do not have a neutral thermal sensation, but do not want any change in temperature either

- 34% do not have a neutral thermal sensation, and they want a change in temperature, however their overall preference is not neutral, such as Figure 197. For instance, they feel warm and they would prefer slightly cooler. In this case, slightly warm would be

the preferred thermal sensation. A few respondents may like an extreme sensation, for instance they already feel cool, but they would prefer even slightly cooler. In this case, a cold thermal sensation is desired.

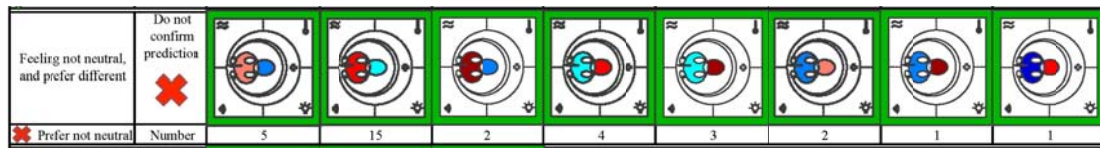


Figure 197: Sample: Do not have a neutral thermal sensation, but their thermal intention does not result in a neutral thermal sensation overall either

It is particularly difficult to predict the comfort status of occupants who fall into these categories, since thermal comfort is predicted based on neutral thermal sensation (ASHRAE, 2010). However, these occupants would prefer sensations other than neutral. Therefore it is difficult to predict their comfort state, as they may feel warm and perfectly happy, whilst based on the thermal comfort studies they are considered uncomfortable and as a result a decision may be taken to reduce the temperature in order to make these occupants feel neutral. However, this may result in their discomfort rather than the expected comfort status. This is backed up by the follow up interviews showing that only 30% of the occupants wanted to feel neutral while working and the majority if them were happy to feel other sensations than neutral, further discussed in section 8.2.4. This suggests that predicting thermal comfort may be more complicated than simply measuring the thermal sensation response. This confirms the findings of other researchers (Humphreys and Nancock, 2007, de Dear, 2011). This part has been discussed in more detail in section 8.2.

8.1.2. PMV Model

In this section, the ASHRAE PMV comfort prediction model is compared against the survey questionnaire regarding the thermal sensation, comfort and satisfaction of the user. The ASHRAE PMV model is based on thermal measurements at the workstation at the time of the survey and is calculated using the ASHRAE Thermal Comfort Tool, explained in section 7.2.3. According to the ASHRAE Standard 55-2010, the PMV model is able to predict 80% of comfort conditions (ASHRAE, 2010). This model is based on the ASHRAE seven point scale, which 'neutral' is considered as a thermally comfortable condition:

- +3 = Hot
- +2 = Warm
- +1 = Slightly warm
- 0 = Neutral

- -1 = Slightly cool
- -2 = Cool
- -3 = Cold

8.1.2.1. Quantitative Analysis

This section investigates the accuracy of the PMV prediction using the SPSS linear regression analysis and boxplot to compare the prediction against the actual survey results.

8.1.2.1.1. Thermal Sensation

This section compares the PMV prediction and surveyed thermal sensation. The detailed descriptive analysis of these two variables is presented in section 8.1.1.2 and their SPSS linear regression analysis is presented in Appendix D. The latter suggests a significant relationship between these two variables (i.e. P value is $0.000 < 0.05$). However, 5% of the surveyed thermal sensation choices can be explained by the ASHRAE PMV prediction model, which is not a significant prediction. Figure 198 presents the boxplot of the ASHRAE PMV prediction model and the surveyed thermal sensation. The inconsistency between the two variables is visible when the PMV model predicts a cool thermal sensation, while the occupants report neutral or slightly cool. In addition, when the PMV model predicts a neutral thermal sensation, the surveyed thermal sensation varies between neutral and slightly warm, as presented in Figure 199. Figure 200 shows the information for separate buildings and it reveals that the PMV model predicts the thermal condition of Building A more accurately and the open plan offices less accurately. It also reveals that the perceived thermal sensation of the respondents in the cellular plan offices has a smaller range compared to the open plan offices regardless of the ASHRAE PMV prediction. It is possible that the availability of thermal control affects this, as very few respondents are comfortable when experiencing the extreme conditions of 'warm' or 'cold'. This is discussed further in section 8.2. When the model predicts a 'slightly cool' environment for over 80% of the occupants, the mean of the perceived thermal sensation of the occupants in all four buildings is set on 'neutral' although there are differences between the buildings. In buildings B, C and D, many respondents report feeling 'slightly warm' when they are expected to feel 'slightly cool'. When the prediction is 'neutral' expecting occupants to feel comfortable, the actual perception of many respondents in all four buildings is 'slightly warm'.

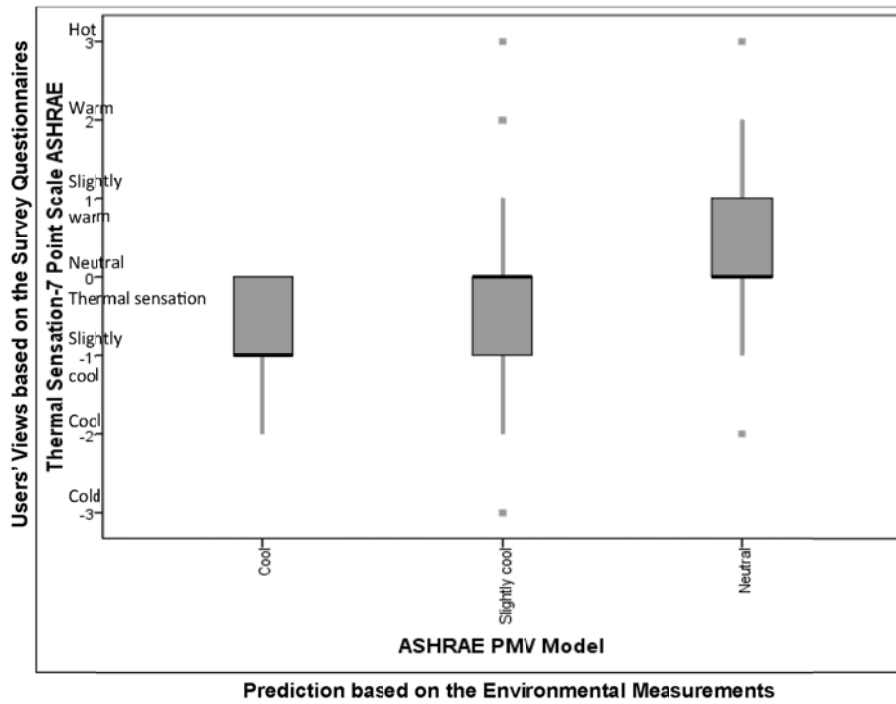


Figure 198: SPSS, boxplot of the ASHRAE PMV prediction model and surveyed seven point scale thermal sensation

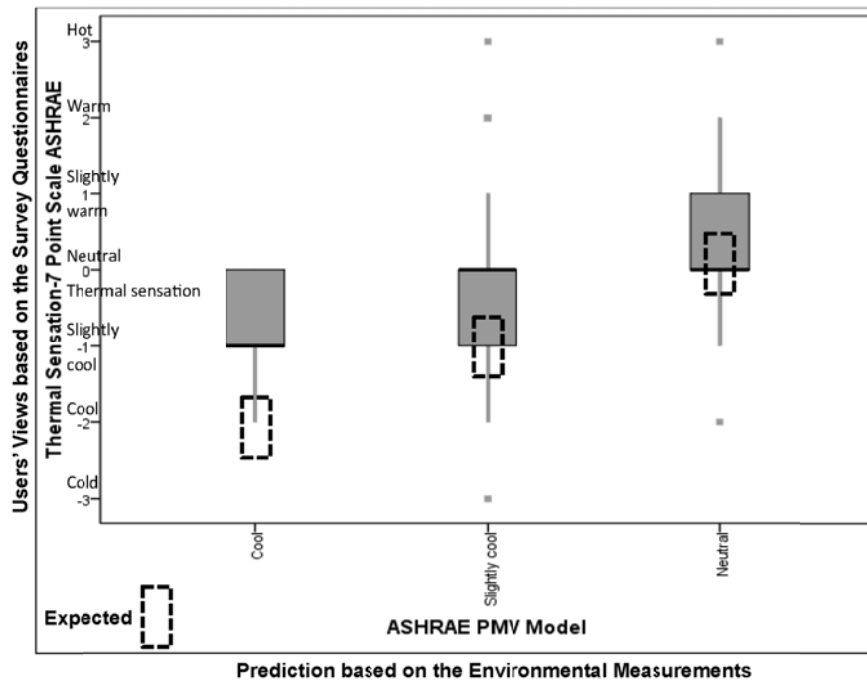


Figure 199: Boxplot presenting what was expected in Figure 198

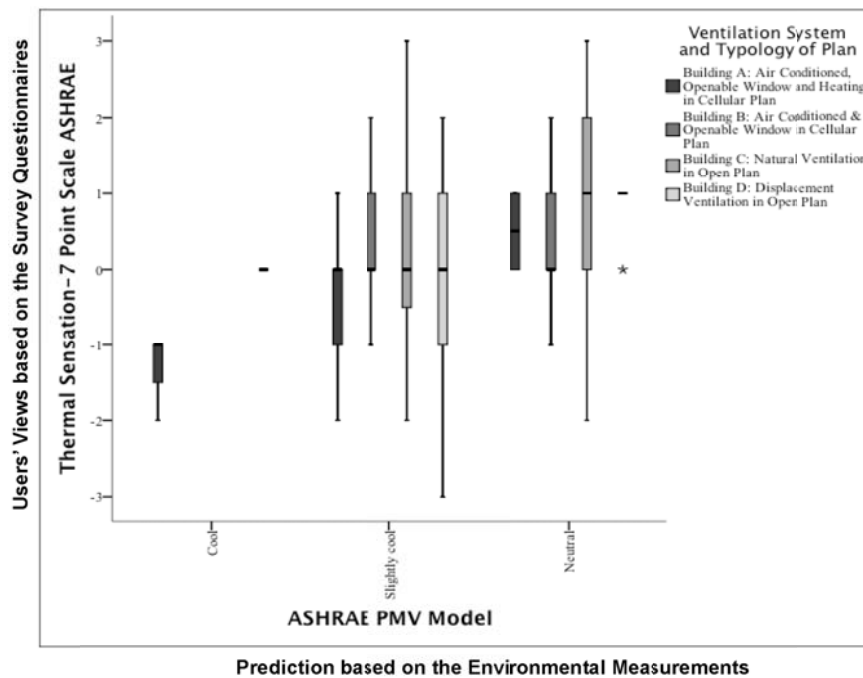


Figure 200: Boxplot of the ASHRAE PMV prediction model and surveyed seven point scale thermal sensation in each building

8.1.2.1.2. Comfort

The SPSS linear regression analysis similar to section 8.1.2.1.1 is applied to compare the ASHRAE PMV model and comfort survey, presented in Appendix D. The comfort question is based on the seven point scale, in which the best and worst options are at the two ends of the scale, as discussed in section 8.1.1.1.2. However, in the ASHRAE PMV model, neutral is considered as comfortable, which is in the middle of the scale, presented in section 8.1.2. Therefore in order to compare these two scales using the SPSS regression analysis, the four point scale is used for the ASHRAE PMV model, in which neutral is at one end of the scale:

- +3 = Neutral
- +2 = Slightly warm/slightly cool
- +1 = Warm/cool
- 0 = Hot/cold

The SPSS regression analysis, presented in Appendix D, suggests no significant relationship between surveyed comfort and the ASHRAE PMV prediction model (i.e. P value is 0.569 > 0.05). Figure 201 is the boxplot of the ASHRAE PMV prediction model and comfort response. It shows an inconsistency between the two variables, presented in Figure 200. Respondents, who are predicted to feel cool or slightly cool, have reported feeling comfortable. Many respondents, who are predicted feeling neutral that is the ASHRAE's

comfort level, have actually reported being neither comfortable nor uncomfortable as they reported neutral as their comfort status. Figure 201 breaks down the information for each building. When the PMV model predicts a ‘slightly cool’ condition, there are similarities between the two open plan offices and also between the two cellular plan offices regardless of the prediction model, as many respondents in all four buildings report feeling ‘comfortable’. The model works better in predicting a ‘neutral’ condition, as majority of respondents report feeling ‘comfortable’ although Building C has a wider range and some respondents report feeling ‘uncomfortable’.

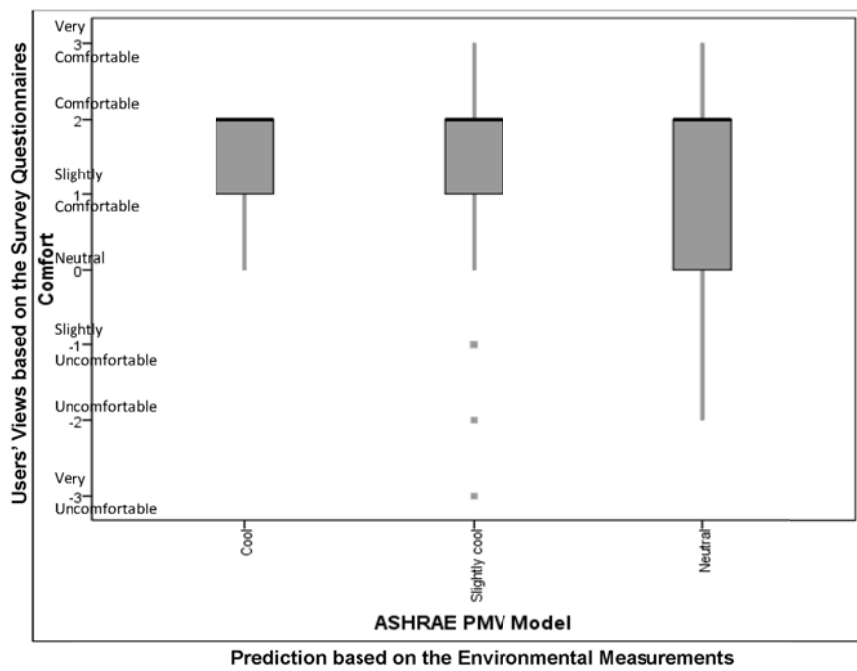


Figure 201: Boxplot of the ASHRAE PMV prediction model and surveyed comfort

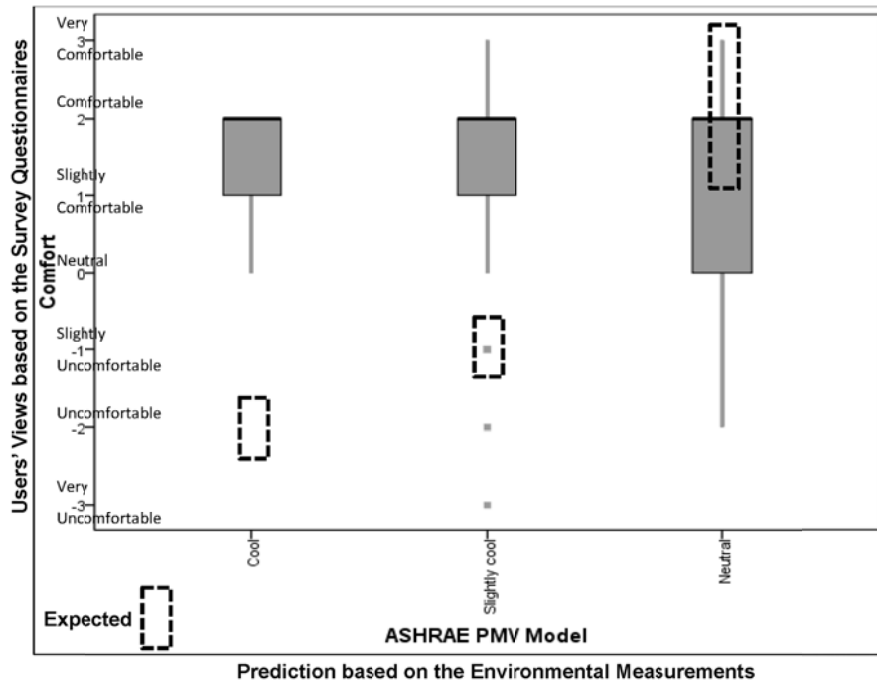


Figure 202: Boxplot presenting what was expected in Figure 201

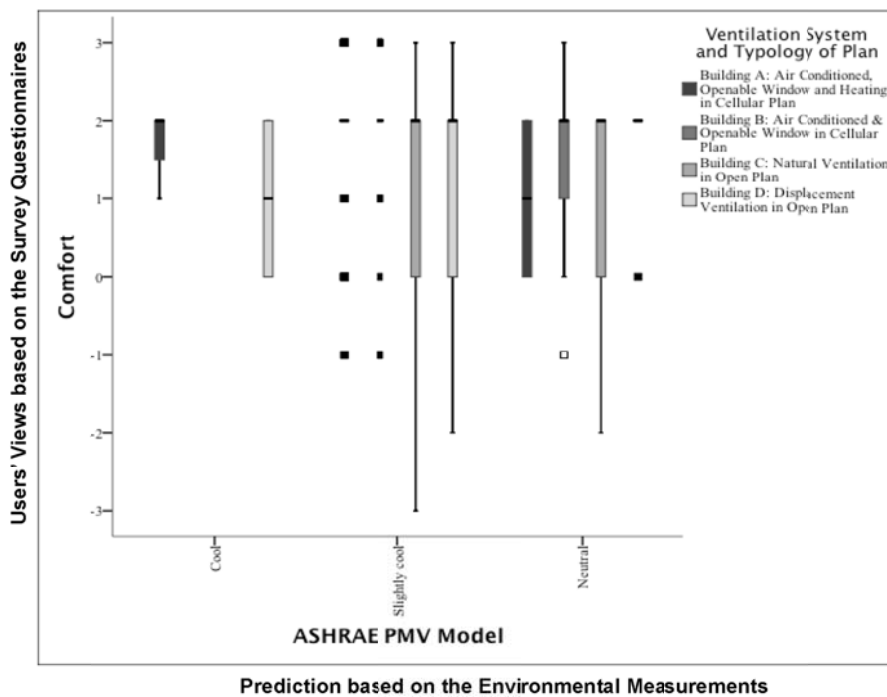


Figure 203: Boxplot of the ASHRAE PMV prediction model and surveyed comfort in each building

8.1.2.1.3. Satisfaction

In this part, the accuracy of the PMV model is compared against the satisfaction survey results using SPSS linear regression analysis, presented in Appendix D. The seven point scale is used for the satisfaction question, explained in section 8.1.1.1.3, in which the best and

worst possible answers are at the two ends of the scale. Similar to section 8.1.2.1.2, the four point scale is used for the ASHRAE PMV model in the regression analysis.

The SPSS regression analysis, presented in Appendix D, suggests no significant relationship between surveyed satisfaction and the ASHRAE PMV prediction model (i.e. P value is $0.694 > 0.05$). Figure 204 shows the boxplot of the ASHRAE PMV model and users' satisfaction response in all four case study buildings. This boxplot also shows an inconsistency between the variables, presented in Figure 204. Respondents who have been predicted to have a neutral thermal sensation as well as a slightly cool thermal sensation have chosen the same rate as their satisfaction level, which is between neutral and satisfied, and their means are close to slightly satisfied, presented in Figure 205. Figure 206 breaks down the information for each building and it shows similar results to the comparison between the PMV model and surveyed comfort level. The two cellular plan offices are very similar and so are the two open plan offices when the PMV model predicts a slightly cool thermal condition. The PMV model is not very successful in predicting the thermal conditions of the cellular plan offices. When they are predicted to be 'slightly cool' majority of respondents report feeling 'satisfied' and when they are predicted to be 'neutral' the perceived satisfaction level drops. The open plan offices have wider ranges of perceived satisfaction level when they are predicted to be 'slightly cool'.

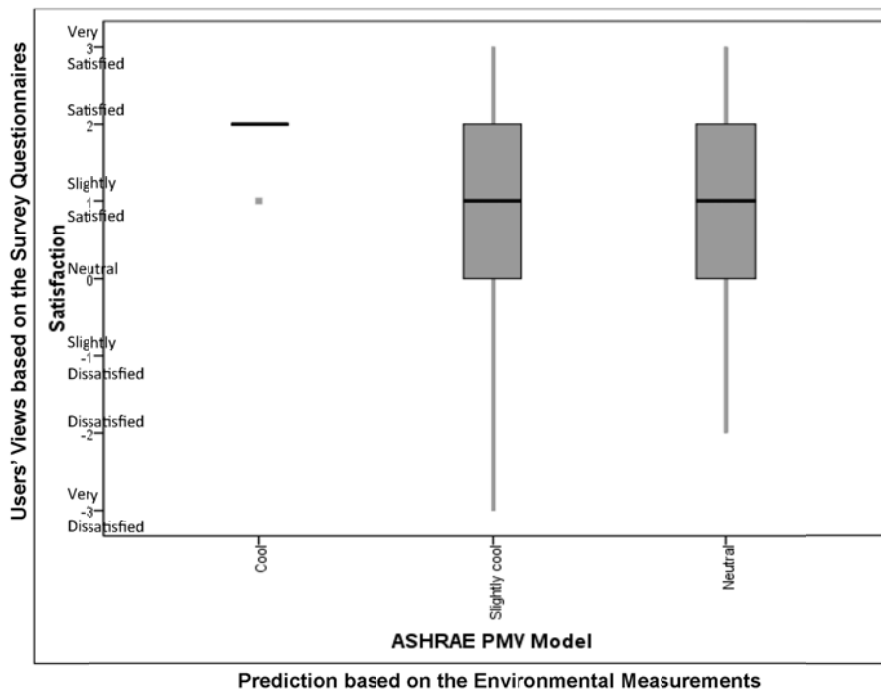


Figure 204: Boxplot of the ASHRAE PMV prediction model and surveyed satisfaction

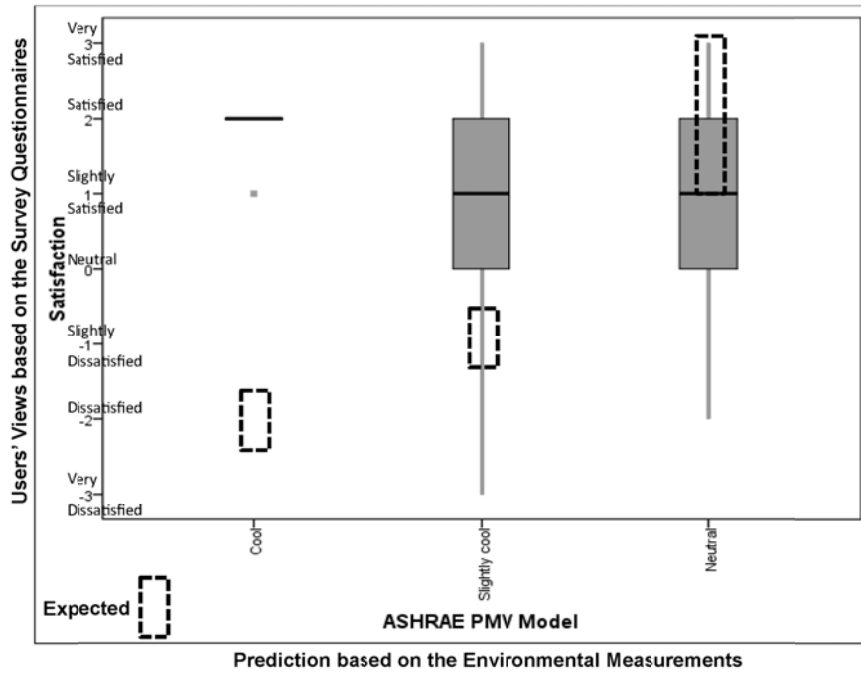


Figure 205: Boxplot presenting what was expected in Figure 204

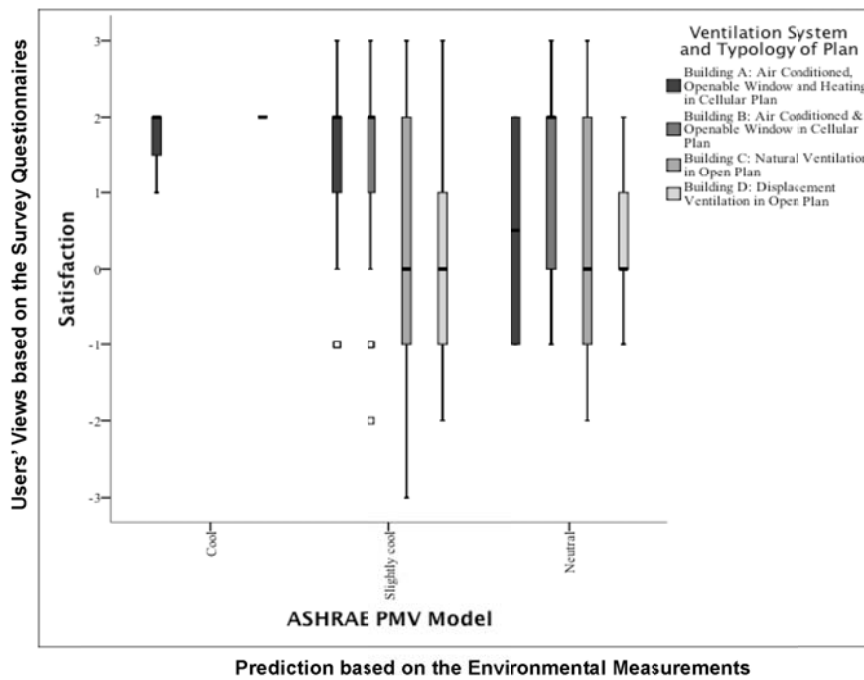
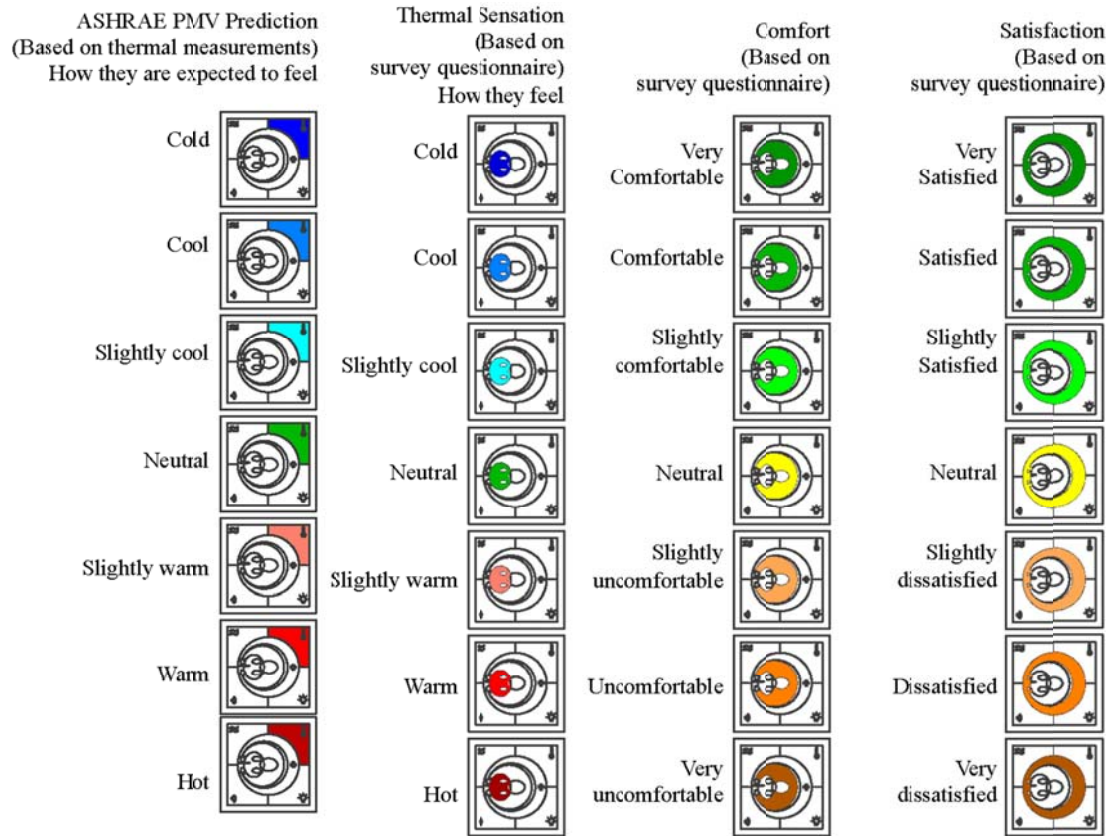


Figure 206: Boxplot of the ASHRAE PMV prediction model and surveyed satisfaction in each building

Quantitative analysis of the ASHRAE PMV thermal comfort prediction model against comfort and satisfaction survey results reveals no particular relationship between the PMV model and any of these variables. Although there is a relationship between the PMV model and surveyed thermal sensation, the extent of this prediction (i.e. 5%) is not significant. These statistics suggest that the ASHRAE PMV prediction model cannot accurately predict the

users' thermal comfort status when it is applied to the actual context of the four case study buildings in this study.

8.1.2.2. Qualitative Analysis



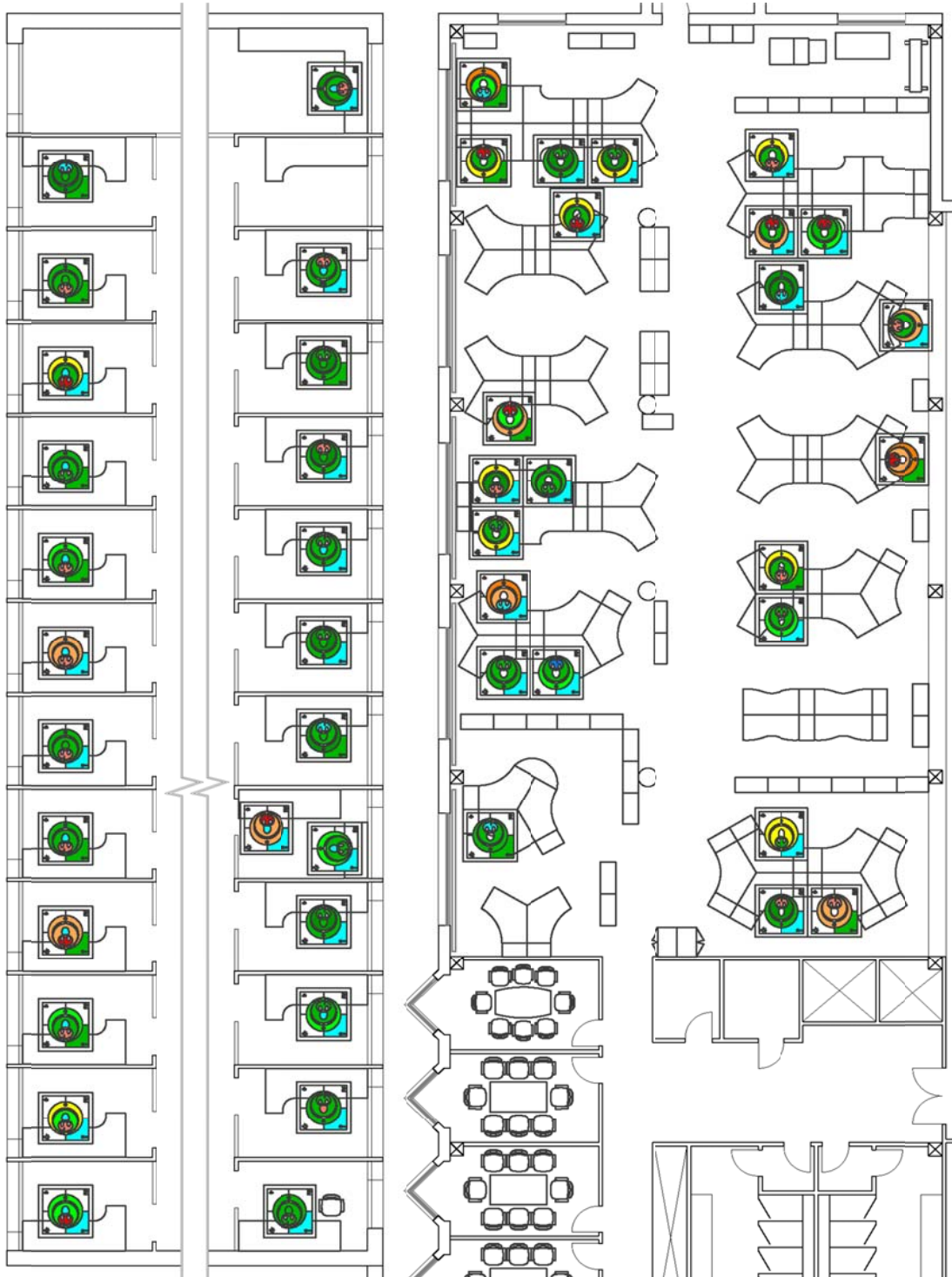


Figure 207: Building A and C: A sample of the qualitative analysis of the PMV model and thermal sensation, comfort and satisfaction, presented properly in Appendix A

Figure 208 is based on the qualitative visual analysis of the ASHRAE PMV model and thermal sensation in all four case study buildings. A sample of this analysis is presented in Figure 207, and the proper pictograms in Appendix A. The PMV model predicts that 78 out of 319 respondents (i.e. 24%) will have a neutral thermal sensation and therefore feel comfortable. The survey results show that only 29 respondents out of those 78 feel neutral. In

addition, the PMV model predicts that 238 out of 319 responses (i.e. 75%) will be slightly cool, but the survey results show that only 51 are slightly cool. 187 out of those 238 respondents (i.e. 79%) reported having thermal sensations other than slightly cool, as 119 participants have a neutral thermal sensation. Overall only 81 out of 319 (i.e. 25%) are consistent between the PMV model and the actual survey results. According to the ASHRAE, the PMV model is expected to predict 80% of the thermal comfort responses (ASHRAE, 2009, ASHRAE, 2010). However, in this study this prediction drops to 25% in the four case study buildings.

All 4 Buildings							
Thermal Sensation	ASHRAE PMV Prediction Model						
	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
Hot			1	1			
Warm			15	12			
Slightly warm			41	23			
Neutral		2	119	29			
Slightly cool			51	11			
Cool		1	9	2			
Cold			2				

Figure 208: Qualitative analysis of the ASHRAE PMV comfort model and thermal sensation survey results, based on the qualitative visual analysis

Figure 209 presents the qualitative comparison between the ASHRAE PMV model, thermal sensation and thermal intention survey results. This table shows that 34 out of 80 respondents are predicted to be neutral and also have a neutral thermal sensation. However, six of them prefer to have sensations other than neutral, such as slightly cool or slightly warm. In addition, PMV predicts 234 will be slightly cool, but only 48 responses on the survey results match the prediction. Based on the prediction, respondents who are predicted to feel slightly cool are expected to want a slightly warmer thermal environment in order to restore their comfort to neutral thermal sensation (ASHRAE, 2010). However, 29 cases out of the 48 responses do not want a slightly warmer thermal condition. 19 respondents are quite happy to feel slightly cool and do not want any change in the temperature. Six participants prefer warmer or much warmer, and one person prefers even slightly cooler than the current slightly cool condition, which is a cool thermal sensation overall. In total, 51 out of 319 (i.e. 16%) are consistent between the ASHRAE PMV prediction model and survey results of thermal sensation and thermal intention. Although as mentioned earlier, 25% of the responses are consistent between the ASHRAE PMV model and thermal sensation survey results, only 16% are consistent between these two as well as the surveyed thermal intention. The latter shows the occupants' desire to change the temperature, which is another measure in evaluating their

comfort status. Therefore the ASHRAE PMV model has been successful in predicting 16% of the thermal comfort situations in this research in total, much less than the expected 80% (ASHRAE, 2010).

Neutral	✓	Feeling neutral, and prefer no change	Confirm prediction ✓						
	✓	Prefer neutral	Number	28					
		Feeling neutral, but prefer different	Do not confirm prediction ✗						
	✗	Prefer not neutral	Number	1	5				
		Feeling not neutral, but prefer no change	Do not confirm prediction ✗						
	✗	Prefer not neutral	Number	2	2	7	1		
		Feeling not neutral and prefer neutral	Do not confirm prediction ✗						
	✓	Prefer neutral	Number	17	3	5			
		Feeling not neutral, but prefer different	Do not confirm prediction ✗						
	✗	Prefer not neutral	Number	1	4	1	1		
	Feeling not neutral, and prefer even more different	Do not confirm prediction ✗							
✗	Prefer not neutral	Number	1	1					

	Feeling not neutral, and prefer neutral	Confirm prediction ✓							
✓	Prefer neutral	Number	22						
	Feeling not neutral, but prefer no change	Do not confirm prediction ✗							
✗	Prefer not neutral	Number	19						
	Feeling not neutral, but prefer different	Do not confirm prediction ✗							
✗	Prefer not neutral	Number	4	2	1				
	Feeling neutral, and prefer no change	Do not confirm prediction ✗							
✓	Prefer neutral	Number	100						
	Feeling neutral, but prefer different	Do not confirm prediction ✗							
✗	Prefer not neutral	Number	11	1	1	7			
			13	1	1				
	Feeling not neutral and prefer neutral	Do not confirm prediction ✗							
✓	Prefer neutral		24	3	4				
	Feeling not neutral and prefer neutral	Do not confirm prediction ✗							
✗	Prefer not neutral	Number	4	1	2	1	1	1	
	Feeling not neutral and prefer neutral	Confirm prediction ✓							
✓	Prefer neutral	Number	1						
	Feeling neutral, and prefer no change	Do not confirm prediction							
✓	Prefer neutral	Number	2						

Figure 209: Qualitative comparison between the ASHRAE PMV prediction, thermal sensation and thermal intention survey results

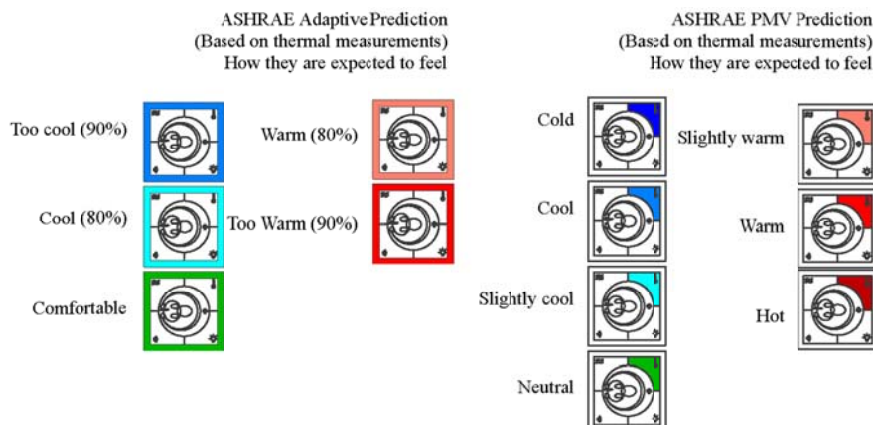
ASHRAE PMV Prediction (How they are expected to feel?) Based on Thermal Measurements	Thermal Sensation of Individual (How they feel?) Based on Survey Questionnaire	Overall Thermal Preference of Individual (How they want to feel?) Based on Survey Questionnaire	Number of Respondents	Prediction Matches Preference?	Number of Respondents
Neutral	Neutral	Neutral	28	✓	52
	Neutral	Not Neutral	6	✗	
	Not neutral	Not Neutral	12	✗	
	Not neutral	Neutral	7	✗	
	Not neutral	Not Neutral	2	✗	
Cool	Cool	Neutral	22	✓	212
	Cool	Not Neutral	19	✗	
	Cool	Not Neutral	7	✗	
	Neutral	Neutral	100	✗	
	Neutral	Not Neutral	20	✗	
	Not cool	Not Neutral	15	✗	
	Not cool	Neutral	31	✗	
Cold	Cold	Neutral	1	✓	1
	Neutral	Neutral	2	✗	2

Figure 210: Based on Figure 209: Qualitative comparison between the ASHRAE PMV prediction, thermal sensation and thermal intention survey results

As mentioned earlier in the adaptive prediction analysis section 8.1.1.2, it is more difficult to predict the comfort status of occupants, who do not want to feel neutral. This part is analysed more intensively later in section 8.2. Section 8.3 examines the consistency of the thermal preference of individuals throughout the day, which reveals another obstacle in predicting the thermal comfort of occupants.

8.1.3. Qualitative Comparison: Adaptive vs. PMV Models

This section investigates the consistency between the two prediction models in the four case study buildings using the qualitative visual analysis method. A sample of this analysis is presented in Figure 211, and the proper pictograms in Appendix A.



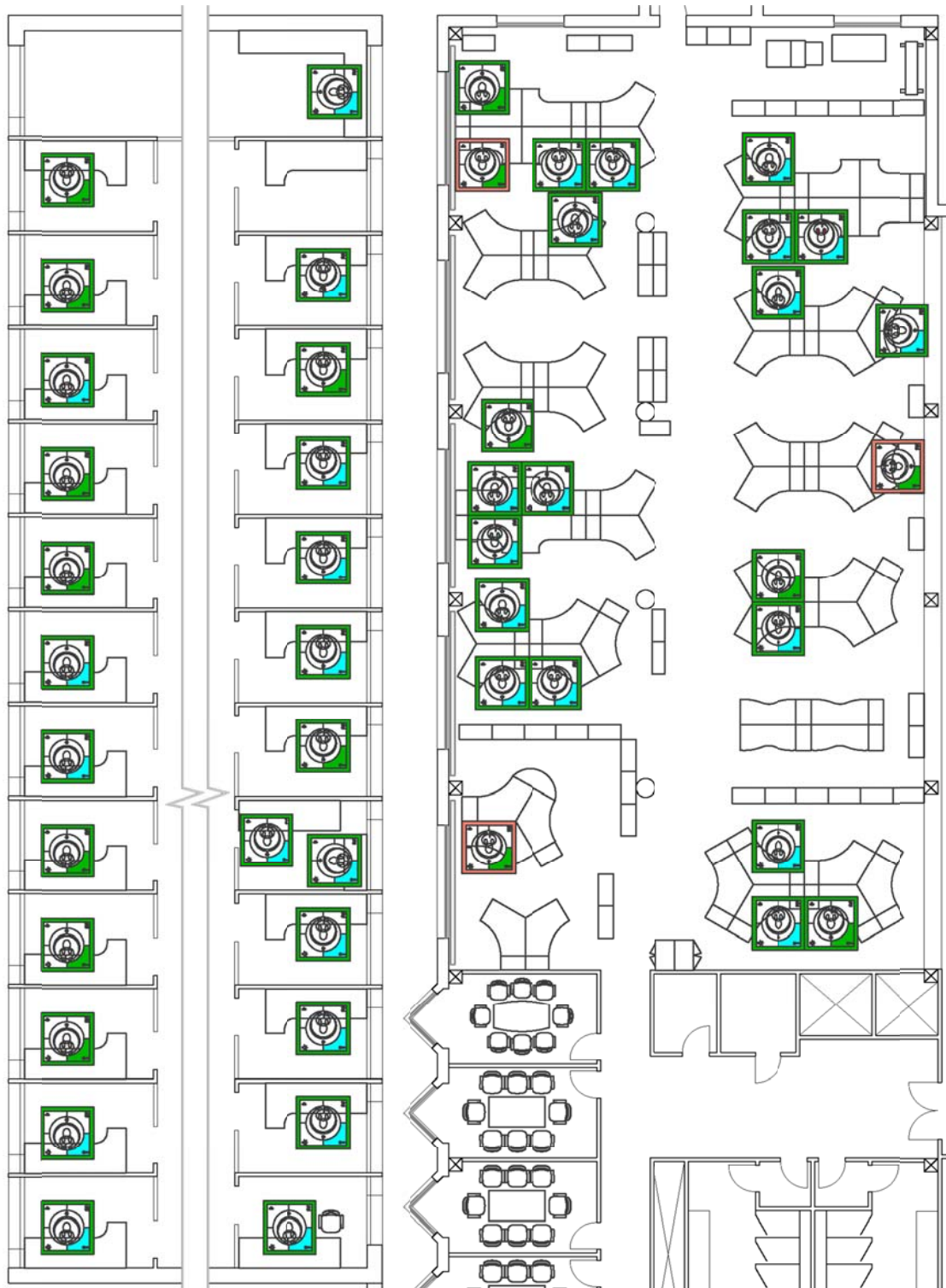


Figure 211: Building A and C: A sample of the qualitative analysis of the adaptive and PMV models, presented properly in Appendix A

Consistency of the ASHRAE PMV and Adaptive Prediction Models	PMV	Adaptive		Building A	Building B	Building C	Building D	Overall
	ASHRAE PMV Prediction Model	ASHRAE Adaptive Prediction Model		Air conditioned, openable window & heating in cellular plan	Air conditioned & openable window in cellular plan	Natural and mechanical ventilation in open plan	Displacement ventilation & openable window in open plan	
PMV and Adaptive predictions are consistent ✓	Cool	Too cool		0	0	0	1	1
PMV and Adaptive predictions are inconsistent ✗	Cool	Cool		0	0	0	1	1
PMV and Adaptive predictions are inconsistent ✗	Cool	Comfortable		3	0	0	0	3
PMV and Adaptive predictions are inconsistent ✗	Slightly cool	Comfortable		88	38	47	61	234
PMV and Adaptive predictions are inconsistent ✗	Slightly Cool	Warm		1	0	0	0	1
PMV and Adaptive predictions are consistent ✓	Neutral	Comfortable		2	46	18	4	70
PMV and Adaptive predictions are inconsistent ✗	Neutral	Warm		0	0	7	2	9

Figure 212: Consistency between the ASHRAE Adaptive and PMV prediction models

Figure 212 is based on the visual recording technique and shows that only 71 out of 319 cases (i.e. 22%) are consistent between the two prediction models.

8.1.4. Adaptive and PMV Models

In section 8.1, the accuracy of the ASHRAE predictions, the adaptive and PMV models, was investigated using quantitative as well as qualitative methods. Both prediction models were compared against the survey results, regarding thermal sensation, comfort and satisfaction. The quantitative analysis shows a relationship between thermal sensation and both prediction models. However, only a small percentage of the survey results can be accurately predicted. No significant relationship was found between the two prediction models and either comfort or satisfaction. In addition, the qualitative analysis reveals that the ASHRAE PMV model was successful in predicting only 16% of the thermal comfort conditions, rather than the expected 80% (ASHRAE, 2010). Although the ASHRAE adaptive model was more successful (i.e. 37%) in predicting thermal comfort conditions, this is still much less than the expected 90% (ASHRAE, 2010). In addition, the two prediction models do not match completely and only in 22% of the cases are they consistent.

Furthermore, respondents reported feeling comfortable in a range wider than the comfort zone defined by ASHRAE Standard 55-2010, as explained in sections 8.1.1.1.2, 8.1.1.1.3, 8.1.2.1.2, and 8.1.2.1.3. In addition, many occupants felt uncomfortable when experiencing the thermal conditions that the ASHRAE predicted as neutral, as explained in sections 8.1.1.1.2, 8.1.1.1.3, 8.1.2.1.2, and 8.1.2.1.3. Moreover, during the interviews, participants acknowledged individual differences in perceiving the thermal environment. Many of them

could not tolerate the thermal conditions that their colleagues would find perfectly comfortable, explained later in section 9.2.1.

The ASHRAE adaptive and PMV prediction models include air temperature, relative humidity, mean radiant temperature, clothing, activity, and location in the room. Adaptive model has an additional variable: outdoor air temperature. Although many factors are included in this analysis, other factors are not included, such as contextual factors. Nicol reports the complexity of measuring thermal comfort, due to numerous variables influence the field (Nicol et al., 2012) such as psychological factors (ASHRAE, 2009), presented in section 3.1.5. Therefore it is difficult to predict user satisfaction and comfort only based on environmental measurements, due to the complexity of the field. This is further discussed in section 10.4. The ASHRAE determines an overall thermal environment, linked to calibrated performance indicators of thermal comfort intended to set equipment and fabric but it is relatively insensitive to individual perceptions of comfort. However, thermal comfort standards are essential in designing the buildings so that the indoor thermal environment of the buildings is closer to the acceptable thermal conditions (Humphreys and Nicol, 2002a), further explained in section 10.5. The danger is to rely solely on the thermal comfort standards and to ignore the complexity of the field, other factors and individual differences. For instance, when the thermal environment of a workstation is within the ASHRAE acceptable range, there is no guarantee that the occupant feels thermally comfortable, further explained in section 10.1.2.

The analysis suggests that thermal environmental conditions that are predicted as comfortable based on the ASHRAE PMV or Adaptive models, which are based on the comfort zone in the ASHRAE Standard 55-2010, do not guarantee user comfort. This is further discussed in Chapter Ten, the discussion chapter.

8.2. Neutral Thermal Sensation

This research questions the association of ‘neutral thermal sensation’ as the basis of thermal comfort standards (ASHRAE, 2010), definition (Hawkes, 2002) and studies (Fanger, 1970). It asks: ‘Do people want to feel neutral?’ (Humphreys and Nancock, 2007). The ASHRAE seven point scale questionnaire is based on evaluating thermal comfort according to users’ expressions of their thermal sensation at the time of the survey questionnaire, and ‘neutral’ indicates users’ comfort (ASHRAE, 2009), explained in section 3.2.2.1. This section is mainly based on the survey questionnaires, comparing the thermal sensation of users and their comfort, satisfaction, and thermal intention. Quantitative and qualitative methods of analysis are applied to the collected data to examine neutral thermal sensation in relation to comfort, satisfaction and thermal intention. The SPSS regression analysis is similarly used in all the quantitative analysis sections. Therefore a sample analysis is presented in section 8.2.1.1 and the rest of the tables and regression analysis are presented in Appendix E. The visual recording technique is applied as the qualitative analysis, which is followed by further intensive interviews.

According to the ASHRAE adaptive prediction model, all four case study buildings in this study are expected to provide comfortable thermal conditions (i.e. 91%), presented in Figure 213 (this is only the prediction, while users report differently, as explained in sections 8.1.1.1.1, 8.1.1.1.2 and 8.1.1.1.3). Therefore, users’ desire for a thermal setting is more likely to be related to their individual requirements at the time of the survey questionnaires, rather than to an uncomfortable thermal environment.

		ASHRAE Adaptive Model				Total
		Too cool	Cool	Comfortable	Warm	
Ventilation System and Typology of Plan	Building A: Air Conditioned, Openable Window and Heating in Cellular Plan	0	0	94	1	95
	Building B: Air Conditioned & Openable Window in Cellular Plan	0	0	76	1	77
	Building C: Natural Ventilation in Open Plan	0	0	66	7	73
	Building D: Displacement Ventilation in Open Plan	1	1	65	1	68
Total	1	1	301	10	313	

Figure 213: The ASHRAE adaptive prediction model

8.2.1. Quantitative Analysis

In this section, the SPSS linear regression analysis is applied. Similar to sections 8.1.2.1.2 and 8.1.2.1.3, a four point scale thermal sensation is used instead of the seven point scale in order

to compare it to comfort and satisfaction. In order to keep the consistency, a four point scale thermal intention is also applied:

- **4 = No change**
- 3 = Slightly cooler/warmer
- 2 = Cooler/warmer
- 1 = Much cooler/warmer

8.2.1.1. Comfort

Figure 214 to Figure 217 demonstrate the SPSS linear regression analysis of comfort based on thermal sensation across all four case study buildings. Comfort is the dependant variable and thermal sensation is the independent variable. Figure 214 is the descriptive statistics for the 313 responses.

	Mean	Std. Deviation	N
Comfort	1.48	1.163	313
Thermal Sensation-4 Point Scale	3.32	.747	313

Figure 214: Descriptive Statistics, SPSS linear regression analysis of comfort based on the four scale thermal sensation

Figure 215 is the SPSS model summary and the R Square in this table indicates that 13.2% of the comfort responses can be explained by participants' thermal sensation.

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.363 ^a	.132	.129	1.085

a. Predictors: (Constant), Thermal Sensation-4 Point Scale

Figure 215: Model Summary, SPSS linear regression analysis of comfort based on the four scale thermal sensation

Figure 216 is the SPSS coefficients analysis and it shows that every degree increase in thermal sensation towards 'neutral' improves the comfort level of the user by 0.565 degree.

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-.401	.280		-1.431	.153
1	Thermal Sensation-4 Point Scale	.565	.082	.363	6.871	.000

a. Dependent Variable: Comfort

Figure 216: Coefficients, SPSS linear regression analysis of comfort based on the four scale thermal sensation

Figure 217 is the SPSS ANOVA analysis and it shows the P value, which is 0.000. Since this P value is less than 0.05, it suggests that there is a strong relationship between comfort and thermal sensation.

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	55.626	1	55.626	47.210	.000 ^b
	Residual	366.444	311	1.178		
	Total	422.070	312			

a. Dependent Variable: Comfort

b. Predictors: (Constant), Thermal Sensation-4 Point Scale

Figure 217: ANOVA, SPSS linear regression analysis of comfort based on the four scale thermal sensation

Figure 218 is the boxplot of surveyed thermal sensation and comfort status. It shows that participants who feel comfortable have a relatively small range of thermal sensations mainly between neutral and slightly warm. In contrast, users who feel uncomfortable have a much wider range of thermal sensation from cool to hot. It suggests that users with an extreme thermal sensation are more likely to be uncomfortable. It also shows that some participants who feel slightly warm are more likely to feel comfortable, while some occupants who feel neutral are likely to feel uncomfortable. The detailed analysis of the four building in Figure 220 confirms these findings and it reveals that occupants of the open plan offices in particular are feeling uncomfortable when experiencing a wider range of thermal sensations. Occupants of the Buildings B, C and D report similarly when feeling 'comfortable' as their thermal sensation ranges between 'neutral' to 'slightly warm'. In addition, occupants report similarly in the two open plan offices when they feel 'slightly uncomfortable' as their thermal sensation covers a wide range between 'cool' to 'slightly warm'. Except these two conditions, the four buildings are quite different in the perceived comfort and thermal sensation of their occupants.

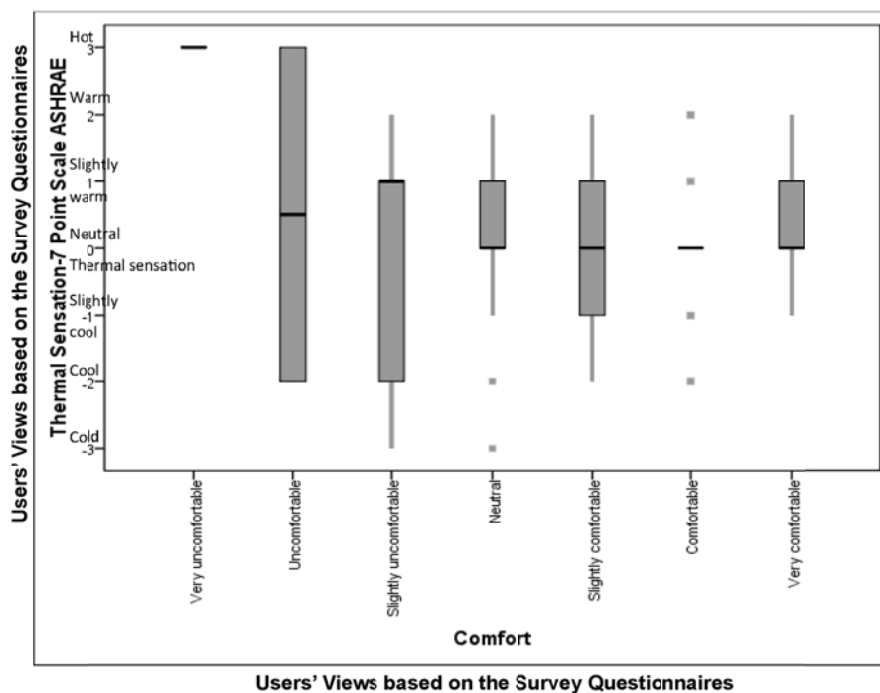


Figure 218: Boxplot of comfort and thermal sensation, the ASHRAE 7 point scale

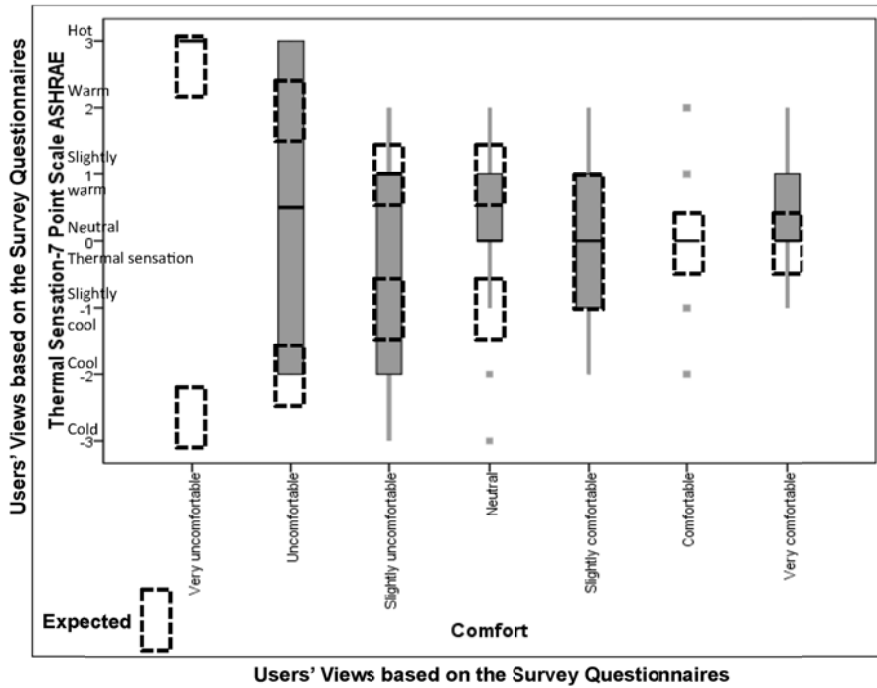


Figure 219: Boxplot presenting what was expected in Figure 218

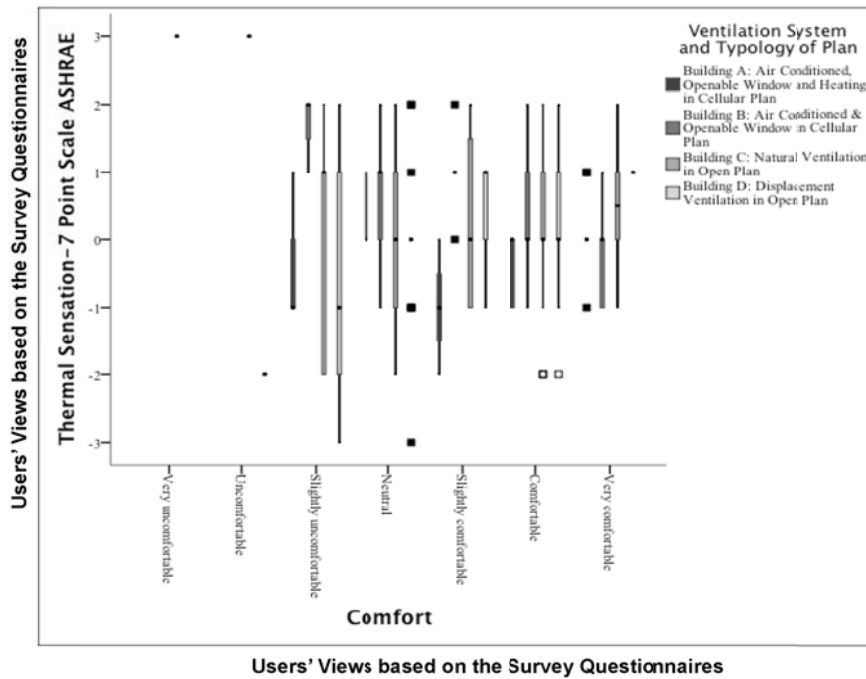


Figure 220: Boxplot of comfort and thermal sensation, the ASHRAE 7 point scale in each building

The quantitative analysis of comfort and thermal sensation reveals a significant relationship between these two factors, and 13.2% of the comfort responses can be explained by participants' thermal sensation status.

8.2.1.2. Satisfaction

Similar to section 8.2.1.1 the SPSS linear regression analysis is applied, which is presented in Appendix E. This analysis shows a significant relationship between thermal sensation and satisfaction (i.e. P value is 0.000). It indicates that 16.9% of the satisfaction responses can be explained by the thermal sensation status. Figure 221 is the boxplot of satisfaction and thermal sensation. It shows that very satisfied participants have a thermal sensation between slightly cool to slightly warm, while dissatisfied users have a much wider range from cool to hot. Participants who feel closer to the extreme conditions of cold or hot are more likely to be dissatisfied. However, there are some respondents with warm or cool thermal sensations, who feel comfortable, while some dissatisfied participants have a neutral thermal sensation. Figure 223 shows the boxplot for separate buildings and it confirms that in both cellular and open plan offices dissatisfied respondents are more likely to experience extreme conditions. In contrast, the majority of 'very satisfied' respondents report feeling between 'slightly cool' to 'slightly warm'. However, buildings are quite different in terms of the perceived satisfaction and thermal sensation of their occupants.

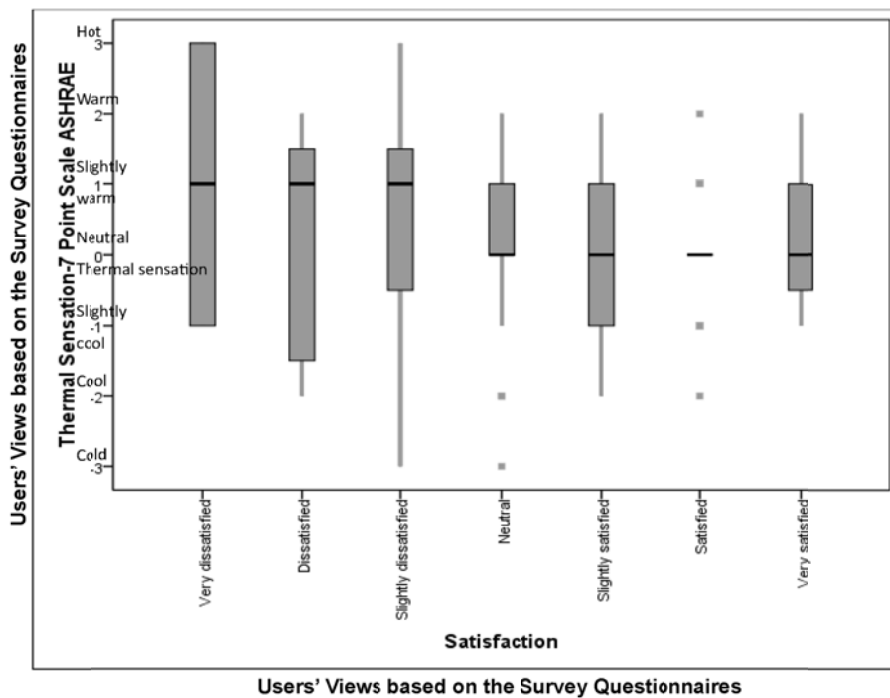
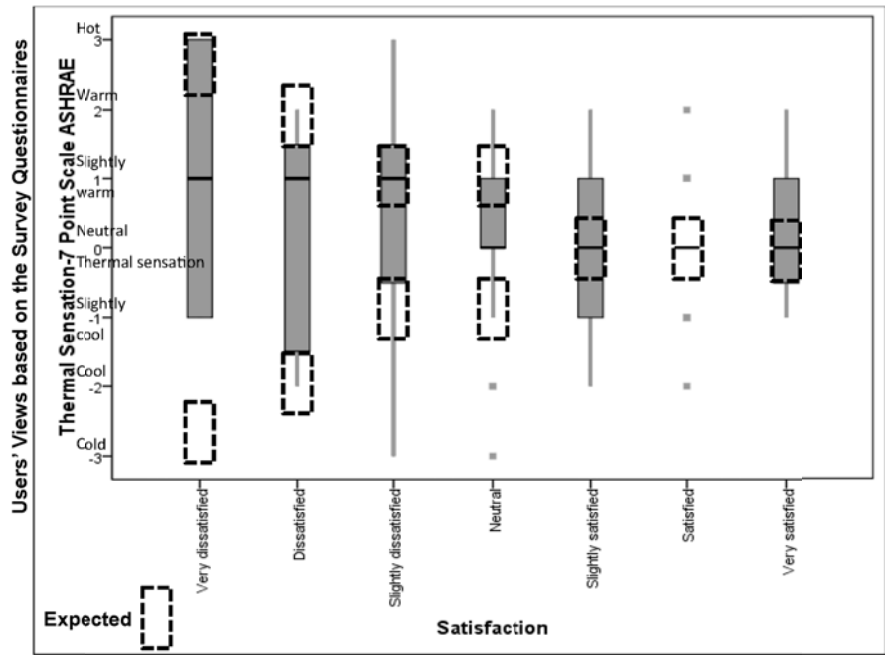
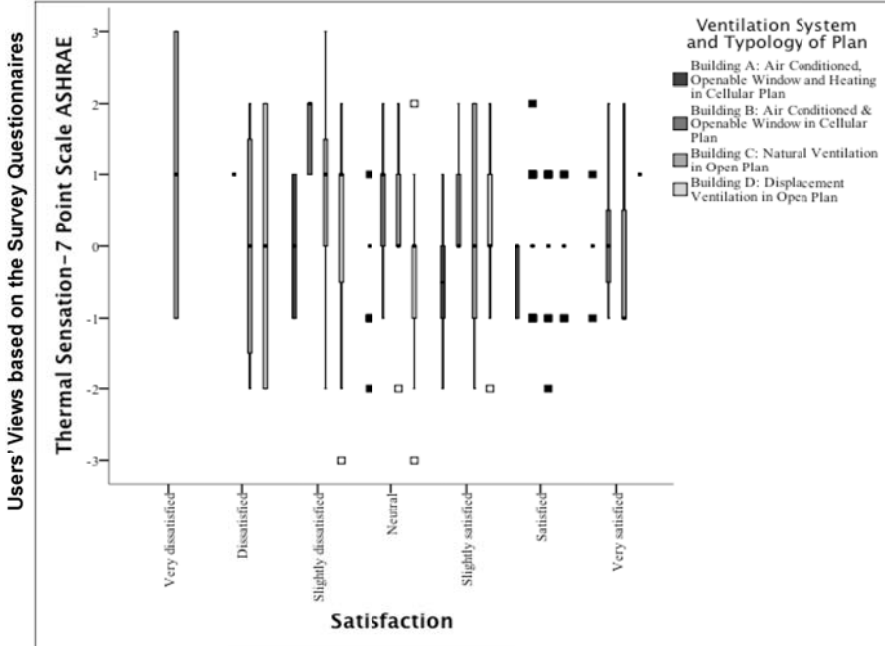


Figure 221: Boxplot of satisfaction and thermal sensation, the ASHRAE 7 point scale



Users' Views based on the Survey Questionnaires

Figure 222: Boxplot presenting what was expected in Figure 221



Users' Views based on the Survey Questionnaires

Figure 223: Boxplot of satisfaction and thermal sensation, the ASHRAE 7 point scale in each building

The statistics indicate a strong relationship between satisfaction and thermal sensation. 16.9% of satisfaction responses can be predicted by the thermal sensation status of the participant, which is slightly more than comfort predictions (i.e. 13.2%).

8.2.1.3. Thermal Intention

Similar to section 8.2.1.1, SPSS linear regression analysis is applied, which is presented in Appendix E. This analysis shows a significant relationship between thermal sensation and satisfaction (i.e. P value is 0.000). It indicates that 46.4% of the thermal sensation variance can be explained by thermal intention, which is quite significant. Figure 224 is the boxplot of the surveyed thermal intention and thermal sensation based on the ASHRAE seven point scale. It shows that apart from a cold thermal sensation, there is a consistency between thermal sensation and thermal intention. For example, respondents with a neutral thermal sensation want no change in the temperature, while respondents with a slightly warm thermal sensation mainly prefer to be slightly cooler. This suggests occupants' strong tendency to restore a neutral thermal sensation. Figure 226 is the boxplot of separate offices and similar responses are visible in each building and a great tendency to have a neutral thermal sensation.

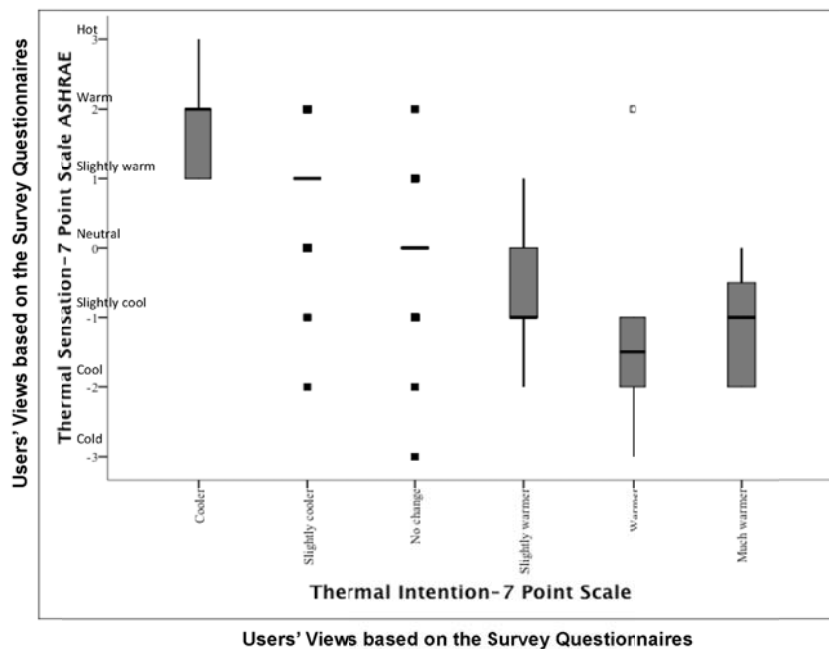


Figure 224: Boxplot of thermal intention and thermal sensation, the ASHRAE 7 point scale

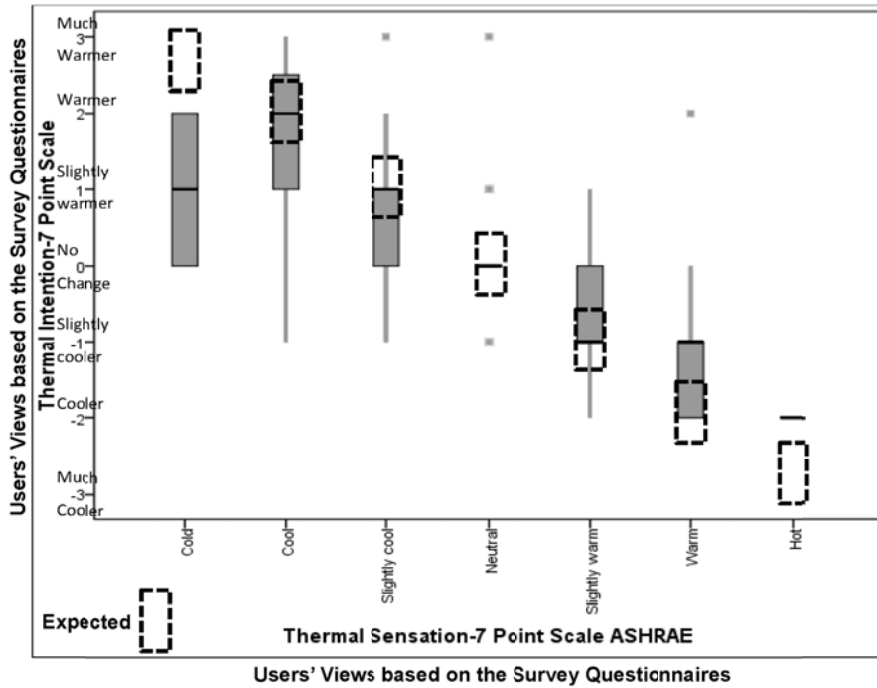


Figure 225: Boxplot presenting what was expected in Figure 224

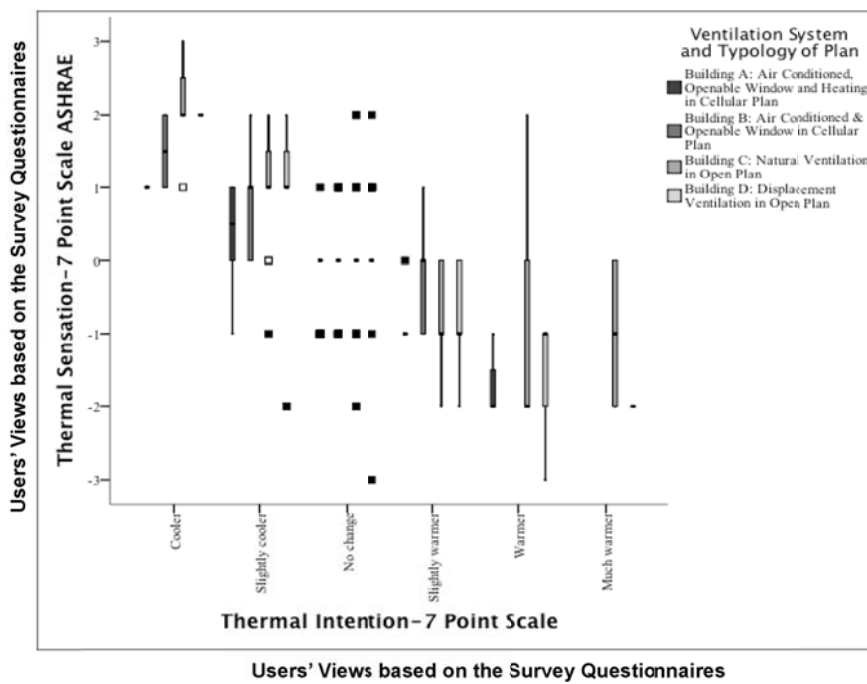
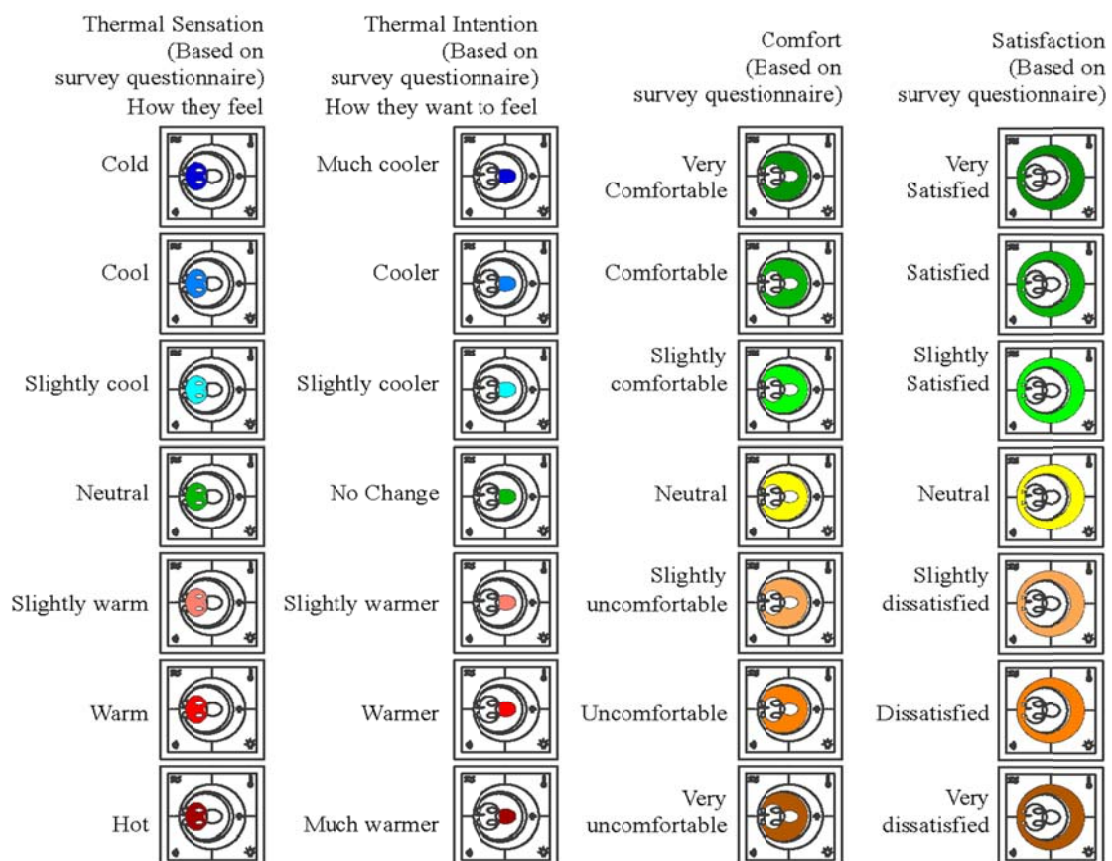


Figure 226: Boxplot of thermal intention and thermal sensation, the ASHRAE 7 point scale in each building

These statistics reveal a very strong relationship between thermal sensation and thermal intention. The boxplot in particular shows this relationship clearly.

8.2.2. Qualitative Analysis

This section investigates occupants' desire to feel neutral in a qualitative way. The presented data in Figure 228 to Figure 236 are based on the visual qualitative analysis of all four buildings. A sample of this analysis is presented in Figure 227, and the proper pictograms in Appendix A. In this research, only comfortable and very comfortable responses are considered as 'comfortable', since this research is looking for high quality standards. Slightly comfortable and neutral responses do not present a comfortable status with confidence, and slightly uncomfortable, uncomfortable and very uncomfortable responses are considered as red flags and mentioned as 'uncomfortable'. In this research, similar instruction is applied to sections 9.1.1.2.2 and 9.2.2, as well as to specify 'satisfied' and 'dissatisfied' responses in sections 8.2.2.2, 9.1.1.2.1 and 9.2.1. It is recognised that various factors influence user's comfort, such as physical, physiological and psychological factors, as discussed in section 3.1.5. Therefore it is not possible to include all of these variables in this analysis and this is the weakness of field studies of thermal comfort (Nicol et al., 2012), explained in section 10.4. Thus the focus of the study is on variables including thermal sensation, thermal intention, comfort, and satisfaction, as illustrated in Figure 227. Although respondents' perception of these variables is subjective, at the time of the survey questionnaire the researcher requested them to consider their view mainly based on the thermal environment, explained in section 6.3.6.



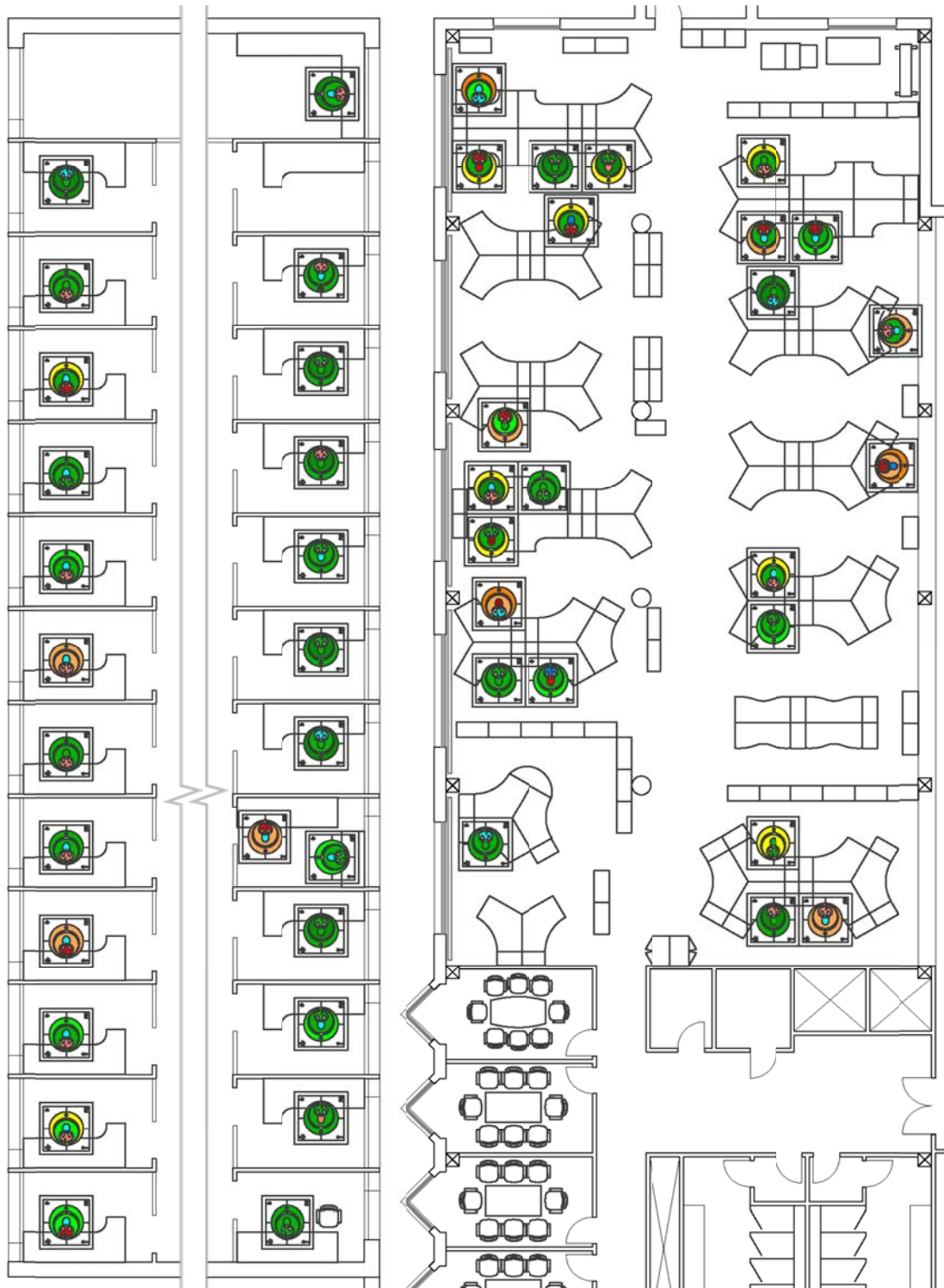


Figure 227: Building A and C: A sample of the qualitative analysis of thermal sensation and thermal intention, comfort and satisfaction, presented in more detail in Appendix A

8.2.2.1. Comfort

In this part, the surveyed thermal sensation and comfort are compared. As explained in section 8.1.1.1.2, only survey results including comfortable or very comfortable are considered as 'comfortable'. Figure 228 shows that 29 out of 147 participants (20%) with a

neutral thermal sensation do not feel comfortable. 81 out of 125 respondents (i.e. 65%), who feel slightly cool or slightly warm, as well as 19 out of 33 participants (i.e. 58%), who feel cool or warm, reported comfortable. Although only a small number of occupants with a neutral thermal sensation are not comfortable (i.e. 20%), overall 95 out of 213 comfortable respondents (i.e. 45%) do not have a neutral thermal sensation. This suggests that occupants, who have sensations other than neutral, are also likely to feel comfortable. This analysis also reveals that 214 out of 313 participants (i.e. 68%) are comfortable, while 148 out of 313 participants (i.e. 47%) have a neutral thermal sensation.

All 4 Buildings							
Comfort	Thermal Sensation						
	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
Very comfortable			6	20	9	1	
Comfortable		3	39	98	27	10	
Slightly comfortable		2	8	7	8	2	
Neutral	1	1	5	21	13	4	
Slightly uncomfortable	1	4	3	1	7	3	
Uncomfortable		1					
Very uncomfortable							

Figure 228: Qualitative analysis of comfort based on thermal sensation in all four buildings

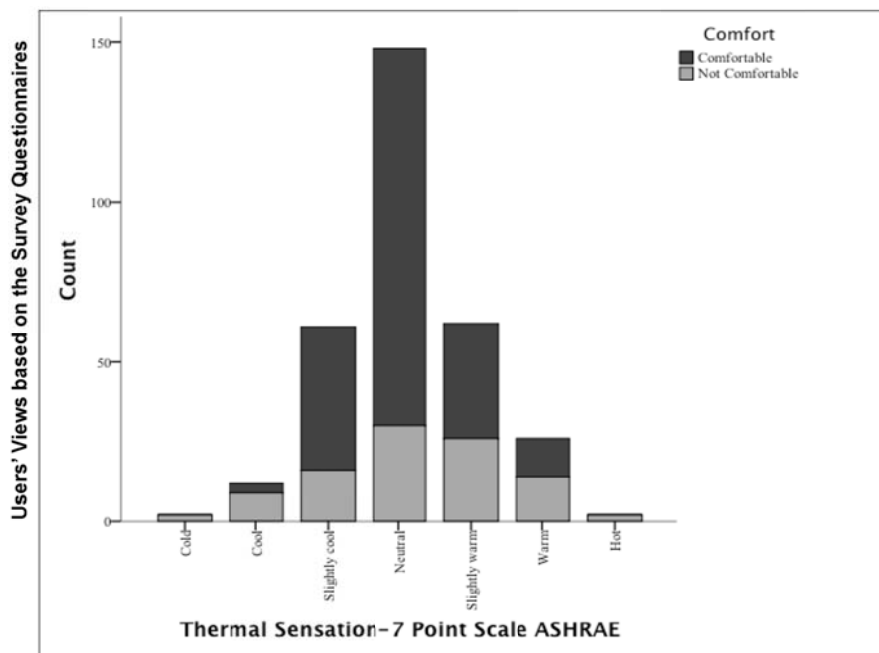


Figure 229: Barchart: Qualitative analysis of comfort based on thermal sensation in all four buildings

8.2.2.2. Satisfaction

Figure 230 shows the comparison between thermal sensation and satisfaction. As explained in sections 8.1.1.1.2 and 8.1.1.1.3, only survey results including satisfied or very satisfied are

considered acceptable and recorded as ‘satisfied’. 53 out of 148 respondents (i.e. 36%) with a neutral thermal sensation are not satisfied. 53 out of 123 participants (i.e. 43%), who feel slightly cool or slightly warm, are satisfied. This suggests that occupants with a neutral thermal sensation are likely to be dissatisfied, while users with sensations other than neutral are likely to feel satisfied. In addition, 57 out of 152 satisfied respondents (i.e. 38%) do not feel neutral. This analysis also reveals that 152 out of 319 participants (i.e. 49%) are satisfied.

All 4 Buildings							
Satisfaction	Thermal Sensation						
	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
Very satisfied			7	12	6	2	
Satisfied		1	26	83	14	1	
Slightly satisfied		3	10	15	8	6	
Neutral	1	3	10	36	15	6	
Slightly dissatisfied	1	3	6	2	17	9	1
Dissatisfied		2	1		2	2	
Very dissatisfied			1				1

Figure 230: Qualitative analysis of satisfaction based on thermal sensation

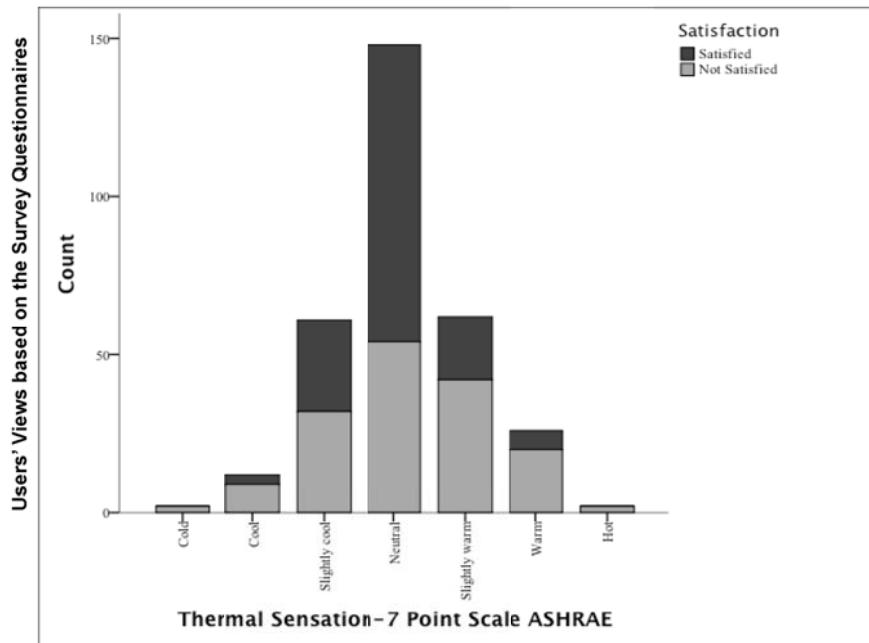


Figure 231: Barchart: Qualitative analysis of satisfaction based on thermal sensation

8.2.2.3. Thermal Intention

Figure 232 presents the comparison between thermal intention and thermal sensation. This table shows that 27 out of 150 respondents (i.e. 18%) with a neutral thermal sensation prefer a change in temperature. 47 out of 170 participants (i.e. 28%), who prefer no change in the

temperature, do not have a neutral thermal sensation. This analysis also reveals that 167 out of 313 participants (i.e. 53%) want no change in the temperature.

All 4 Buildings							
Thermal Intention	Thermal Sensation						
	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
Much warmer		1	3	1			
Warmer	1	6	4	1		1	
Slightly warmer		2	25	13	1		
No Change	1	1	26	123	16	3	
Slightly cooler		1	2	12	43	15	
Cooler					5	8	2
Much cooler							

Figure 232: Qualitative analysis of thermal intention based on thermal sensation

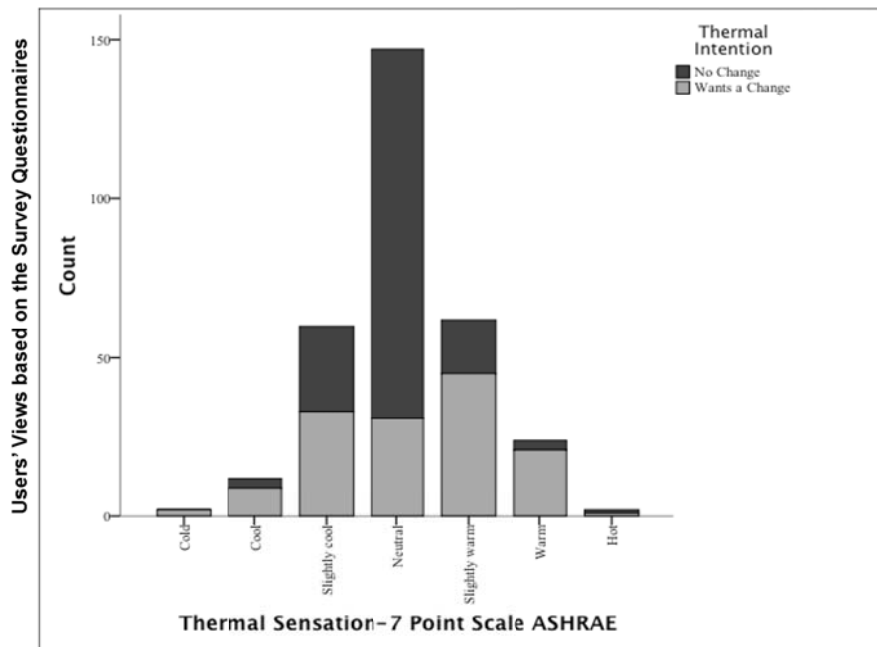


Figure 233: Barchar: Qualitative analysis of thermal intention based on thermal sensation

Figure 234 is based on Figure 232 and it examines whether or not occupants prefer a neutral thermal sensation. The occupants of the first group prefer to have a neutral thermal sensation (i.e. to feel neutral), as the proportions of their thermal sensation and thermal intention are the same. When they are combined the overall outcome is a 'neutral' thermal preference. For instance, they may feel neutral and want no change, or they feel slightly cool would prefer a slightly warmer condition, in which case their overall desire is to feel neutral. The first category includes 65% of the occupants overall, and it is the only category, in which the occupants are seeking a neutral thermal sensation. The participants who fall into the second category (i.e. 9%) feel neutral, but they would prefer other thermal sensations, such as slightly warmer or much cooler. In the third category (i.e. 15%), respondents do not feel neutral, but

they want no change in the temperature either. The fourth category (i.e. 10%) includes respondents with sensations other than neutral, but their overall preference is not neutral. The last category (i.e. 1%) includes occupants with an extreme thermal preference. For example, they may already feel slightly cool, but prefer even slightly cooler. Although the percentage of the participants who fall into individual categories (2 to 5) is not significant, the overall percentage of them (i.e. 35%) is quite significant. These categories include the occupants, who prefer sensations other than neutral when working.


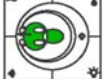

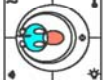
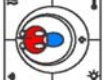

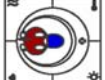
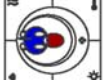

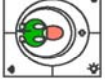
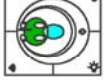
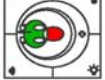
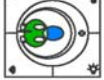
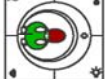
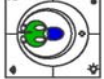


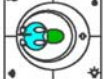
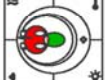
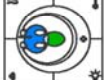

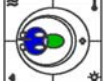

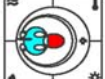

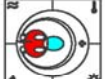

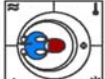
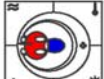
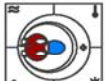
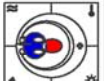



All 4 Buildings						
Categories		Neutral?			Numbers	Percentage
1	Overall thermal preference is neutral	 Want Neutral			124	38.80%
					68	21.45%
					14	4.42%
					0	0%
2	Feeling neutral, but want a change in temperature	 Do NOT want neutral			24	7.57%
					2	0.63%
					1	0.32%
3	Do not feel neutral, but don't want any change in temperature	 Do NOT want neutral			43	13%
					4	1.26%
					1	0.32%
4	Overall thermal preference is NOT neutral	 Do NOT want neutral			9	2.84%
					20	6.31%
					1	0.32%
					3	0.95%
5	Extreme	 Do NOT want neutral			5	1.58%
Total					319	100%

Figure 234: Qualitative analysis of neutral thermal sensation and thermal intention

Figure 235 and Figure 236 show the categories in each building. They indicate that the number of the occupants, who prefer sensations other than neutral, is approximately 40% in three of the buildings. However, this number drops to 20% in Building A.

					245				
Categories		Neutral?			Building A Numbers	Building B Numbers	Building C Numbers	Building D Numbers	All 4 Buildings Numbers
1	Overall thermal preference is neutral	Want Neutral ✓			55	27	18	24	124
					18	20	13	17	68
					2	2	8	2	14
					0	0	0	0	0
2	Feeling neutral, but want a change in temperature	Do NOT want neutral ✗			3	11	5	5	24
					1	0	1	0	2
					0	0	1	0	1
3	Do not feel neutral, but don't want any change in temperature	Do NOT want neutral ✗			11	13	10	9	43
					0	0	3	1	4
					0	0	0	1	1
4	Ovrall thermal preference is NOT neutral	Do NOT want neutral ✗			0	2	4	3	9
					3	6	6	5	20
					0	0	0	1	1
					0	0	2	1	3
5	Extreme	Do NOT want neutral ✗			1	1	2	1	5

Figure 235: Comparison between the four offices in terms of the neutral thermal sensation

Case Study Building	Building A		Building B		Building C		Building D		Total	
	N	%	N	%	N	%	N	%	N	%
Want neutral thermal sensation	75	80%	49	60%	39	53%	43	61%	205	65%
Don't want neutral thermal sensation	19	20%	33	40%	34	47%	27	39%	112	35%
Total	94	100%	82	100%	73	100%	70	100%	317	100%

Figure 236: Comparing the neutral thermal sensation in the four case study buildings

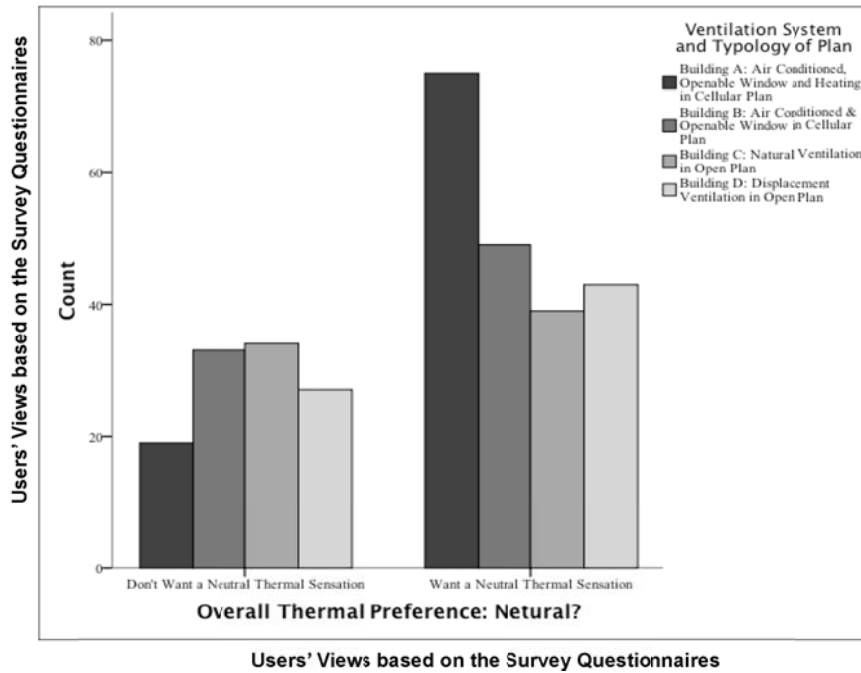


Figure 237: Bar chart: Comparing the neutral thermal sensation in the four case study buildings

Clothing and other variables may influence this analysis, however the observation during the survey questionnaires reveals that respondents were aware of their overall preference regardless of clothing or other variables. The conversation during the survey questionnaires shows that the majority of the respondents, who preferred sensations other than neutral, were aware that they don't want to feel 'neutral' and many explained 'I know this may be odd, but I really want to feel very warm'. The qualitative analysis indicates that up to 47% of the occupants in this study prefer thermal sensations other than neutral when working. It suggests that participants' intention to change the thermal environment is more important than whether or not they would consider their thermal environment neutral, which is discussed more intensively later in section 9.1. The results indicate that although occupants may feel neutral, they are likely to prefer different thermal sensations, such as slightly cool or warm. In other cases, they may feel slightly cool or slightly warm, but they are happy with the thermal environment and they do not want any change in the temperature. This suggests that occupants are more likely to prefer sensations other than neutral while working.

8.2.3. Quantitative vs. Qualitative Analysis

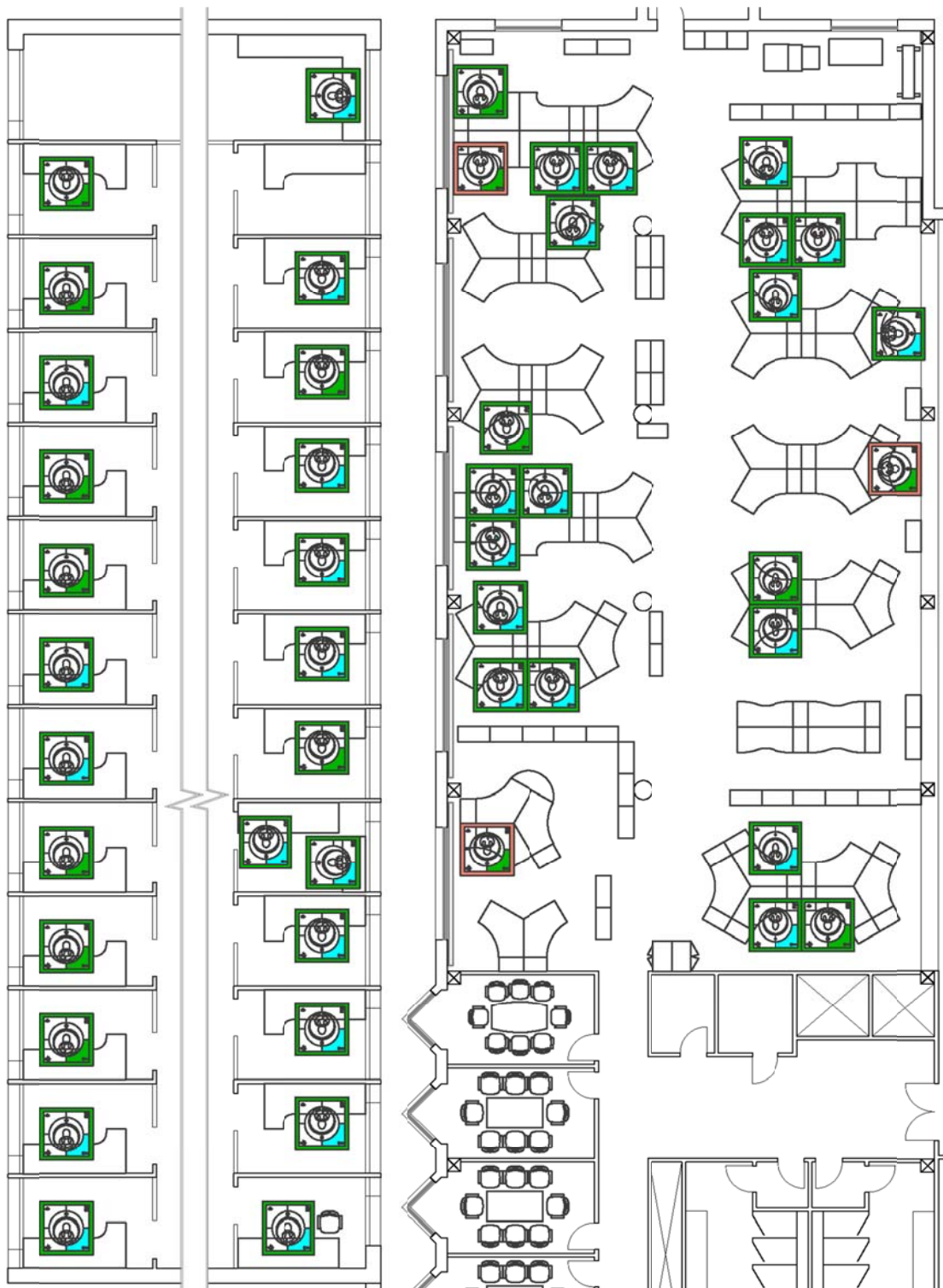


Figure 238: Building A and C: A sample of the qualitative analysis of the ASHRAE adaptive and PMV comfort prediction models, presented properly in Appendix A

Quantitative analysis shows a significant relationship between thermal sensation and individual variables like comfort, satisfaction and thermal intention, since the P value of each

case is 0.000 (i.e. < 0.05), explained in sections 8.1.1.1.1, 8.1.1.1.2 and 8.1.1.1.3. In addition, statistics indicate the following:

- 13.2% of the comfort responses can be explained by participants' thermal sensation vote. Overall, 68% of the participants are comfortable, while 47% have a neutral thermal sensation.
- 16.9% of the satisfaction responses can be explained by the thermal sensation status. Overall, 49% of the participants are satisfied.
- 46.4% of the thermal sensation variance can be explained by thermal intention, which is quite significant. Overall, 53% of the participants want no change in the temperature.

These analyses and thermal intention analysis in particular (i.e. 46%) suggest that thermal sensation has a very strong relationship with comfort, satisfaction and thermal intention. Although, the number of respondents, who are comfortable (i.e. 68%), is slightly high, the number of participants, who feel neutral (i.e. 47%), is close to respondents, who are satisfied (i.e. 49%) and desire no thermal change (i.e. 53%). This also suggests a strong relationship between neutral thermal sensation and variables, such as satisfaction and thermal intention. These statistics confirm the application of thermal sensation, and in particular the 'neutral thermal sensation', as the basis of thermal comfort studies (Fanger, 1973, Nicol et al., 2012), definitions (Hawkes, 2002) and comfort zone standards (ASHRAE, 2010). Hawkes describes thermal comfort as an 'intermediate point, when neither cold nor hot' (Hawkes, 2002).

In contrast, the qualitative analysis reveals that:

- 65% of the respondents with 'slightly cool' or 'slightly warm' thermal sensations, and 58% of the respondents with 'cool' or 'warm' thermal sensations are comfortable.
- 45% of the respondents with thermal sensations other than neutral feel comfortable. This suggests that occupants who have sensations other than neutral are also likely to feel comfortable.
- 36% of the participants, who feel neutral, are not satisfied. In contrast, 43% of the occupants with thermal sensations other than neutral are satisfied. This suggests that occupants with a neutral thermal sensation are likely not to feel satisfied, while users with sensations other than neutral are likely to feel satisfied.
- Up to 47% of the occupants prefer thermal sensations other than neutral. This suggests that occupants are likely to prefer sensations other than neutral.

The qualitative analysis suggests that occupants are likely to prefer thermal sensations other than neutral. This finding challenges the application of the ‘neutral thermal sensation’ as the basis of thermal comfort, and it confirms Humphreys’ findings in 2007 that in 868 comparisons ‘on 57% of occasions the desired sensation was other than neutral’ (Humphreys and Nancock, 2007). The qualitative analysis in this thesis suggests that the ‘neutral thermal sensation’ is less likely to indicate comfort and satisfaction, and consequently thermal comfort. This is in contrast with the findings of the quantitative analysis in this study. Although quantitative analysis provides useful information, such as the strong relationship between thermal sensation and variables including comfort, satisfaction and thermal intention, it is quite limited in interpreting and extracting meanings. For instance, it cannot interpret that respondents with a neutral thermal sensation are not comfortable, as they may prefer other sensations like warmth. This study suggests that relying solely on the application of quantitative analysis is associated with a risk of misjudgement, which is further discussed in the discussion chapter, section 10.2.

8.2.4. Neutral Thermal Sensation

This research questions the association of ‘neutral thermal sensation’ as the basis of the standard ‘comfort zone’, as indicated in the ASHRAE Standard 55-2010 (ASHRAE, 2010). The ASHRAE presents the seven point scale on thermal sensation surveys as hot, warm, slightly warm, neutral, slightly cool, cool and cold, in which neutral is considered to be the comfort level (ASHRAE, 2010). The ASHRAE handbook explains that ‘acceptability is determined by the percentage of occupants who have responded neutral or satisfied (0, +1, +2, or +3) with their thermal environment’ (ASHRAE, 2009). This research challenges the application of ‘neutral thermal sensation’ as the basis of the ASHRAE ‘comfort zone’. It suggests that many occupants feel comfortable when experiencing sensations other than neutral when working. This confirms Humphreys’ findings stating that ‘there were significant differences among the respondents in the thermal sensations they desired, confirming that some characteristically preferred to feel warmer than others’ (Humphreys and Nancock, 2007). Although Humphreys published this paper in 2007, neutral thermal sensation is still the basis of thermal comfort standards. This is associated with a risk of incorrect assumptions as Humphreys states ‘Do the findings much affect the conclusions to be drawn from a comfort survey?’ (Humphreys and Nancock, 2007).

In this research, there is a significant difference between the findings of the quantitative and qualitative analyses. Quantitative analysis shows a strong relationship between thermal

sensation and variables such as comfort, satisfaction and thermal intention, which is in line with comfort standards (ASHRAE, 2009, ASHRAE, 2010). However, the qualitative visual analysis reveals other findings that challenge the findings of the quantitative method. The visual recording indicates that up to 47% of the occupants prefer thermal sensations other than neutral. This suggests that occupants are likely to prefer sensations other than neutral, which confirms Humphreys' findings (Humphreys and Nancock, 2007). This study suggests that the quantitative appraisal could be associated with a risk of misjudgement.

Further in depth qualitative research in the form of semi-structured interviews reveal other outcomes in support of the qualitative findings. In all four buildings, 70% of the participants acknowledged individual differences in perceiving the thermal environment. In both cellular and open plan offices, occupants mentioned this very clearly without being asked, like, 'You know, we are very different and we like different temperatures'. They explained that an optimum temperature that satisfies them all does not exist. In the cellular plan offices, occupants are pleased to have a personal room to be able to set the temperature according to their individual needs, without interfering with other colleagues' preferences or vice versa. They mentioned that when they enter other staff's personal rooms, often they cannot tolerate the thermal conditions in that room. This is the main reason they prefer not to share an office. In the open plan offices in response to their preference in having central control or individual thermal control, 80% of the occupants initially chose central control simply because of individual differences. They were afraid of individuals arguing about setting the temperature, or occupants with extreme preferences getting hold of the temperature control. Comments were made, including: 'Oh, I prefer central control, because I don't like others fighting to set the temperature. Oh, I have seen it before. You know, I used to share a room with 7-8 people and some people wanted warm, some cold'. Furthermore, participants of the open plan offices had many complaints regarding individual differences in perceiving the thermal environment, such as 'He (pointing towards an individual) has the window open all the time, he likes it cool, but I really can't work when I feel cool', or: 'Well, I always feel very warm and like to open the window, but some people don't like the draught, so I just tolerate being warm, what else can I do?', 'I know it's just me, but I always like it so warm, so I wear layers (showing the layers in her drawer)'. Interviews suggest individual differences in perceiving the thermal environment. This finding is in contrast with the view of the universal 'comfort zone' that aims to find an 'optimum' temperature that satisfies all (Fanger, 1970, ASHRAE, 2010).

Moreover, other interview questions included the temperature preference on the ASHRAE seven point scale when working. In response, 40% of the respondents chose between slightly cool or cool conditions, so that they feel fresh and not too sleepy to work. 30% selected

slightly warm or warm, because of lack of movement when working at their desks, and 30% were happy to have a neutral thermal sensation when working. These interview findings also support the view that many users prefer thermal sensations other than neutral, which supports the qualitative findings in section 8.2.2. The qualitative analysis of the four case study buildings in this research suggests that occupants prefer other thermal sensations than neutral. Therefore, neutral thermal sensation is less likely to be accurately applied as the basis of thermal comfort standards. This is in line with Humphreys' question: 'Do people sometimes prefer sensations other than 'neutral?', and his findings stating: 'There were significant differences among the respondents in the thermal sensations they desired, confirming that some characteristically preferred to feel warmer than others' (Humphreys and Nancock, 2007).

8.3. Consistency in Thermal Preference

This section questions the consistency of the thermal preference of the user throughout the day. Currently, the standard 'comfort zone' aims to provide a steady thermal condition for everyone constantly. This section asks: 'Do occupants want to have a steady thermal condition?' and 'Is it possible that their thermal preference changes at different times?' In this research, each participant filled in the survey questionnaire three times a day, morning, early and late afternoon. In order to examine this consistency, the outcome of surveyed thermal sensation and thermal intention of the individual is compared at those three times. The visual recording analysis is applied for a qualitative analysis according to the meaning.

Figure 239 and Figure 240 show how to analyse the pictograms. It is an example of the inconsistency in overall thermal preference. This is visible as the colour of the head of the person changes, while the colour of the body of the person does not change. The colour of the body of the person is consistently green, which indicates a consistent 'neutral' thermal sensation throughout the day. However, the colour of the head of the person, which shows the user's desire to change the temperature, changes throughout the day. It is light red in the morning and early afternoon, which shows a 'slightly warmer' thermal intention. However, it changes to green in the late afternoon, which indicates 'no change'. It shows that although the individual feels neutral during the day, their thermal intention changes from 'slightly warmer' in the morning and early afternoon to 'no change' in the late afternoon. In this case, the overall thermal preference of the person changes from 'slightly warm' in the morning and early afternoon to 'neutral' in the late afternoon. Therefore, the thermal preference of this occupant is 'not consistent', which is demonstrated with a red cross in the pictogram. This indicates that the person is comfortable feeling 'slightly warm' at the beginning and midday and 'neutral' closer to the end of the working day, rather than a consistent thermal preference throughout the day.

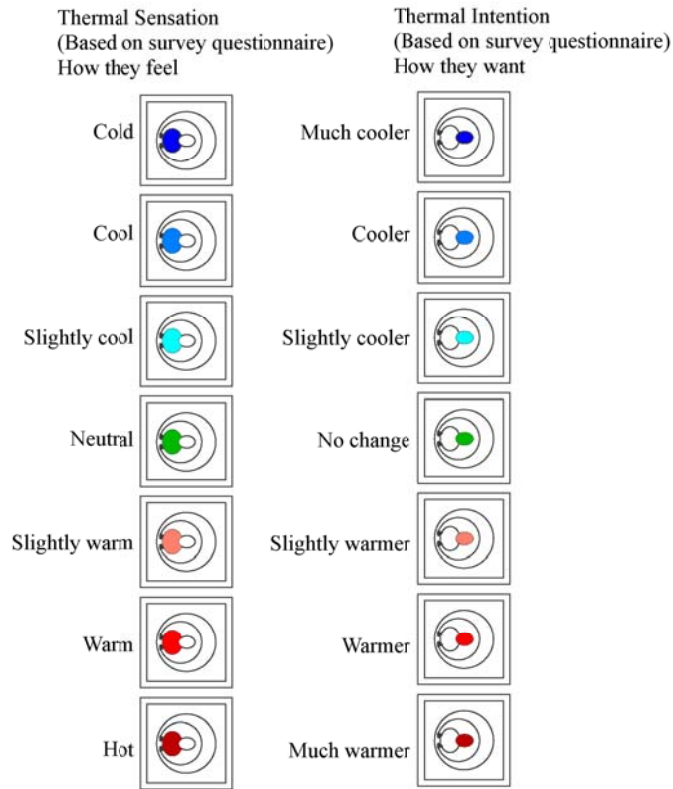


Figure 239: Thermal sensation and thermal intention of the occupant, based on survey questionnaire

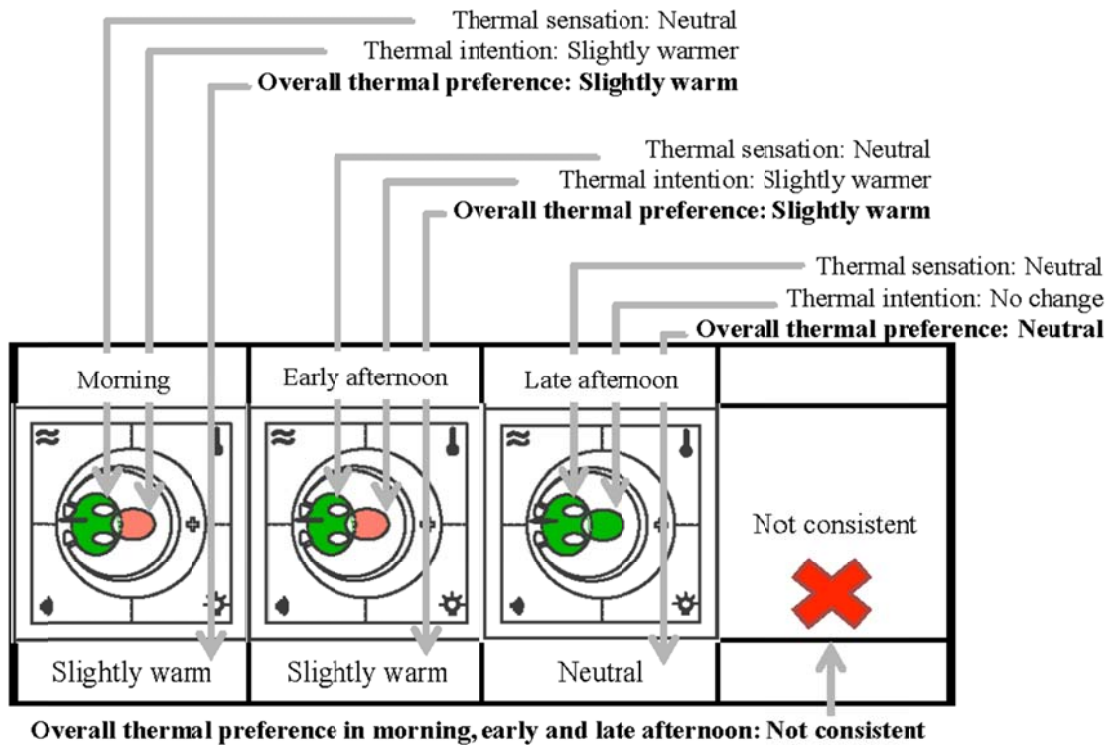


Figure 240: Overall thermal preference is inconsistent and it changes from 'slightly warm' in the morning and early afternoon to 'neutral' in the late afternoon (all based on survey questionnaires)

8.3.1. Morning, Early and Late Afternoon

In this section, the consistency of occupants' preference in having a steady thermal sensation during the day is examined in the four case study buildings. Before showing the results of the buildings, the consistency, inconsistency and extreme cases of inconsistency are explained. These qualities are represented respectively by a green tick, a red cross and two red crosses. The time of the survey questionnaire is written on top of the pictogram, while the overall thermal preference of the individual at the particular time is written underneath it.

8.3.1.1.1. Consistency

The thermal preference is consistent when the outcome of the combination of thermal sensation and thermal preference is consistent between all three recordings regarding an individual. Figure 241 is an example of a very simple consistent thermal preference, in which the user's thermal sensation is consistently 'neutral' and thermal intention is consistently 'no change'. Thus the overall thermal preference of the individual is neutral and it does not change in all three recordings. This consistency is represented by a green tick.

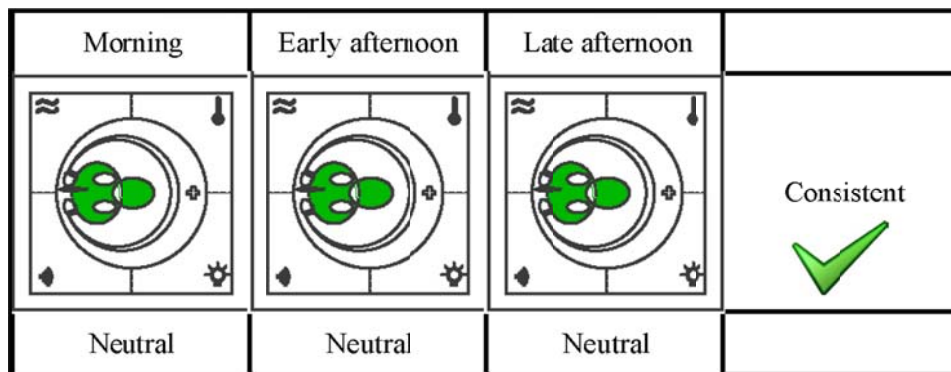


Figure 241: Overall thermal preference is consistently 'neutral' in the morning, early and late afternoon

Figure 242 presents another simple example of consistency. In this example, the user's thermal sensation is consistently warm and thermal intention is consistently 'cooler'. Therefore the overall thermal preference is 'neutral', and it is consistent in all three recordings.

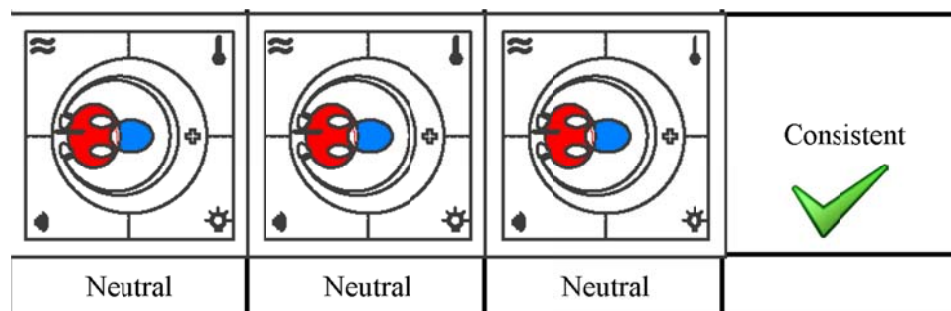


Figure 242: Overall thermal preference is consistently 'neutral' in the morning, early and late afternoon

The overall thermal preference may be other than 'neutral', such as slightly warm or slightly cool. It is important that the thermal preference, regardless of what it is, does not change in all three recordings in order to be considered consistent. For instance, Figure 243 shows an individual who has a 'slightly warm' preference and this thermal preference is consistent between the morning, early and late afternoon recordings.

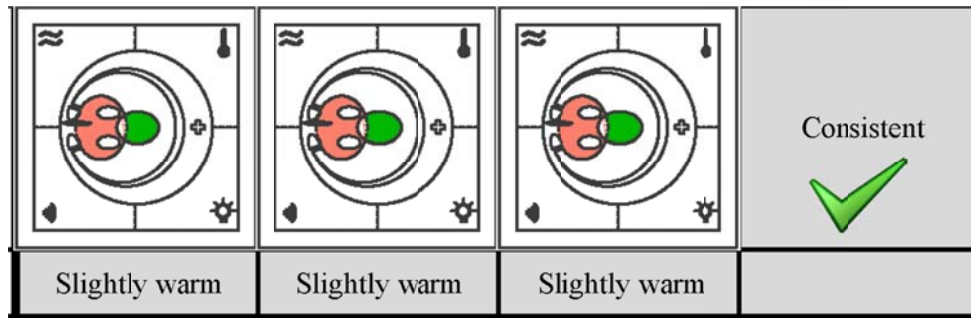


Figure 243: Overall thermal preference is consistently 'slightly warm' in the morning, early and late afternoon

Figure 244 shows another example, in which the person's thermal sensation has changed during the day, but the outcomes of the combination of thermal sensation and thermal intention are consistently 'slightly cool' in the morning recordings as well as the early and late afternoon recordings. Therefore, this person has a consistent thermal preference throughout the day. Figure 245 is another example of this consistency, in which the overall thermal preference is 'neutral'.

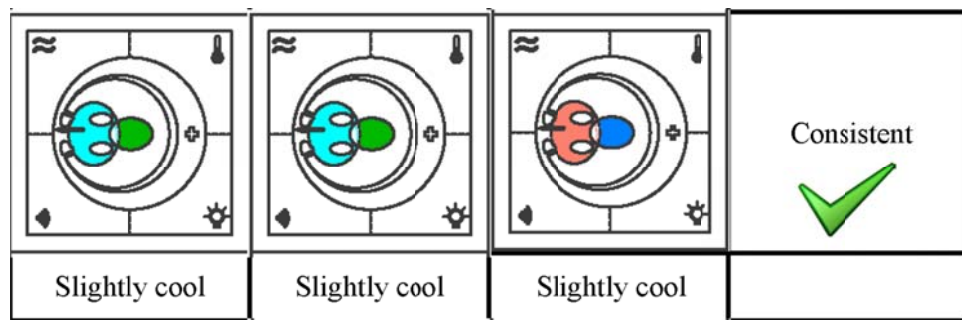


Figure 244: Overall thermal preference is consistently 'slightly cool' in the morning, early and late afternoon observations

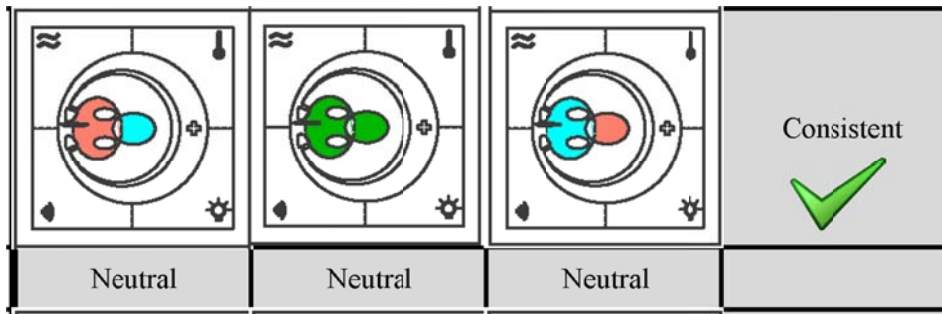


Figure 245: Overall thermal preference is consistently 'neutral' in the morning, early and late afternoon observations

8.3.1.1.2. Inconsistency

In contrast, the overall thermal preference is marked as 'not consistent', when there is a difference between thermal preferences of an individual throughout the day. For instance, Figure 246 shows a simple example of this inconsistency, in which the person feels neutral in the morning and their thermal intention is slightly warmer. So the outcome of thermal preference is 'slightly warm' in the morning. In the early afternoon, the person feels slightly cool and would prefer slightly warmer. In this case, the outcome of thermal preference in the early afternoon is 'neutral'. Although the thermal sensation has changed from morning to early afternoon, the thermal intention is the same. In the late afternoon, the person feels neutral again like the morning, however no change in the temperature is desired. So the outcome of the thermal preference is 'neutral' in the late afternoon. The overall thermal preference of this person changes from slightly warm in the morning to neutral in both early and late afternoon. Therefore it lacks the consistency throughout the day and it is presented with a red cross as a sign of inconsistency.

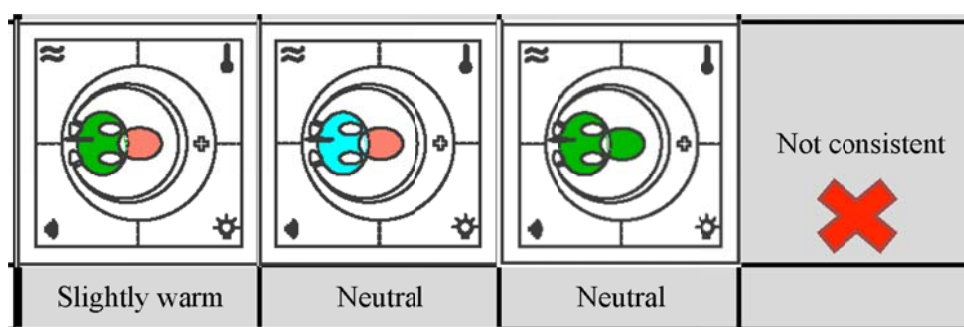


Figure 246: Overall thermal preference is inconsistent, and it changes from 'slightly warm' in the morning to 'neutral' in the early and late afternoon

Figure 247 is another example of inconsistency in overall thermal preference. The occupant wants 'slightly warm' in the morning and 'neutral' in the early and late afternoon.

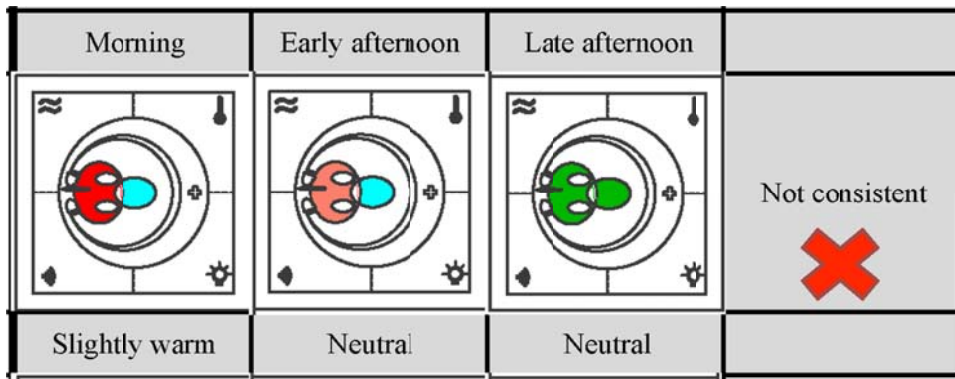


Figure 247: Overall thermal preference is inconsistent, and it changes from 'slightly warm' in the morning to 'neutral' in the early and late afternoon

Figure 248 shows a case in which the thermal preference changes from 'slightly cool' to 'cool' and back to 'neutral'. Although there is more than a slight change in the person's desire for the thermal environment, the ranges are between 'neutral' to 'cool', which are still related.

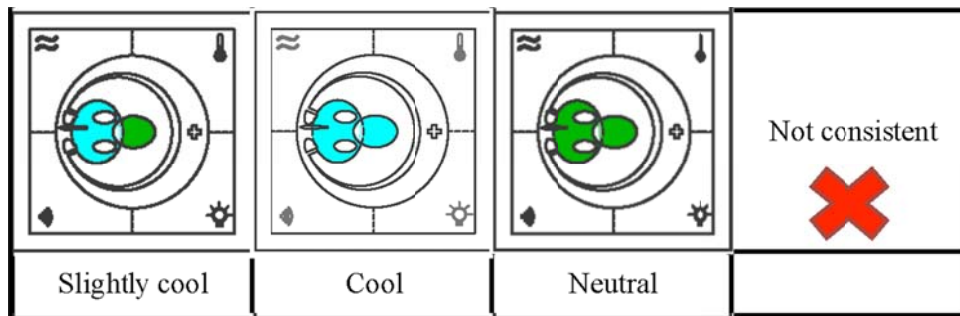


Figure 248: Overall thermal preference is inconsistent, and it changes from 'slightly cool' in the morning to 'cool' in the early afternoon and 'neutral' in the late afternoon

8.3.1.1.3. Extreme Cases of Inconsistency

Figure 249 demonstrates an extreme case in which the thermal preference of the individual flips from 'slightly cool' in the morning to 'slightly warm' in the late afternoon. Figure 250 is another extreme case of inconsistency in thermal preference in the morning, early and late afternoon.

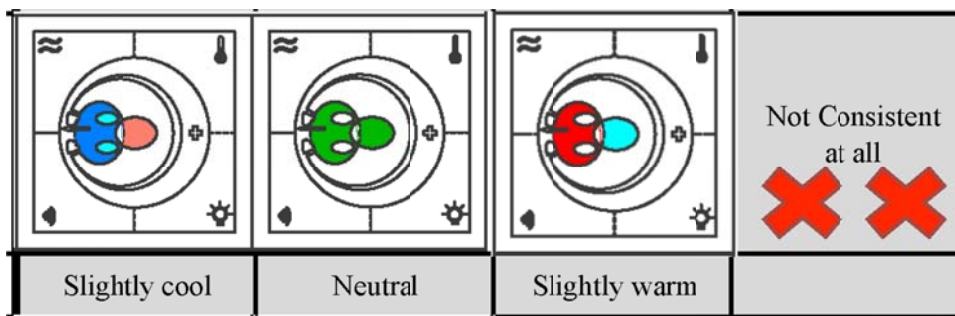


Figure 249: Overall thermal preference is extremely inconsistent, and it flips from 'slightly cool' in the morning to 'slightly warm' in the late afternoon

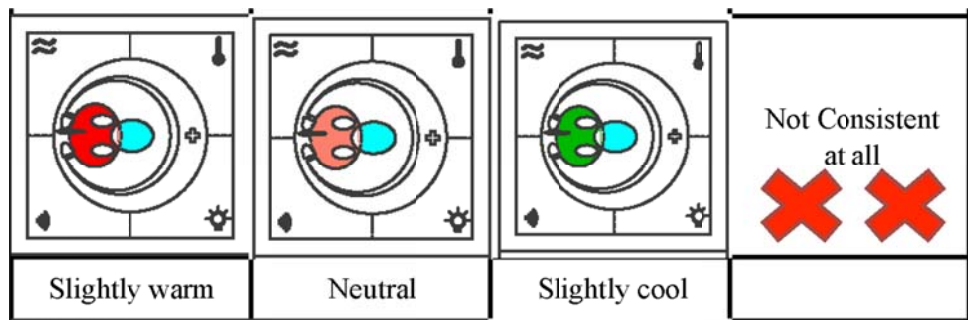


Figure 250: Overall thermal preference is extremely inconsistent, and it flips from 'slightly warm' in the morning to 'slightly cool' in the late afternoon

8.3.2. Consistency of Thermal Preference

The morning, early and late afternoon survey questionnaires of thermal sensation and thermal intention of every participant is presented in Figure 251 and Figure 252. The name of the building and time of the day are specified at the top of the pictogram.

Building A				Building B			
Do the occupant want to feel neutral? during a day: morning, early and late afternoon?			Consistency in thermal preference	Do the occupant want to feel neutral? during a day: morning, early and late afternoon?			Consistency in thermal preference
Morning	Early afternoon	Late afternoon		Morning	Early afternoon	Late afternoon	
			Consistent ✓				Not consistent ✗
Neutral	Neutral	Neutral		Slightly warm	Neutral	Neutral	
			Consistent ✓				Consistent ✓
Neutral	Neutral	Neutral		Neutral	Neutral	Neutral	
			Consistent ✓				Consistent ✓
Neutral	Neutral			Neutral	Neutral	Neutral	
			Not consistent ✗				Consistent ✓
	Slightly cool	Neutral		Neutral	Neutral	Neutral	
			Not consistent ✗				Not consistent ✗
Slightly cool	Slightly cool	Neutral		Slightly warm	Neutral	Neutral	
			Consistent ✓				Not consistent ✗
Neutral	Neutral			Slightly warm	Neutral	Neutral	
			Not consistent ✗				Not consistent ✗
Neutral	Slightly cool	Slightly cool		Slightly cool	Neutral	Neutral	
			Consistent ✓				Not consistent at all ✗ ✗
Neutral	Neutral	Neutral		Neutral	Slightly cool	Slightly warm	
			Consistent ✓				Not consistent ✗
Neutral	Neutral	Neutral		Neutral	Neutral	Slightly cool	
			Not consistent ✗				Not consistent ✗
Slightly cool	Neutral	Neutral		Slightly warm	Neutral	Slightly warm	

Building A				Building B			
Do the occupant want to feel neutral? during a day: morning, early and late afternoon?			Consistency in thermal preference				
Morning	Early afternoon	Late afternoon					
			Consistent ✓				✗
Neutral	Neutral	Neutral					
			Consistent ✓				✗ ✗
Neutral	Neutral	Neutral					
			Consistent ✓				✓
Neutral	Neutral						
			Not consistent ✗				✗
Neutral	Neutral	Slightly warm					
			Consistent ✓				✗
Neutral	Neutral	Neutral					
			Consistent ✓				✗
Neutral	Neutral						
			Not consistent ✗				✗
Neutral	Neutral	Slightly warm					
			Consistent ✓				✓
Neutral	Neutral	Neutral					
			Consistent ✓				✗
Slightly cool	Slightly cool	Slightly cool					
			Consistent ✓				✗ ✗
Neutral	Neutral	Neutral					

Building A				Building B			
Do the occupant want to feel neutral? during a day: morning, early and late afternoon?			Consistency in thermal preference				
Morning	Early afternoon	Late afternoon		Morning	Early afternoon	Late afternoon	
			Not consistent ✗				Not consistent ✗
Slightly cool	Cool	Neutral		Neutral	Slightly cool	Cool	
			Consistent ✓				Not Consistent at all ✗ ✗
Neutral	Neutral	Neutral		Slightly warm	Slightly cool	Slightly cool	
			Consistent ✓				Consistent ✓
Neutral	Neutral	Neutral			Neutral	Neutral	
			Consistent ✓				Not consistent ✗
Slightly cool	Slightly cool	Slightly cool		Slightly warm	Neutral	Neutral	
			Consistent ✓				Not consistent ✗
	Neutral	Neutral		Neutral	Neutral	Slightly warm	
			Consistent ✓				Not consistent ✗
Neutral	Neutral	Neutral		Slightly cool	Neutral		
			Not consistent ✗				
Neutral	Slightly warm	Neutral					
			Consistent ✓				
Neutral	Neutral	Neutral					
			Not consistent ✗				
Neutral	Neutral	Slightly cool					
			Consistent ✓				
Slightly cool	Slightly cool	Slightly cool					

Figure 251: The visual recording analysis of consistency in overall thermal preference of each individual in Building A and Building B in the morning, early and late afternoon

Building C				Building D			
Do the occupant want to feel neutral? during a day: morning, early and late afternoon?			Consistency in thermal preference	Do the occupant want to feel neutral? during a day: morning, early and late afternoon?			Consistency in thermal preference
Morning	Early afternoon	Late afternoon		Morning	Early afternoon	Late afternoon	
			Not consistent ✖				Not Consistent at all ✖ ✖
Slightly warm	Neutral	Neutral		Slightly cool	Neutral	Slightly warm	
			Consistent ✔				Not Consistent at all ✖ ✖
Neutral	Neutral	Neutral		Cold	Slightly warm		
			Not consistent ✖				Consistent ✔
Slightly warm	Slightly warm	Neutral		Slightly warm	Slightly warm	Slightly warm	
			Consistent ✔				Not consistent ✖
Neutral	Neutral	Neutral		Neutral	Slightly warm	Neutral	
			Not consistent at all ✖ ✖				Not consistent ✖
Very hot		Neutral		Slightly warm	Neutral	Neutral	
			Consistent ✔				Not consistent ✖
Neutral	Neutral	Neutral		Neutral	Neutral	Slightly cool	
			Consistent ✔				Not consistent ✖
	Neutral	Neutral			Slightly warm	Neutral	
			Not consistent ✖				Not consistent ✖
Neutral	Slightly warm			Slightly warm	Neutral	Neutral	
			Not Consistent at all ✖ ✖				Consistent ✔
Neutral	Slightly cool	Slightly warm		Neutral	Neutral	Neutral	
			Not consistent ✖				Consistent ✔
Slightly cool		Neutral		Neutral	Neutral	Neutral	

Building C				Building D			
			✗				✗
			✓				✗ ✗
			✓				✗ ✗
			✗				✓
			✗ ✗				✗
			✗ ✗				✗ ✗
			✗				✗
			✗				✓
			✗				✓
			✓				✓
Building C				Building D			

Building C				Building D			
Morning	Early afternoon	Late afternoon		Morning	Early afternoon	Late afternoon	
			Consistent ✓				Consistent ✓
Slightly cool	Slightly cool	Slightly cool		Neutral	Neutral	Neutral	
			Consistent ✓				Consistent ✓
Neutral	Neutral			Neutral	Neutral	Neutral	
			Not consistent ✗				Not consistent ✗
	Neutral	Slightly cool		Slightly warm		Neutral	
			Consistent ✓				
Neutral	Neutral	Neutral					

Figure 252: The visual recording analysis of consistency in overall thermal preference of every participant in Building C and Building D in the morning, early and late afternoon

Consistency of Thermal Preference of Occupants During the day		Building A	Building B	Building C	Building D	All 4 Buildings
Consistent	✓	21	6	10	9	46
Not consistent	✗	9	16	10	9	44
Not consistent at all	✗✗	0	4	4	5	13

Figure 253: Consistency of thermal preference of occupants throughout the day

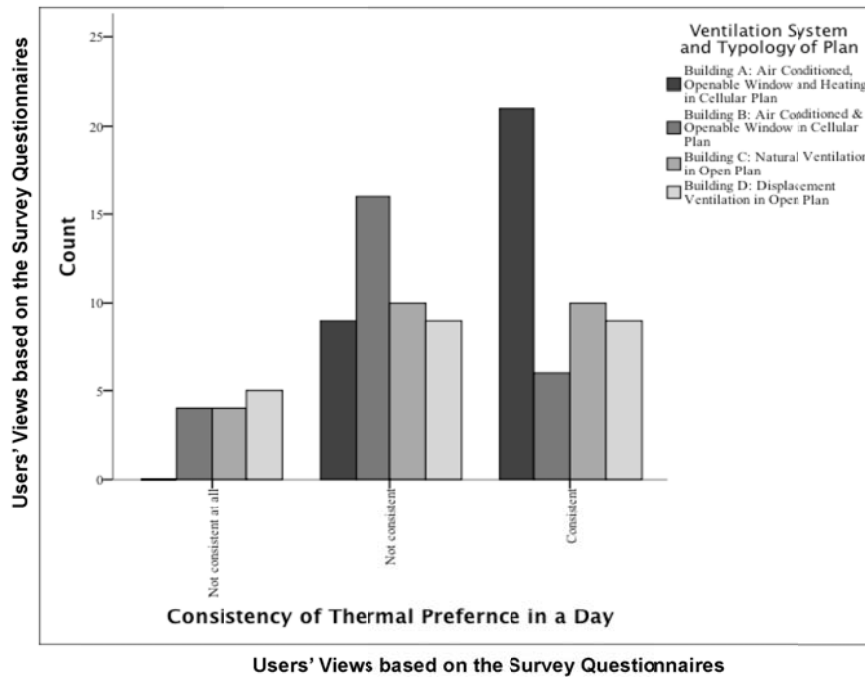


Figure 254: Bar chart: Consistency of thermal preference of occupants throughout the day

46 out of 103 participants in the four case study buildings (i.e. 45%) have consistency in their thermal preferences in the morning, early and late afternoon. However, in 57 cases (i.e. 42%) there is limited inconsistency between individual's thermal preferences during the day. 13 individuals (i.e. 13%) have extreme preferences during the day. Overall, more than half of the participants in this study (i.e. 55%) have different thermal preferences during the day and their desired set point of temperature changes. This suggests that an individual is likely to feel comfortable experiencing different thermal conditions.

The following results can be drawn from the qualitative analysis of each building based on Figure 251 Figure 252 and Figure 253 as well:

- Building A: 27 out of 30 participants of Building A (i.e. 90%) want to feel neutral at least at one point in the day. This leaves 3 participants (i.e. 10%), who do not want to feel neutral at any time during the day. 9 out of 27 respondents (i.e. 33%), who want to feel neutral, prefer a sensation other than neutral at another point in the day. Overall, 12 out of 30 participants (i.e. 40%) do not want to feel neutral at least at one point in the day.
- Building B: 23 out of 26 participants of Building B (i.e. 88%) want to feel neutral at least at one point in the day, which leaves 3 participants (i.e. 12%) with no desire to feel neutral at all. 18 out of 23 respondents (i.e. 78%), who want to feel neutral,

prefer a different sensation than neutral at another point in the day. Overall, 21 out of 26 participants (i.e. 80%) do not want to feel neutral at least at some point in the day.

- Building C: 20 out of 24 participants of Building C (i.e. 83%) want to feel neutral at least at one point in the day, which leaves 4 participants (i.e. 17%) with no desire to feel neutral at all. 11 out of 20 respondents (i.e. 55%), who want to feel neutral, prefer a different sensation than neutral at another point in the day. Overall, 15 out of 24 participants (i.e. 63%) do not want to feel neutral at least at some point in the day.
- Building D: 19 out of 23 participants of Building D (i.e. 83%) want to feel neutral at least at one point in the day, which leaves 4 participants (i.e. 17%) with no desire to feel neutral. 12 out of 19 respondents (i.e. 63%), who want to feel neutral at least at one point in the day, prefer a different sensation than neutral at another point in the day. Overall, 16 out of 23 participants (i.e. 70%) do not want to feel neutral at least at some point in the day.
- All the four buildings overall: 89 out of 103 participants in all case studies (i.e. 86%) want to feel neutral at least at one point in the day, which leaves 14 participants (i.e. 14%) with no desire to feel neutral. 53 out of 89 respondents (i.e. 60%), who want to feel neutral, prefer a different sensation than neutral at another point in the day. Overall, 67 out of 103 participants (i.e. 65%) do not want to feel neutral at least at some point in the day.

These analyses indicate that although 86% of the respondents prefer a neutral thermal sensation at least at one point in the day, 60% of them prefer to have a different sensation at another time in the day. This suggests that if a participant prefers to have a neutral thermal sensation at the time of the survey, it does not guarantee that if the survey is repeated they still want to have the neutral thermal sensation. In fact, there is 60% chance that they do not want to feel neutral. In addition, these results challenge the theory that occupants are comfortable when they feel neutral, as 65% of the participants in this study do not want to feel neutral at least at some point in the day.

8.3.3. Thermal Preference During a Day

Overall, most individuals (i.e. 55%) in this study prefer different thermal settings throughout the day. This suggests that a particular thermal setting is less likely to satisfy a particular individual at all times. It proposes that thermal comfort is subject to change. This challenges

the steady state theory, which is based on providing a steady thermal sensation for everyone constantly. This is further discussed in the discussion chapter, section 10.1.2.7.

8.4. Summary

In this chapter, the view of universal ‘comfort zone’ was examined through three objectives. Firstly, the accuracy of the most widely used comfort zone, the ASHRAE Standard 55-2010, was examined in the case study buildings in this study. Secondly, the application of the ‘neutral thermal sensation’ as the basis of standard ‘comfort zones’ was questioned. Thirdly, the consistency of thermal preference of users throughout the day was examined. Quantitative and qualitative analyses were applied on the collected data.

The results indicate that the ASHRAE comfort predictions do not apply to the case study buildings in this study, as it shows it has limits. There is a possibility that the ASHRAE comfort predictions can be applied to other buildings, since every building has a different context and findings of one building may not be applied to other buildings (Nicol et al., 2012). Intensive contextual analysis shows differences in the four case study buildings, as presented in sections 8.1 and 8.2. In addition, the basis of the comfort zone, neutral thermal sensation, does not indicate thermal comfort amongst the participants in this study. Furthermore, in this research most individuals prefer different thermal settings throughout the day. The first two findings reveal the inaccuracy of the standard ‘comfort zone’ and its basis, while the third finding proposes that thermal comfort is dynamic rather than fixed. This is in contrast with the standard ‘comfort zone’ in providing a uniform thermal environment for occupants in the workplace. It suggests that a standard ‘comfort zone’ that satisfies everyone is less likely to apply to the real world context of the workplace. These findings are further discussed in Chapter Ten, the discussion chapter.

CHAPTER 9

STAGE II: INDIVIDUAL THERMAL CONTROL

9. Stage II: Individual Thermal Control

As explained earlier, this thesis is based on the challenge in the field of thermal comfort between the steady state and adaptive comfort theories, which are followed by distinct approaches respectively ‘comfort zone’ and ‘adaptive opportunity’, described in Chapter Three. Chapter Eight questioned the application of the standard ‘comfort zone’. This chapter will investigate the application of the ‘adaptive opportunity’ or ‘individual thermal control’ in the Norwegian and British workplace contexts. This is explored by examining the active role of the user and investigating user satisfaction in environments with high and low levels of thermal control.

The active role of the user is investigated through examining the impact of their decision to change the thermal environment on their satisfaction and comfort. The user’s intention to adjust the thermal environment is called the ‘thermal control intention’ or ‘thermal intention’ in this thesis. In the second part of this chapter, the satisfaction, comfort, health and productivity of users are compared in two workplaces that provide high and low opportunities for controlling the thermal environment. The two air conditioned Norwegian cellular plan case studies in this research have high levels of individual thermal control. Every occupant is provided with an openable window, blinds, door and the ability to adjust the temperature. In contrast, the two mechanically and naturally ventilated British open plan case study buildings have low levels of thermal control. Only occupants seated around the perimeter of the building can access limited openable windows and blinds, while the majority of the occupants seated closer to the centre of the open plan office have no opportunity to adjust their thermal environment.

Quantitative and qualitative methods are applied to analyse these objectives. As explained before, a survey questionnaire is applied to record the users’ immediate response to the thermal environment at the workstation. This is followed by simultaneous thermal measurements to record the thermal conditions. Further intensive interviews are followed to investigate users’ view of thermal control. Similar to Chapter Eight, these analyses are based on over 300 responses, which is the total number of respondents, according to the survey questionnaires. These 300 responses include approximately 30 participants in each of the 4 buildings, who responded to the survey questionnaire 3 times a day, morning, early and late afternoon.

9.1. Thermal Intention

9.1.1. Occupants' Satisfaction and Comfort

In this section, the impact of the users' intention to adjust the thermal environment on their satisfaction and comfort is examined. Users' thermal intention is the desire to change the air temperature, air movement or air quality of their surrounding environment.

Thermal intention is recorded through survey questionnaires. The participants responded to the following questions regarding their desire to change the temperature, as well as how they evaluate air movement and air quality, presented in Figure 255. In addition, the questionnaire includes their satisfaction, comfort and productivity, presented in Figure 70. Simultaneously, the researcher measured the thermal environment, including the air temperature, air movement and carbon dioxide level, and recorded them on a separate questionnaire, presented in Figure 71. The analysis in Chapter Seven regarding the building performance of the case studies shows that the thermal environment (i.e. sections 7.2.2 and 7.2.3.2) and air quality (i.e. section 7.2.5) of the buildings are within the acceptable range based on the standards. Therefore, the thermal intention of the user is less likely to be related to the poor indoor air quality or uncomfortable thermal environment. Rather, individual requirements are the main criteria in the users' desire to adjust the thermal environment. This is supported by the interviews.

9. Compared to normal, currently my productivity is

Much higher Higher Slightly higher The same Slightly lower Lower Much lower No strong opinion

7. Currently at my desk, the following is

	Strongly adequate	Adequate	Slightly adequate	Neutral	Slightly inadequate	Inadequate	Strongly inadequate	No strong opinion
a. Air movement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
b. Fresh air	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
c. Light level	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Figure 255: Thermal intention questions, including temperature, air movement and air quality

9.1.1.1. Quantitative Analysis

As explained in section 8.1, the traditional quantitative method, which is the linear regression analysis (Jaakkola et al., 1989, de Dear and Brager, 1998, Busch, 1992, Frank et al., 1999, Brager and De Dear, 2000, Raja et al., 2001, de Dear and Brager, 2002, Wong et al., 2002, Feriadi and Wong, 2004, Bouden and Ghrab, 2005, Rijal et al., 2007) is applied using the

SPSS. A similar process is applied to evaluate the relationship between thermal control intention and variables, including satisfaction and comfort. Therefore a sample of this analysis is presented in section 9.1.1.1.1, while the rest of the SPSS regression analyses are presented in Appendix H.

9.1.1.1.1. Satisfaction

Figure 256 to Figure 257 demonstrate the SPSS linear regression analysis of satisfaction and thermal control intention of the user regarding temperature, air movement, and indoor air quality, which encompasses 313 responses.

	Mean	Std. Deviation	N
Satisfaction	1.00	1.334	313
Thermal Intention-4 Point Scale	3.41	.738	313
Air Movement Intention	.60	1.520	313
Indoor Air Quality Intention	.74	1.546	313

Figure 256: Descriptive Statistics, SPSS linear regression analysis of satisfaction and thermal control intention, including temperature, air quality and air movement intention

Figure 257 indicates that satisfaction can be explained based on the thermal control intention, since the P value is 0.000, which is less than 0.05.

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	153.909	3	51.303	39.524	.000^b
	Residual	401.088	309	1.298		
	Total	554.997	312			

a. Dependent Variable: Satisfaction

b. Predictors: (Constant), Indoor Air Quality Intention, Thermal Intention-4 Point Scale, Air Movement Intention

Figure 257: ANOVA, SPSS linear regression analysis of satisfaction and thermal control intention, including temperature, air quality and air movement intention

The R square in the model summary table in Figure 258 indicates that 27.7% of variance in satisfaction can be explained by the thermal control intention, including thermal, air movement, and indoor air quality intention. This R square is greater than thermal sensation's R square (i.e. 16.9%), which is presented in section 8.2.1.2. This suggests that thermal control intention is more likely to explain satisfaction.

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.527 ^a	.277	.270	1.139	.277	39.524	3	309	.000

a. Predictors: (Constant), Indoor Air Quality Intention, Thermal Intention-4 Point Scale, Air Movement Intention

Figure 258: Model Summary, SPSS linear regression analysis of satisfaction and thermal control intention, including temperature, air quality and air movement intention

The coefficients analysis in Figure 259 shows that by improving thermal intention towards no change, satisfaction improves by 0.815 degree. Air movement intention is less effective (i.e.

0.126 degree), and indoor air quality intention is even less effective (i.e. 0.044 degree). This analysis shows that satisfaction is likely to be improved by a decrease in users' desire to change the temperature more than air movement or indoor air quality.

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	
	B	Std. Error	Beta			
1	(Constant)	-1.888	.311		-6.077	.000
	Thermal Intention-4 Point Scale	.815	.090	.451	9.046	.000
	Air Movement Intention	.126	.079	.143	1.591	.113
	Indoor Air Quality Intention	.044	.077	.051	.570	.569

a. Dependent Variable: Satisfaction

Figure 259: Coefficients, SPSS linear regression analysis of satisfaction and thermal control intention, including temperature, air quality and air movement intention

Figure 260 shows the boxplot of satisfaction and thermal control intention. The latter is based on a four point scale as follows:

- **4 = No thermal control intention**
- 3 = Low thermal control intention
- 2 = Medium thermal control intention
- 1 = High thermal control intention

Figure 261 demonstrates good correlation between the two variables and that participants with higher levels of satisfaction have less desire to control the thermal environment and vice versa. Figure 262 breaks down the information for each building and it shows that occupants of the cellular plan offices are more satisfied and desire less environmental change. In contrast, occupants of the open plan offices report more dissatisfaction levels and demand higher degrees of environmental control.

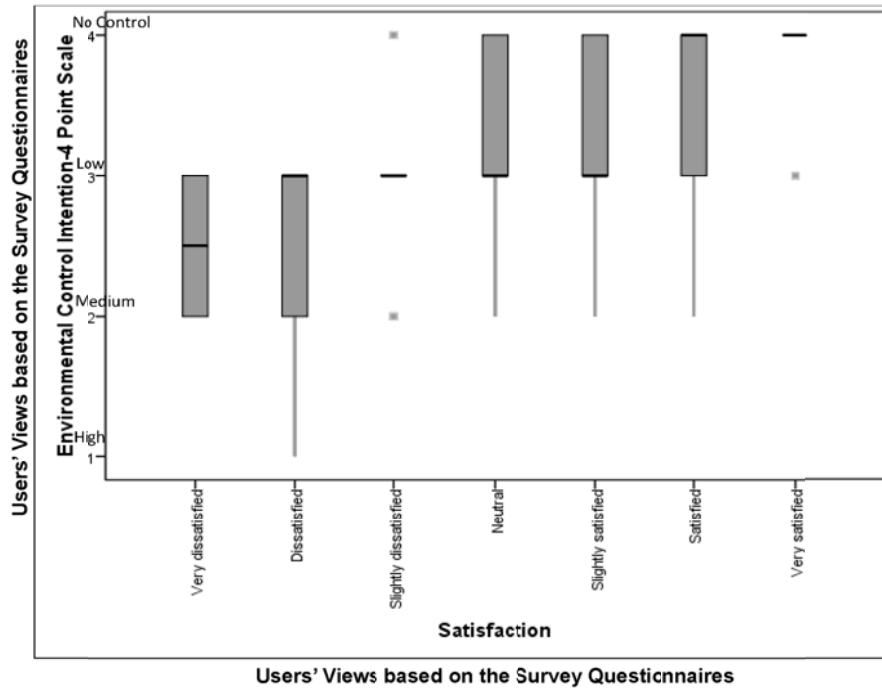


Figure 260: Boxplot of satisfaction and thermal control intention, including temperature, air quality and air movement intention

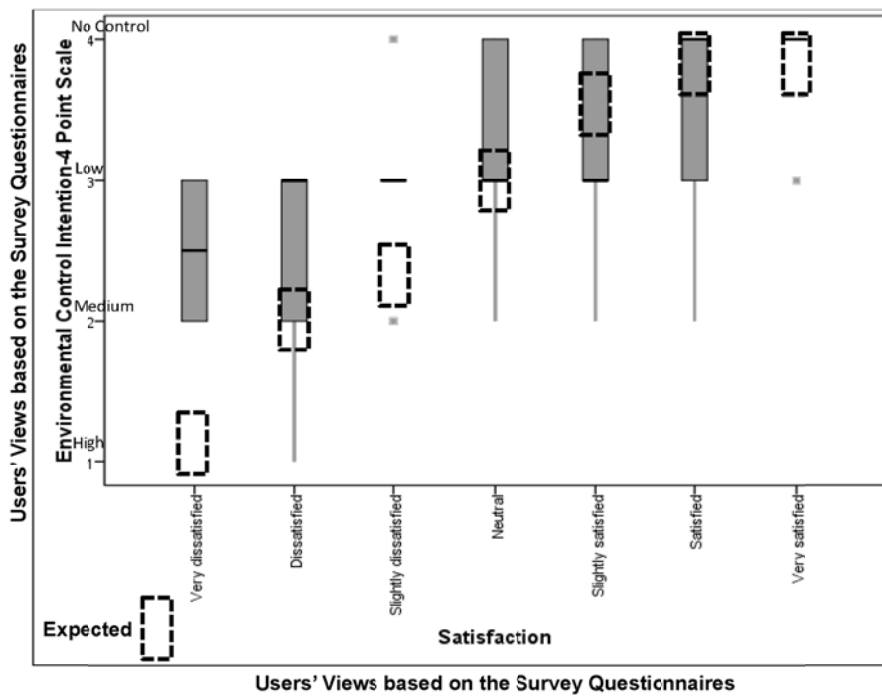


Figure 261: Boxplot presenting what was expected in Figure 260

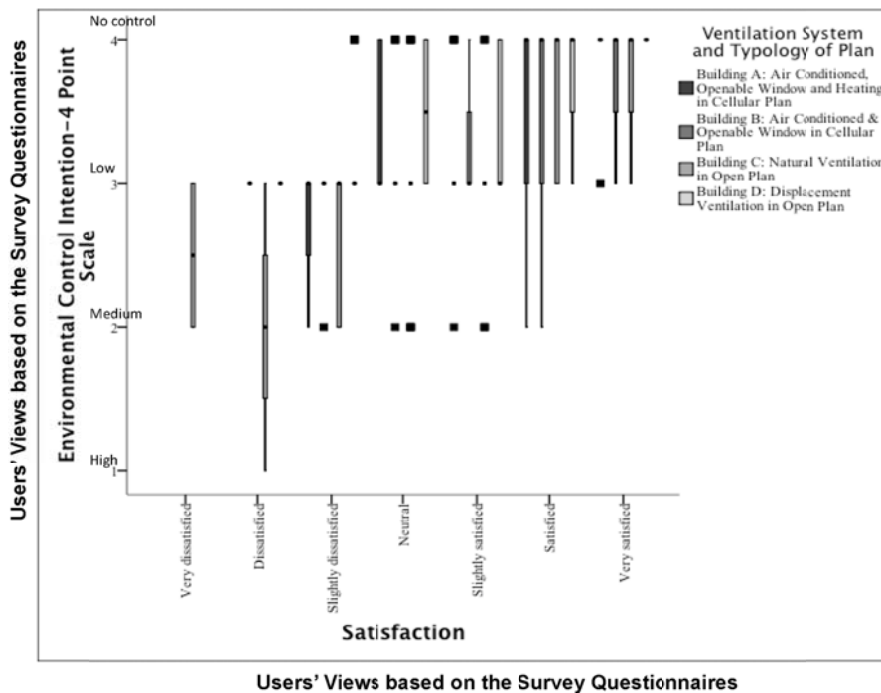


Figure 262: Boxplot of satisfaction and thermal control intention for each building

The results indicate a significant relationship between satisfaction and thermal control intention, including temperature, air movement and indoor air quality. The desire to change the temperature influences satisfaction more than the other two variables, which confirms findings of other researchers (Auliciems and Szokolay, 1997). The results propose that the more occupants are satisfied, the less likely their intention to apply control over the thermal environment. In addition, the results suggest that satisfaction is explained better by thermal control intention, rather than thermal sensation.

9.1.1.1.2. Comfort

Similar to section 9.1.1.1.1, linear regression analysis is applied, presented in Appendix H. The results suggest a significant relationship between users' comfort and their thermal control intention (i.e. P value is $0.000 < 0.05$). 18.8% of variance in comfort can be explained by the thermal control intention, while section 8.2.1.1 showed that 13.2% of the variance in comfort can be explained by thermal sensation. This suggests that thermal control intention is more likely to explain comfort status compared to thermal sensation.

Figure 263 is the boxplot of comfort and thermal control intention. Respondents with higher levels of comfort have less desire to control the thermal environment and vice versa. This is more visible when users report very comfortable and very uncomfortable. Nevertheless, slight inconsistency is visible regarding the neutral level of comfort, as some participants desire to

apply no control over the thermal environment. Overall, Figure 264 shows a good correlation between the two variables. Figure 265 breaks down the information in each building and shows that occupants of the cellular plan offices are more comfortable and desire less environmental change. On the contrary, occupants of the open plan offices report more discomfort levels and demand higher degrees of environmental control.

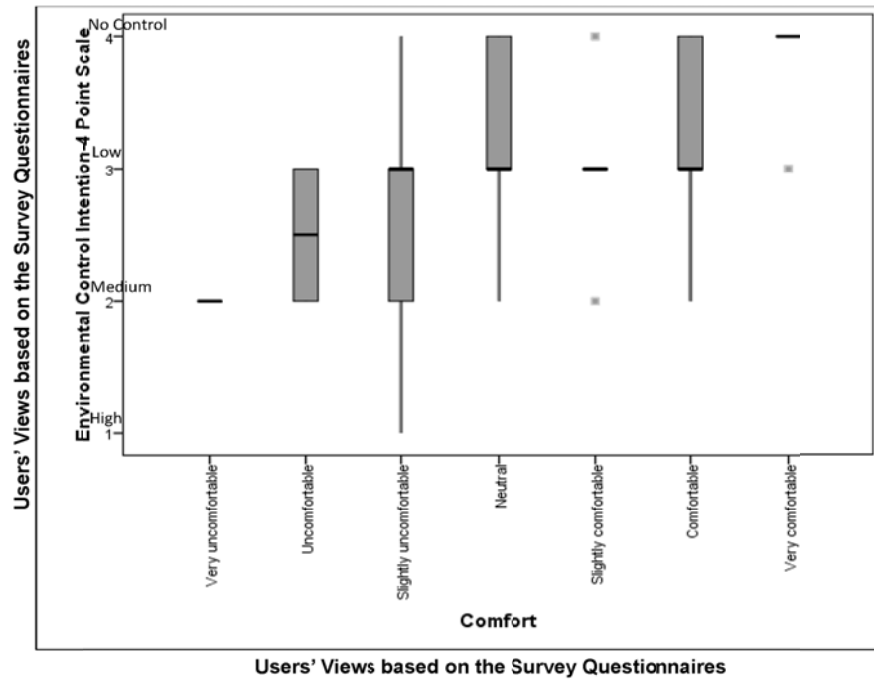


Figure 263: Boxplot of comfort and thermal control intention, including temperature, air quality and air movement intention

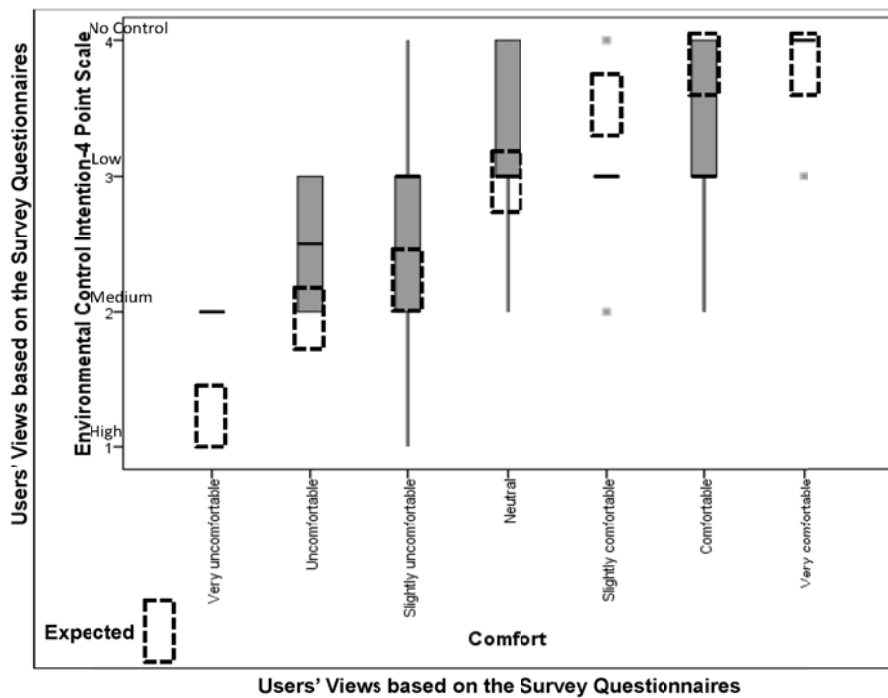


Figure 264: Boxplot presenting what was expected in Figure 263

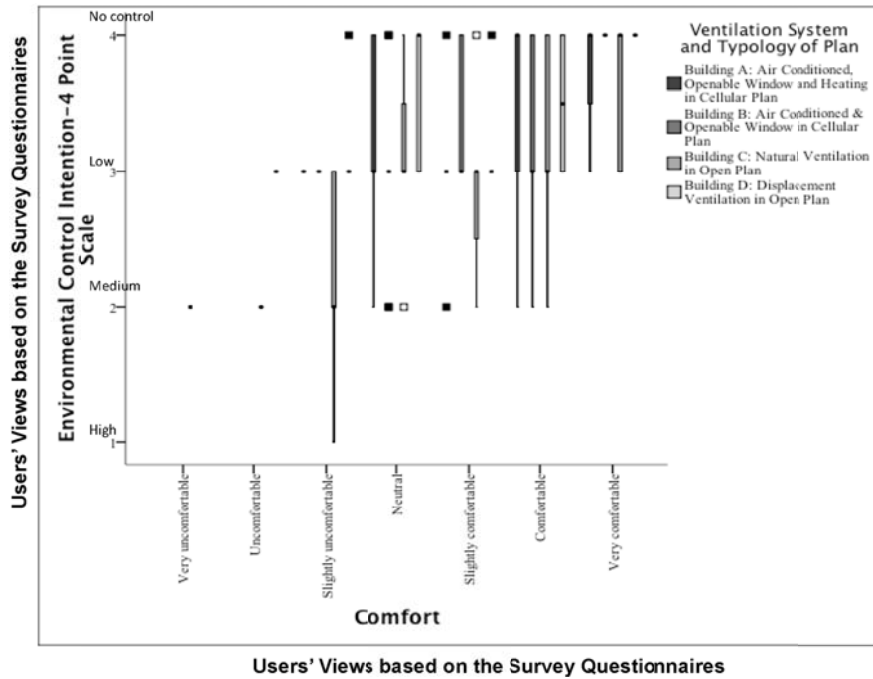
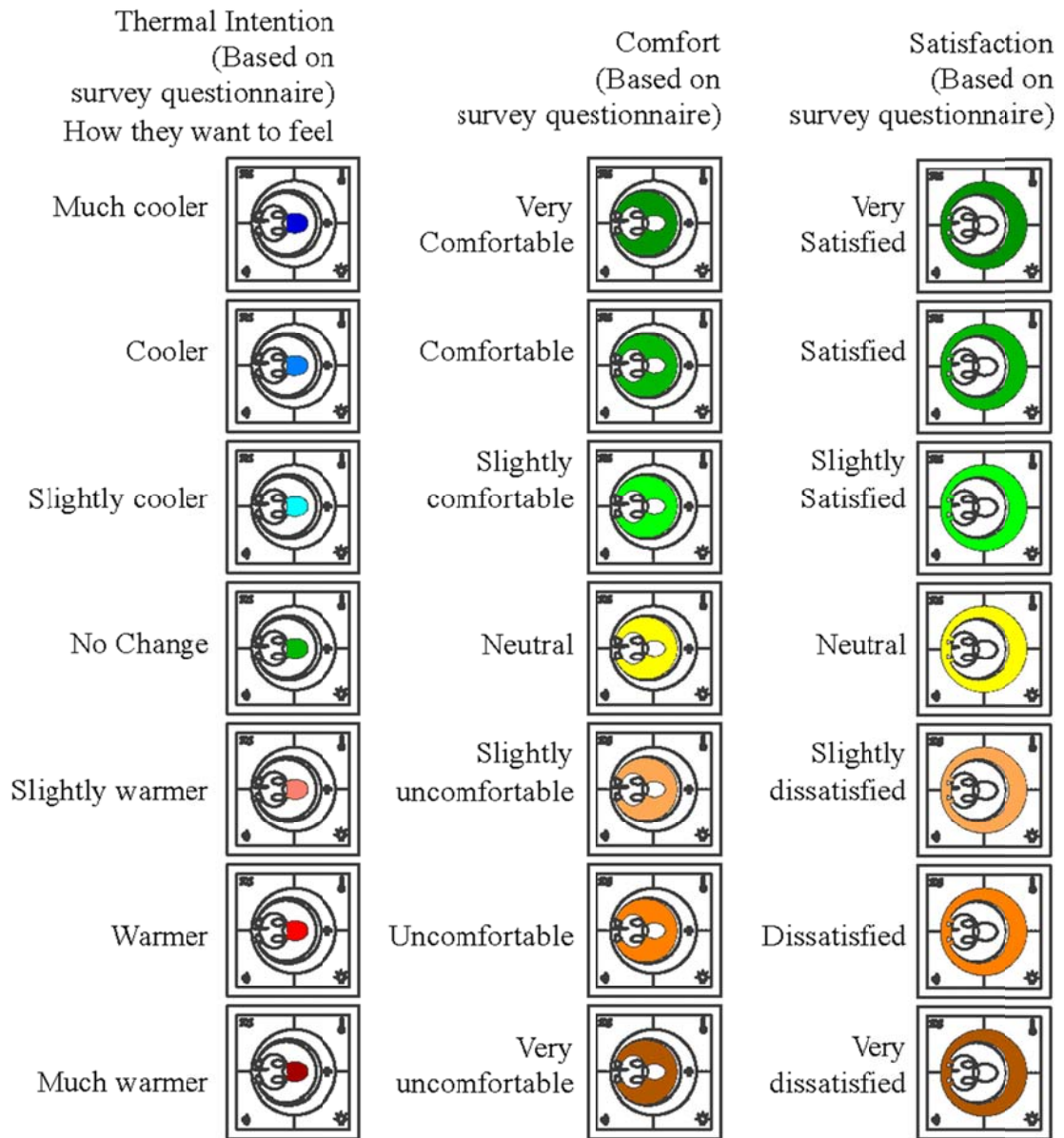


Figure 265: Boxplot of comfort and thermal control intention for each building

The results indicate a significant relationship between comfort and thermal control intention, including temperature, air movement and air quality. User's desire to change the temperature has greater impact on comfort compared to the other two variables. The results suggest that occupants with a desire to adjust the thermal environment are more likely to be uncomfortable.

9.1.1.2. Qualitative Analysis

In this section, qualitative analysis is applied on the same data, using the visual recording technique, introduced in sections 5.2.3 and 6.1.6. The qualitative method allows more detailed analysis and interpretation according to the meaning. A sample of this analysis is presented in Figure 266, and the detailed pictograms in Appendix A.



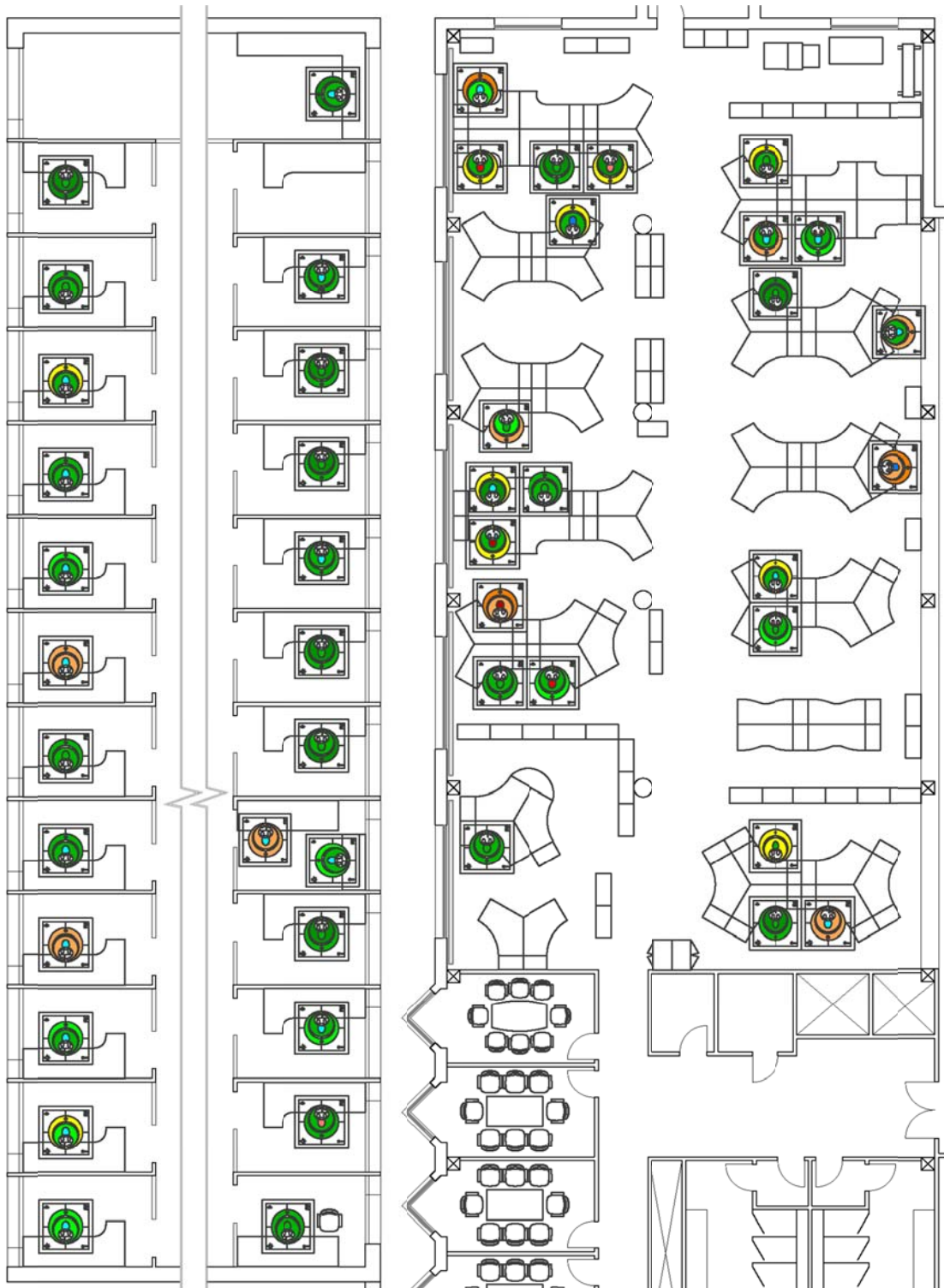


Figure 266: Building A and C: A sample of the qualitative analysis of thermal intention and thermal satisfaction and comfort, presented properly in Appendix A

9.1.1.2.1. Satisfaction

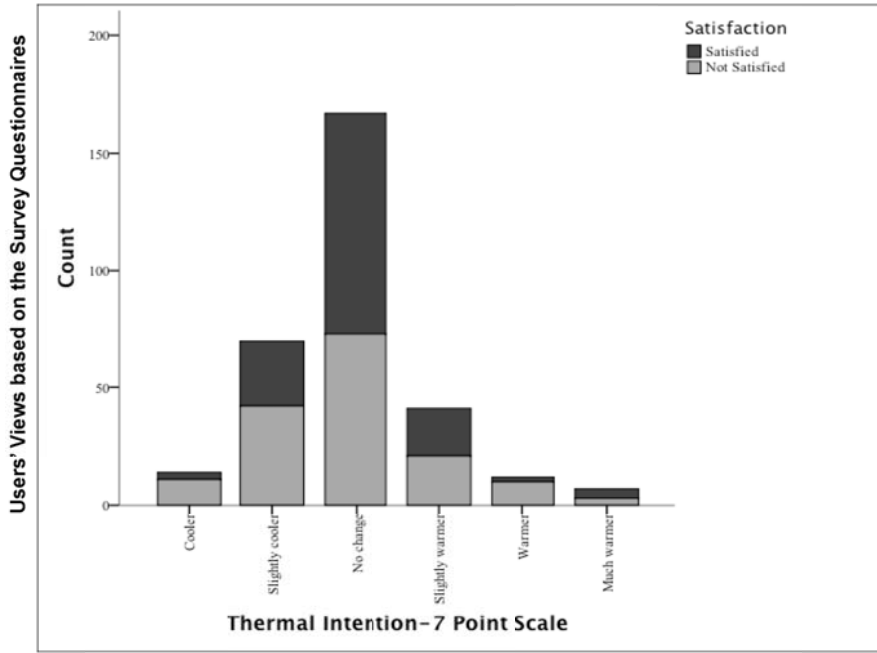
Figure 267 and

Ventilation Intention	Satisfaction						
	Very dissatisfied	Dissatisfied	Slightly dissatisfied	Neutral	Slightly satisfied	Satisfied	Very satisfied
No control	1	3	6	32	19	92	23
Low			17	31	20	28	5
Medium	1	3	12	7	5	2	
High		1	4	3		1	

present the relationship between satisfaction and respectively temperature and ventilation control intentions. The latter includes air movement and air quality. Only survey results including ‘satisfied’ and ‘very satisfied’ are considered acceptable and recorded as ‘satisfied’, explained in sections 8.2.2.1 and 8.2.2.2. 114 out of 151 satisfied respondents (i.e. 75%) have no desire to change the temperature, and 24% of them want a slight change in the temperature, such as slightly cooler or slightly warmer. Only one satisfied respondent wants more than a slight change in the temperature. 43 out of 48 dissatisfied participants, including very dissatisfied, dissatisfied and slightly dissatisfied, (i.e. 90%) want to adjust the temperature. This suggests that occupants’ satisfaction improves as their tendency to change the temperature reduces.

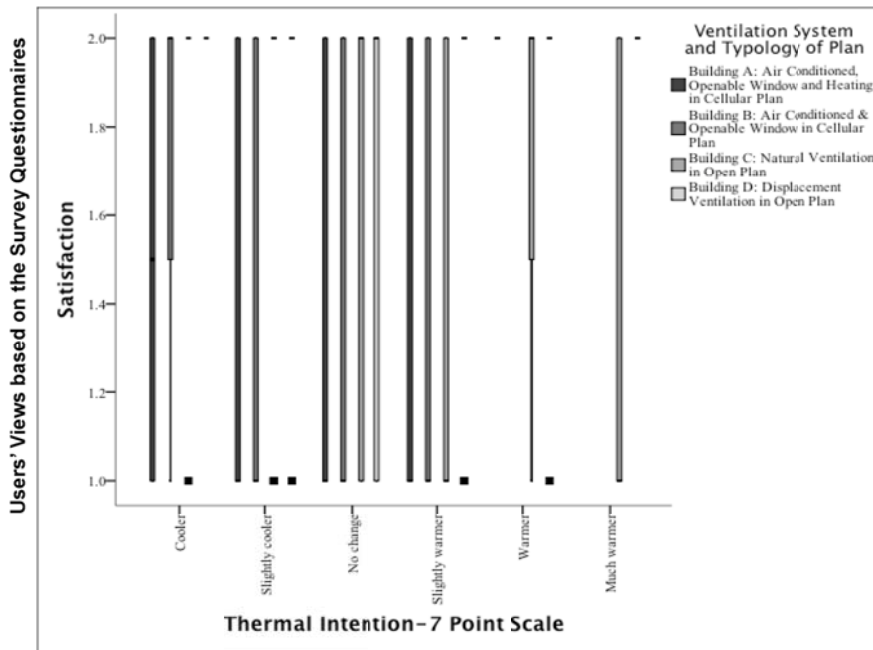
Temperature Control Intention	Satisfaction						
	Very dissatisfied	Dissatisfied	Slightly dissatisfied	Neutral	Slightly satisfied	Satisfied	Very satisfied
Much warmer	1	1					
Warmer		1	3	7	3		
Slightly warmer			4	10	9	17	2
No Change			5	37	14	91	23
Slightly cooler		4	20	16	16	14	3
Cooler	1	1	7	3	2	1	
Much cooler							

Figure 267: Qualitative analysis of satisfaction and temperature control intention



Users' Views based on the Survey Questionnaires

Figure 268: Bar chart: Qualitative analysis of satisfaction and temperature control intention



Users' Views based on the Survey Questionnaires

Figure 269: Boxplot: analysis of satisfaction and temperature control intention for each building

Ventilation Intention	Satisfaction						
	Very dissatisfied	Dissatisfied	Slightly dissatisfied	Neutral	Slightly satisfied	Satisfied	Very satisfied
No control	1	3	6	32	19	92	23
Low			17	31	20	28	5
Medium	1	3	12	7	5	2	
High		1	4	3		1	

shows 115 out of 151 satisfied respondents (i.e. 76%) want no change in ventilation, including air movement and air quality. 32 of them (i.e. 21%) want a slight change, and only 3 of them (i.e. 2%) want more than a slight change in ventilation. 38 out of 48 dissatisfied participants (i.e. 79%) want a change in ventilation, and 21 of them (i.e. 44%) want more than a slight change. This indicates that users' satisfaction improves as their tendency to adjust the ventilation decreases.

Ventilation Intention	Satisfaction						
	Very dissatisfied	Dissatisfied	Slightly dissatisfied	Neutral	Slightly satisfied	Satisfied	Very satisfied
No control	1	3	6	32	19	92	23
Low			17	31	20	28	5
Medium	1	3	12	7	5	2	
High		1	4	3		1	

Figure 270: Qualitative analysis of satisfaction and ventilation intention

Figure 271 shows the relationship between satisfaction and thermal control intention, including temperature and ventilation. Figure 270 is similar to Figure 271, showing the relationship in more detail by directly using the visual recordings. The thermal control intention is measured from 0 to 6; the former presents no control intention and the latter very high control intention. 89 out of 151 satisfied participants (i.e. 59%) want no change in temperature or ventilation. 46 of them (i.e. 30%) want a slight change either in temperature or ventilation, and only 16 of them (i.e. 11%) want more than a slight change. All of the respondents with a very satisfied vote want no or just a slight change in temperature or ventilation. All of the dissatisfied participants want to adjust the thermal environment. 41 out of 48 dissatisfied participants (i.e. 85%) want more than a slight change in temperature and ventilation. This shows the significant influence of thermal control intention on satisfaction and it suggests when occupants' desire to adjust the thermal environment decreases, their satisfaction level increases.

Satisfaction and Thermal Control Intention (Temperature + Ventilation)							
	Very dissatisfied	Dissatisfied	Slightly dissatisfied	Neutral	Slightly satisfied	Satisfied	Very satisfied
0				15	9	70	19
1		2	5	28	14	37	9
2	1		16	18	17	13	
3		3	13	8	4	3	
4	1	1	5	4			
5		1					
6							

Figure 271: Qualitative analysis of satisfaction and thermal control intention (including temperature and ventilation)

Very Satisfied or Satisfied	Want no change										
	89	19	70								
	Want a slight change										
46	5	4	14	1	6	16					
Want more changes											
16	4	3	7	1	1						
Slightly Satisfied or Neutral	Want no change										
	24	9	15								
	Want a slight change										
	42	3	6	5	19	5	4				
	Want more changes										
21	2	13	2	1	1	1	1				
Want more changes											
30	2	1	12	2	2	2	1	5	1	2	
Slightly Dissatisfied, Dissatisfied or Very Dissatisfied	Want a slight change										
	7	1	2	2	2						
	Want more changes										
	34	3	1	13	1	7	1	1	5	2	
Want more changes											
7	3	1	1	1	1						

Figure 272: Qualitative analysis of satisfaction and thermal control intention, including temperature and ventilation

The quantitative analysis indicates a significant relationship between satisfaction and thermal control intention, including temperature, air movement and air quality. The analysis based on the qualitative visual recordings proposes that thermal control intention has a significant influence on satisfaction. 75% of the satisfied respondents do not want any change in the temperature and 76% in ventilation. 59% of them want no change in either temperature or ventilation and 30% of them want a slight adjustment in only one variable. Overall, 89% of them want no or a slight change in either of the thermal factors. This suggests that occupants' satisfaction improves as their tendency to change the temperature and ventilation reduces. 90% of the dissatisfied participants want to change the temperature, and 79% the ventilation. 100% of the dissatisfied participants want to adjust the thermal environment and 85% of them want more than a slight adjustment. This suggests that occupants' dissatisfaction improves as

their tendency to apply control over the temperature and ventilation increases. Dissatisfied occupants are more likely to adjust the temperature or ventilation.

9.1.1.2.2. Comfort

Figure 273 and Figure 276, based on the visual recordings, examine the impact on comfort of respectively temperature and ventilation control intentions. Only comfortable and very comfortable responses are considered as ‘comfortable’, explained in section 8.2.2.1. 137 out of 214 comfortable participants (i.e. 64%) do not want to adjust the temperature, and 68 of them (i.e. 32%) want a small adjustment. 24 out of 26 uncomfortable respondents (i.e. 92%) want to change the temperature, while 11 of them (i.e. 42%) want more than a slight adjustment. This suggests that occupants with a desire to change the temperature are more likely to be uncomfortable.

All 4 Buildings							
Comfort and Thermal Intention							
	Very Uncomfortable	Uncomfortable	Slightly Uncomfortable	Neutral	Slightly Comfortable	Comfortable	Very Comfortable
Much warmer		1	1	1	1	1	
Warmer			3	3	4	3	
Slightly warmer			4	5	3	28	1
No Change			2	23	8	103	34
Slightly cooler			9	14	11	36	3
Cooler		1	5	4		5	
Much cooler							

Figure 273: Qualitative analysis of comfort based on thermal intention

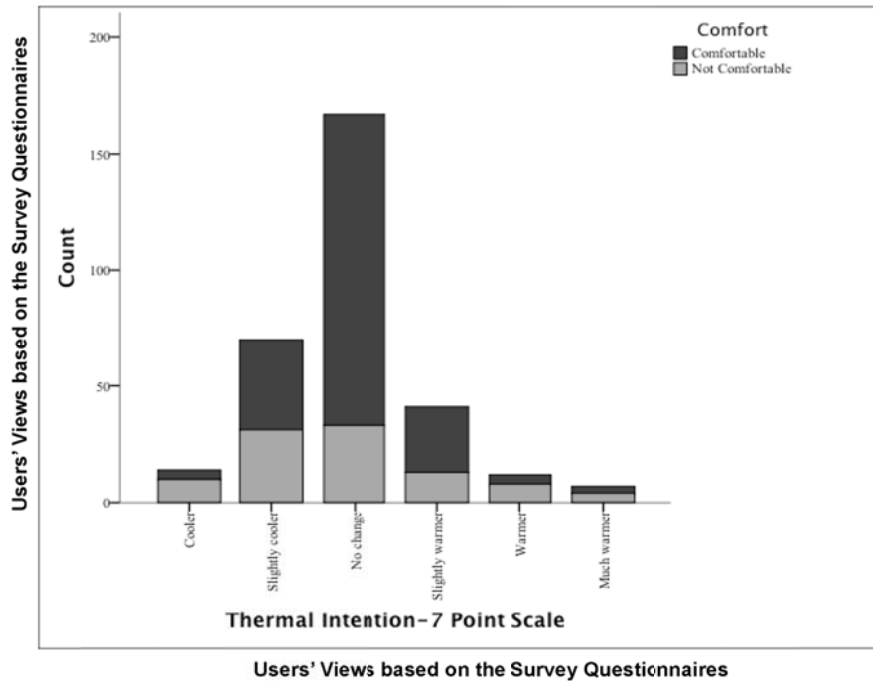


Figure 274: Bar chart: analysis of comfort based on thermal intention

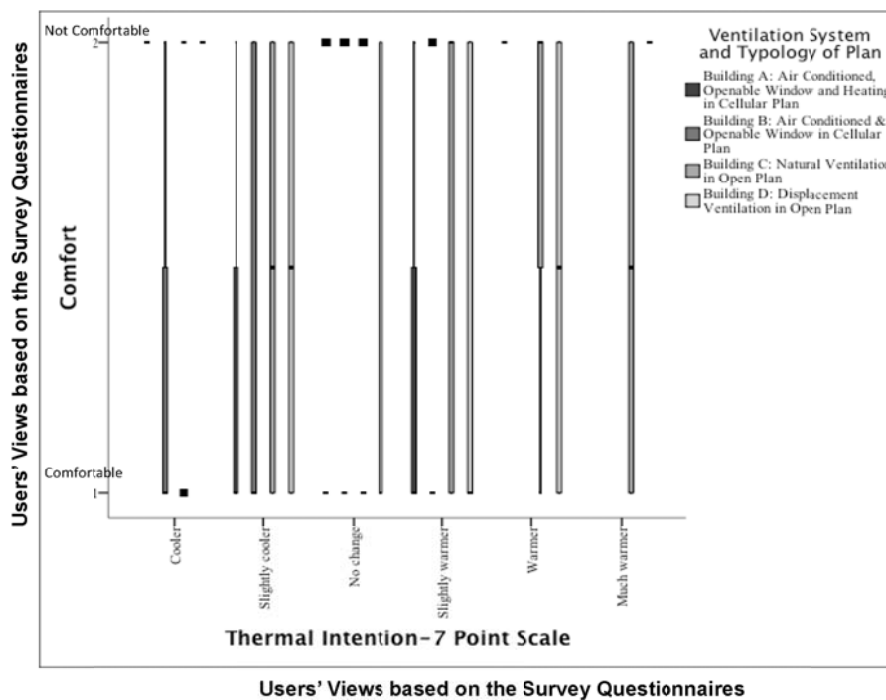


Figure 275: Boxplot: analysis of comfort based on thermal intention for each building

138 out of 214 comfortable participants (i.e. 64%) do not want to regulate the ventilation, and 57 of them (i.e. 27%) want a small regulation. 18 out of 26 uncomfortable respondents (i.e. 69%) want to change the ventilation, while 9 of them (i.e. 35%) want more than a slight change. Overall, 91% of the comfortable occupants want no or a slight change in the ventilation. This suggests that occupants with less desire to regulate the ventilation are more likely to be comfortable.

All 4 Buildings							
	Ventilation Control Intention		Comfort				
	Very Uncomfortable	Uncomfortable	Slightly Uncomfortable	Neutral	Slightly Comfortable	Comfortable	Very Comfortable
No control		1	7	20	10	107	31
Low control			9	24	11	51	6
Medium control		1	7	3	4	12	1
High control			1	3	2	6	

Figure 276: Qualitative analysis of comfort based on ventilation intention, including air quality and air movement

In Figure 277, 0 represents ‘no control’ and 6 represents ‘high control’. Based on Figure 277 and Figure 278, 98 out of 214 comfortable occupants (i.e. 46%) want no change in the temperature or ventilation, and 66 of them (i.e. 31%) want a slight change either in the temperature or ventilation. All of the 26 uncomfortable respondents (i.e. 100%) want a change in the thermal environment, and 19 of them (i.e. 73%) want more than a slight adjustment. The more the comfort level decreases, the more the occupants’ desire to apply control over the thermal environment increases. This suggests that occupants with a desire to change the temperature or ventilation are more likely to be uncomfortable and vice versa.

All 4 Buildings							
	Thermal Control Intention (Thermal + Ventilation)			Comfort			
	Very Uncomfortable	Uncomfortable	Slightly Uncomfortable	Neutral	Slightly Comfortable	Comfortable	Very Comfortable
0				12	4	70	28
1			7	14	7	57	9
2			8	14	7	31	1
3		1	5	7	7	15	
4		1	2	3	2	3	
5			2				
6							

Figure 277: Qualitative analysis of comfort based on thermal control intention

Very Comfortable or Comfortable	Want no change										
	98	28	70								
	Want a slight change										
	66	6	1	2	22	24	11				
	Want more changes										
	43	1	7	4	3	1	21	3	1	1	1
Want more changes											
7	2	4	1								
Slightly Comfortable or Neutral	Want no change										
	16	4	12								
	Want a slight change										
	21	3	1	3	10	1	3				
	Want more changes										
	16	1	1	5	3	1	1	3	1		
Want more changes											
24	1	3	2	8	2	1	3	2	1	1	
Slightly Uncomfortable, Uncomfortable or Very Uncomfortable	Want a slight change										
	7	1	3	3							
	Want more changes										
	17	2	1	4	2	1	1	2	2	1	1
Want more changes											
2	1	1									

Figure 278: Qualitative analysis of comfort and thermal control intention, including temperature and ventilation

The results show a strong relationship between comfort and thermal control intention, including temperature, air movement and air quality. The analysis based on the visual recordings show that 64% of the comfortable respondents do not want any change in the temperature and 32% of them want a small adjustment. 64% of them want no change in the ventilation and 27% of them want a slight change. Overall, 77% of them want no or a slight change in either temperature or ventilation. This proposes that when users' desire to adjust the thermal environment reduces, their comfort level improves. 92% of the uncomfortable respondents want to regulate the temperature and 42% of them want more than a slight change. 69% of them intend to adjust the ventilation and 35% of them want more than a small

adjustment. Overall, 100% of the uncomfortable occupants want to control the thermal environment, including temperature and ventilation, and 73% of them want more than a slight adjustment. This suggests that occupants with a desire to change the thermal environment are more likely to be uncomfortable.

9.1.2. Thermal Intention

The quantitative analysis of satisfaction and comfort indicates a significant relationship between these variables and thermal control intention, including temperature, air movement and air quality. Temperature control has more influence on user comfort and satisfaction than air movement and air quality. The results suggest that people with low thermal control intentions are more likely to be comfortable and vice versa.

The analysis based on the qualitative visual recordings indicate that overall, 89% of the satisfied respondents want no or just a slight adjustment in either temperature or ventilation. This suggests that occupants' satisfaction improves as their tendency to change the thermal environment reduces. 100% of the dissatisfied participants want to adjust the thermal environment, and they are more likely to change the temperature (i.e. 90%) than ventilation (i.e. 79%). This suggests that occupants' dissatisfaction increases as their tendency to apply control over the temperature and ventilation increases. The qualitative analysis of comfort shows that 77% of the comfortable respondents want no or a slight change in either temperature or ventilation. In contrast, 100% of the uncomfortable respondents want to control the thermal environment, including temperature and ventilation, and 73% of them want more than a slight adjustment. This suggests that occupants with a desire to change the thermal environment are more likely to be uncomfortable and as their desire reduces, their comfort level increases. This is in line with the active role of the user, which is the basis of the adaptive principle (Nicol and Humphreys, 1973b, Nicol et al., 2012), indicating users' desire to actively restore their comfort when feeling thermally uncomfortable. This section is further discussed in Chapter Ten, the discussion chapter.

9.2. Individual Thermal Control: Cellular vs. Open Plan Offices

This section investigates the impact of ‘individual thermal control’ on users’ satisfaction, comfort, health, and productivity in the Norwegian and British workplace contexts with respectively high and low levels of thermal control. As explained, the two air conditioned Norwegian cellular plan offices provide every user with control over a window, blinds, door, and the ability to adjust the temperature. In contrast, the two mechanically and naturally ventilated British open plan offices provide limited access to windows and blinds for occupants seated around the perimeter of the building. Occupants farther away from windows are not provided with any means to control their thermal environment.

Quantitative analysis is applied to compare the variables in the four case study buildings. As discussed in Chapter Seven, the thermal performance of all four buildings of this study is within the acceptable range according to the ASHRAE Standard 55-2010. The thermal measurements of over 90% of the workstations fit in the ASHRAE ‘comfort zone’, presented in section 7.2.3.2. In addition, the indoor air quality of the four buildings is within the acceptable range, presented in section 7.2.5. Furthermore, at the time of the survey questionnaire respondents were asked to answer the questions based on their immediate response to the thermal environment and to exclude other factors, such as psychological and job related factors. Moreover, follow up interviews were applied to further investigate users’ view of thermal control. Therefore, users’ satisfaction, comfort, health, and productivity are more likely to be influenced by thermal environment and availability of thermal control.

9.2.1. Satisfaction

Occupants’ satisfaction level is collected through the ASHRAE seven point scale survey questionnaire, explained in section 3.2.2.1. The SPSS linear regression analysis was applied to examine the relationship between satisfaction and type of plan, which indicates high and low thermal control levels, presented in Appendix J. The P value (i.e. 0.000) is less than 0.05, which suggests a significant relationship between satisfaction and type of plan: open and cellular plan offices. Figure 279 is a detailed comparison of satisfaction between the open plan and cellular plan workplaces using the SPSS frequency analysis. Only satisfied and very satisfied responses are considered as ‘satisfied’, explained in section 8.2.2.1 and 8.2.2.2.

Ventilation System and Typology of Plan		Frequency	Percent	Valid Percent	Cumulative Percent
Building A: Air Conditioned, Valid Openable Window and Heating in Cellular Plan	Slightly dissatisfied	4	4.2	4.2	4.2
	Neutral	17	17.9	17.9	22.1
	Slightly satisfied	14	14.7	14.7	36.8
	Satisfied	52	54.7	54.7	91.6
	Very satisfied	8	8.4	8.4	100.0
	Total	95	100.0	100.0	
Building B: Air Conditioned Valid & Openable Window in Cellular Plan	Dissatisfied	1	1.3	1.3	1.3
	Slightly dissatisfied	5	6.5	6.5	7.8
	Neutral	13	16.9	16.9	24.7
	Slightly satisfied	8	10.4	10.4	35.1
	Satisfied	38	49.4	49.4	84.4
	Very satisfied	12	15.6	15.6	100.0
Total	77	100.0	100.0		
Building C: Natural Valid Ventilation in Open Plan	Very dissatisfied	2	2.7	2.7	2.7
	Dissatisfied	4	5.5	5.5	8.2
	Slightly dissatisfied	15	20.5	20.5	28.8
	Neutral	17	23.3	23.3	52.1
	Slightly satisfied	11	15.1	15.1	67.1
	Satisfied	20	27.4	27.4	94.5
Very satisfied	4	5.5	5.5	100.0	
Total	73	100.0	100.0		
Building D: Displacement Valid Ventilation in Open Plan	Dissatisfied	2	2.9	2.9	2.9
	Slightly dissatisfied	15	22.1	22.1	25.0
	Neutral	24	35.3	35.3	60.3
	Slightly satisfied	9	13.2	13.2	73.5
	Satisfied	15	22.1	22.1	95.6
	Very satisfied	3	4.4	4.4	100.0
Total	68	100.0	100.0		

Figure 279: SPSS, frequency analysis of satisfaction between the four case study buildings

Based on this analysis, the total percentage of respondents in every building who reported either satisfied or very satisfied is as follows:

- Building A; air conditioned, openable window and heating in a cellular plan office: 63.1% satisfied
- Building B; air conditioned and openable window in a cellular plan office: 64.9% satisfied
- Building C; natural ventilation in an open plan office: 32% satisfied
- Building D; displacement ventilation in an open plan office: 27.5% satisfied

The satisfaction levels of the two open plan offices are close (i.e. 30%), and the satisfaction levels in the two cellular plan offices are also close (i.e. 60%). There is a significant difference between the satisfaction levels in the open and cellular plan offices, approximately 30% difference. The occupants of the cellular plan offices are much more satisfied compared to the occupants of the open plan offices. Figure 280 presents the differences in satisfaction level between the four buildings. The darker lines representing the two cellular plan offices

are almost identical, and the ‘satisfied’ responses are quite exposed. There is a relationship between the lighter lines representing the open plan offices. In both buildings, neutral and slightly dissatisfied lines are more exposed compared to the cellular plan offices. However, in Building D more respondents have voted for neutral, while in Building C more respondents have been ‘slightly dissatisfied’.

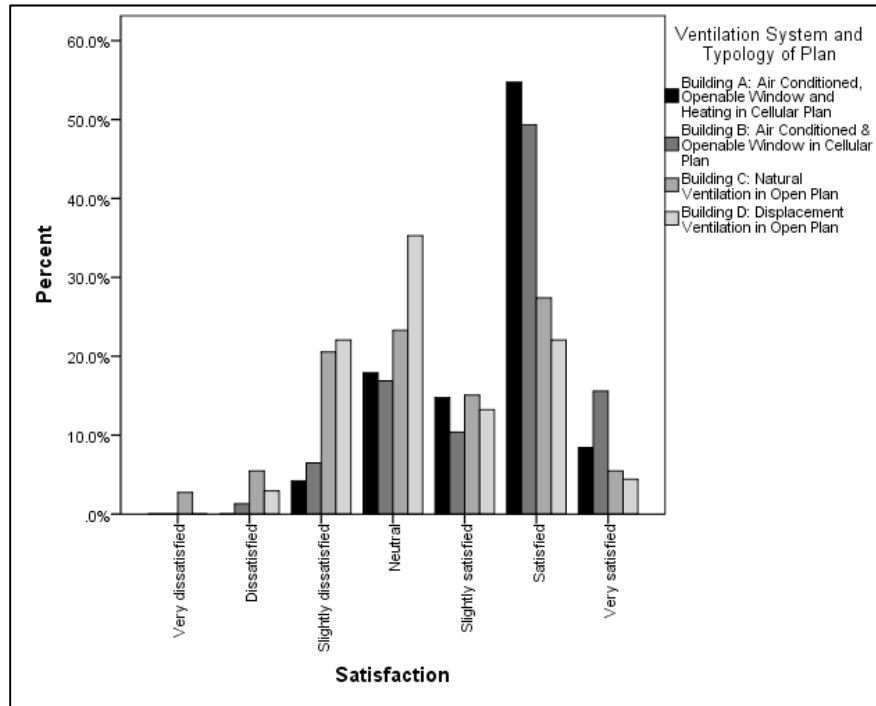


Figure 280: Satisfaction level in the four case study buildings

Overall these results suggest much higher satisfaction levels in the cellular plan compared to the open plan offices (i.e. 30% difference). In addition, during the interviews, occupants of the cellular plan offices reported high levels of satisfaction, particularly in regard to the availability of thermal control in their personal offices. In all four buildings, participants were asked: ‘How do you consider the building overall?’ After respondents explained their satisfaction, over 90% of them immediately mentioned the temperature fluctuation as the most disturbing aspect of their workplace regardless of their satisfaction, open or cellular offices. However, the availability of thermal control in the personal offices increases users’ satisfaction. In the cellular plan office, when occupants are unhappy with the thermal environment, over 70% of them actively apply some sort of control to adjust the temperature, such as to regulate the window, blind, door, or thermostat. On the contrary, when the occupants of the open plan offices find the temperature inconvenient, they have no choice but to tolerate it. They explained: ‘Well, I change layers, but there is nothing more I can do’. A few people reported going out or having a cup of tea when feeling thermally uncomfortable,

which is a passive behaviour and not related to the control opportunity that buildings provide for users.

Furthermore, in response to: ‘Would you like to move into an open plan layout?’, over 90% of the cellular plan respondents disagreed. They preferred personal offices because of individual thermal control and privacy. They explained that individual differences make them appreciate different temperatures. For instance, many of the respondents could not tolerate temperatures that other colleagues find perfectly fine. They mentioned that when they walk into their colleagues’ offices, they find the thermal environment very uncomfortable, such as too warm, cool or ‘stuffy’. In the open plan offices, respondents explained that due to individual differences in perceiving the thermal environment, it is not possible to satisfy all the occupants, who share an office. They complained because of the lack of availability of thermal control. Most of them passively adjusted themselves to the thermal environment by changing layers of clothing. However, they did not find this small adjustment sufficient. They explained that changing layers of clothing does not solve the lack of fresh air, there is a limit to reducing clothing layers and it is difficult to put on gloves while typing to warm up cold hands. Some occupants had gone to the extreme of wearing several clothing layers or a sleeping bag in the office in order to adjust to the temperature, presented in Figure 281 and Figure 282.



Figure 281: Wearing clothing layers and Figure 282: a sleeping bag to warm up in the open plan office

9.2.2. Comfort

Users' comfort level is collected through the ASHRAE seven point scale survey questionnaire, explained in section 3.2.2.1. The SPSS linear regression analysis is applied to examine the relationship between comfort level and high and low levels of thermal control, presented in Appendix K. It shows a significant relationship between comfort and the type of plan, including open and cellular plan offices, since the P value (i.e. 0.000) is less than 0.05. Figure 283 is the SPSS frequency analysis of comfort level in the four buildings. Only comfortable and very comfortable responses are considered as 'comfortable', further explanation is presented in section 8.2.2.1.

Ventilation System and Typology of Plan		Frequency	Percent	Valid Percent	Cumulative Percent
Building A: Air Conditioned, Valid Openable Window and Heating in Cellular Plan	Slightly uncomfortable	3	3.2	3.2	3.2
	Neutral	11	11.6	11.6	14.7
	Slightly comfortable	7	7.4	7.4	22.1
	Comfortable	59	62.1	62.1	84.2
	Very comfortable	15	15.8	15.8	100.0
	Total	95	100.0	100.0	
Building B: Air Conditioned Valid & Openable Window in Cellular Plan	Slightly uncomfortable	3	3.9	3.9	3.9
	Neutral	10	13.0	13.0	16.9
	Slightly comfortable	5	6.5	6.5	23.4
	Comfortable	46	59.7	59.7	83.1
	Very comfortable	13	16.9	16.9	100.0
	Total	77	100.0	100.0	
Building C: Natural Valid Ventilation in Open Plan	Very uncomfortable	1	1.4	1.4	1.4
	Uncomfortable	1	1.4	1.4	2.7
	Slightly uncomfortable	9	12.3	12.3	15.1
	Neutral	12	16.4	16.4	31.5
	Slightly comfortable	8	11.0	11.0	42.5
	Comfortable	36	49.3	49.3	91.8
	Very comfortable	6	8.2	8.2	100.0
	Total	73	100.0	100.0	
Building D: Displacement Valid Ventilation in Open Plan	Uncomfortable	1	1.5	1.5	1.5
	Slightly uncomfortable	6	8.8	8.8	10.3
	Neutral	17	25.0	25.0	35.3
	Slightly comfortable	5	7.4	7.4	42.6
	Comfortable	36	52.9	52.9	95.6
	Very comfortable	3	4.4	4.4	100.0
	Total	68	100.0	100.0	

Figure 283: SPSS, frequency analysis of comfort level between the four case study buildings

Based on this analysis, the comfort level in every building is as follows:

- Building A; air conditioned, openable window and heating in a cellular plan office: 77.9% comfortable
- Building B; air conditioned and openable window in a cellular plan office: 76.6% comfortable
- Building C; natural ventilation in an open plan office: 56.9% comfortable
- Building D; displacement ventilation in an open plan office: 58% comfortable

The percentages of comfort responses in both cellular plan offices are close (i.e. 1.3% difference) and above 75%. The percentages of comfort responses in both open plan offices are also close (i.e. 1.1% difference), which is above 55%. There is a significant difference between the comfort level in the open plan offices and cellular plan offices, approximately 20% difference. The occupants of the cellular plan offices are much more comfortable compared to the occupants of the open plan offices. Figure 284 demonstrates the differences in comfort levels between the four case study buildings.

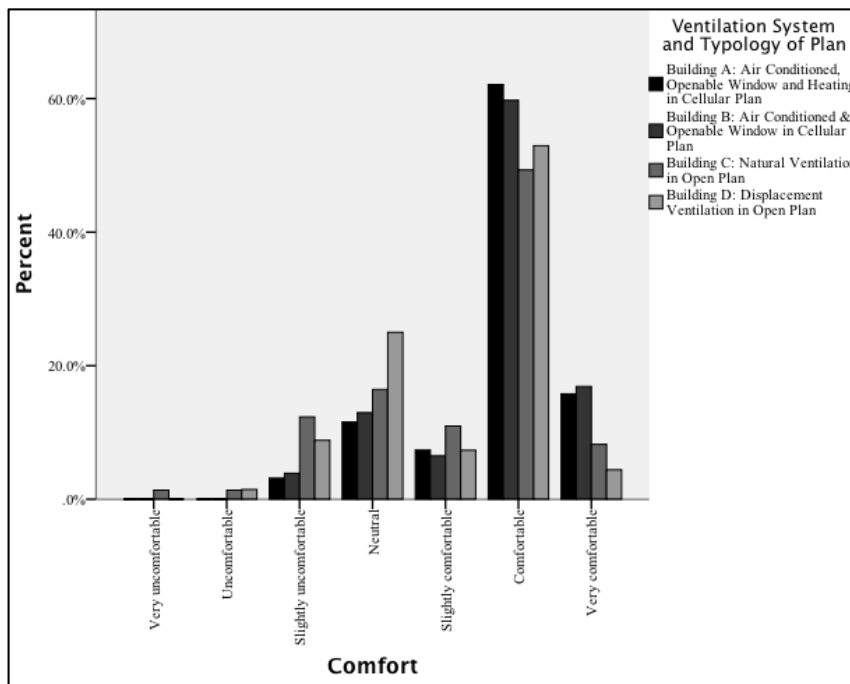


Figure 284: Comfort level in the four case study buildings

Overall, these results suggest that the comfort level is at least 20% higher in the air conditioned cellular plan offices with a high levels of thermal control compared to the naturally and mechanically ventilated open plan offices with limited thermal control.

9.2.3. Health

264 out of 313 respondents completed all of the sick building syndrome questions about dry or watery eyes, blocked or runny nose, dry or irritated throat, chest tightness, headache, and tiredness. In order to eliminate symptoms that were not related to the work environment, participants were asked if they experienced their symptoms during the weekend and whether or not they were related to the work environment. Based on this information as well as respondents who were not sure of a symptom, a few respondents have been eliminated from the test results. This is the main reason for the slight difference in the number of respondents

regarding each question. Quantitative SPSS linear regression analysis is applied to examine the relationship between type of plan and each symptom. The results show a significant relationship between each symptom and the type of plan: open or cellular plan offices. A sample of the analysis is presented in Appendix I. The calculated P values are as follows. Other than the blocked or runny nose symptom, the P values of the other symptoms, as well as the overall evaluation of health, are less than 0.05. This shows a strong relationship between these symptoms and the type of plan.

- Dry or watery eyes: P value is 0.008
- Blocked or runny nose: P value is 0.509, which is over 0.05, which suggests no significant relationship between this symptom and the type of plan.
- Dry or irritated throat: P value is 0.000
- Chest tightness: P value is 0.017
- Headache: P value is 0.000
- Tiredness: P value is 0.000
- Overall health: P value is 0.000

A detailed frequency table of each symptom is presented in Appendix L. The frequency of each symptom is higher in the two open plan offices compared to the cellular plan offices. 105 out of 134 participants (i.e. 78%) of the two cellular plan offices, while 65 out of 130 participants (i.e. 50%) of two the open plan offices never suffer from any symptoms. Almost 80% of the occupants of the cellular plan offices have responded 'never' to all of the symptoms, while fewer participants responded in the same way in the open plan offices. Headache and tiredness are the most common symptoms in the two buildings. The difference between the frequency of these symptoms in the open and cellular plan offices is more visible.

- 130 out of 145 participants (i.e. 90%) of the two cellular plan offices, while 63 out of 130 participants (i.e. 48%) of two the open plan offices never suffer from headaches
- No participant (i.e. 0%) of the two cellular plan offices, while 9 out of 130 participants (i.e. 7%) of the two open plan offices constantly suffer from headaches
- 88 out of 139 participants (i.e. 63%) of the two cellular plan offices and 37 out of 129 participants (i.e. 29%) of the two open plan offices never suffer from headaches
- No participant (i.e. 0%) of the two cellular plan offices and 8 out of 129 participants (i.e. 6%) of the two open plan offices constantly suffer from headaches

The results suggest that participants of the open plan offices suffer more from headaches and tiredness compared to the cellular plan respondents. The following bar charts show a detailed comparison of each symptom between the four case study buildings.

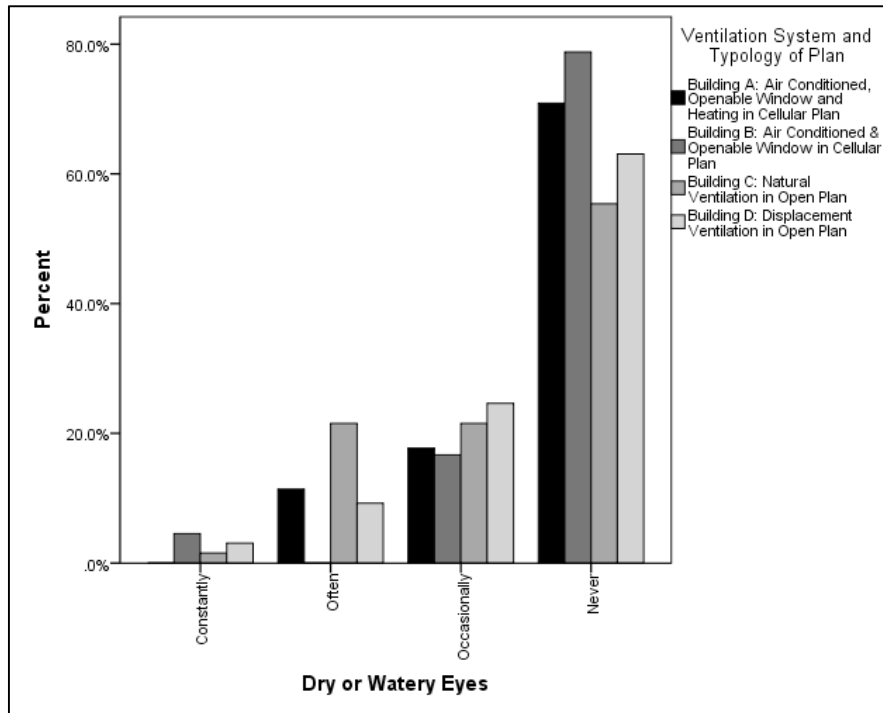


Figure 285: Comparison of dry or watery eyes symptom across the four case study buildings

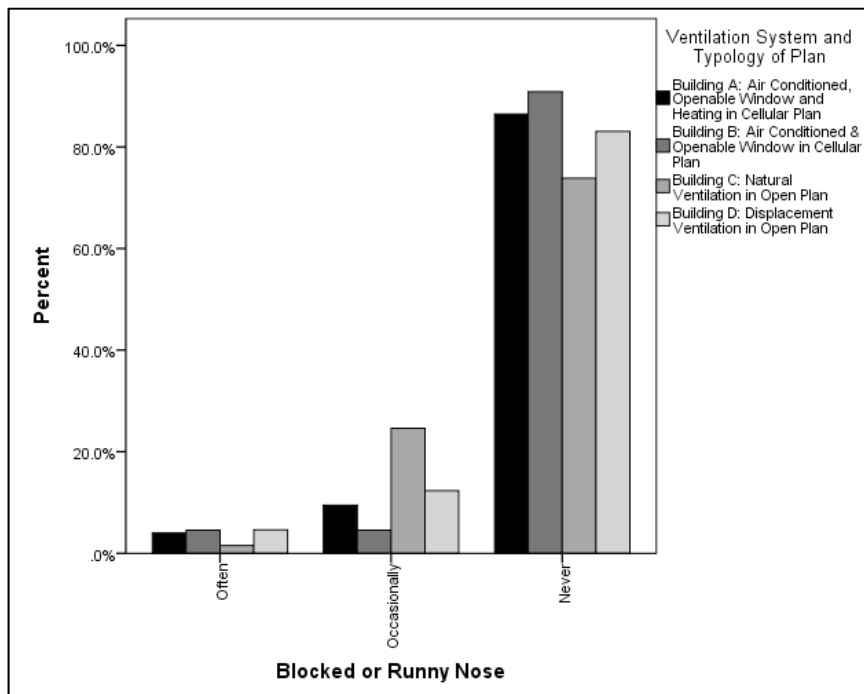


Figure 286: Comparison of blocked or runny nose symptom across the four case study buildings

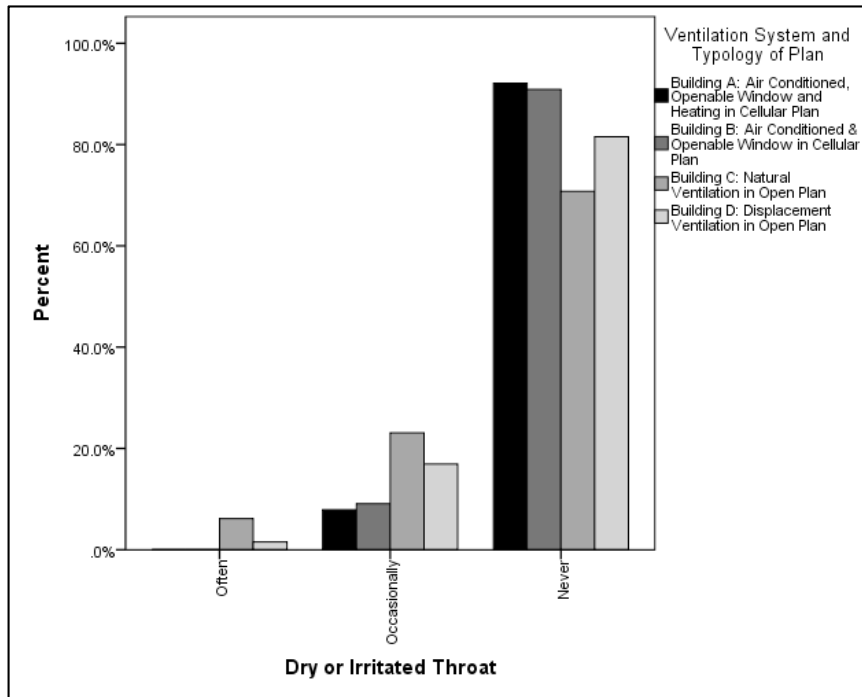


Figure 287: Comparison of dry or irritated throat symptom across the four case study buildings

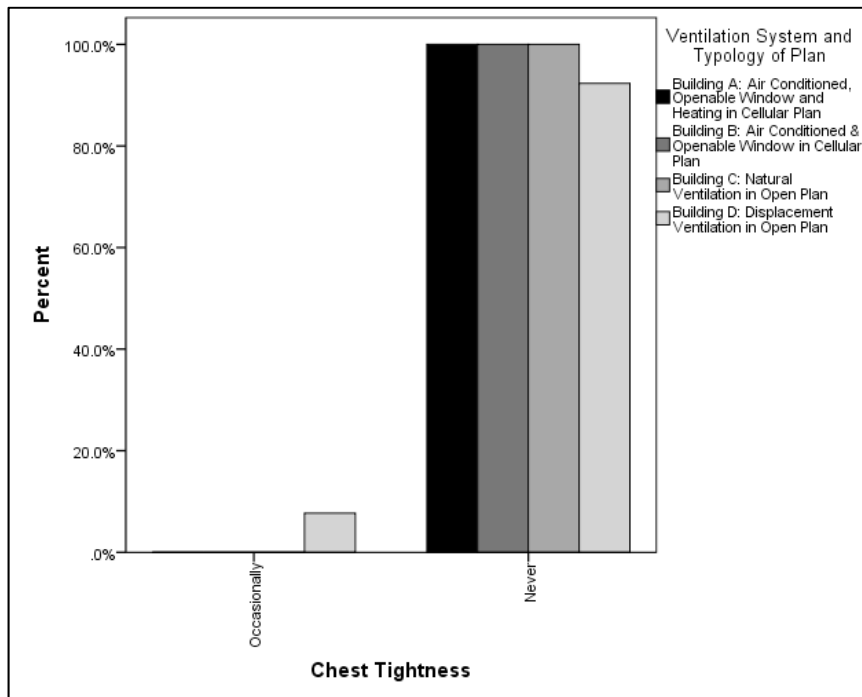


Figure 288: Comparison of chest tightness symptom across the four case study buildings

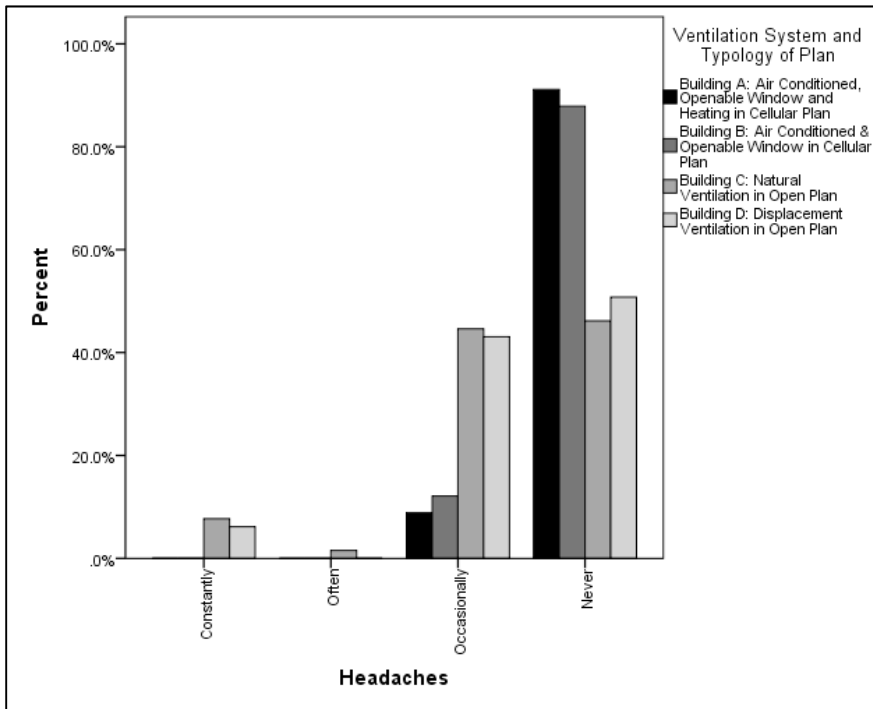


Figure 289: Comparison of headaches symptom across the four case study buildings

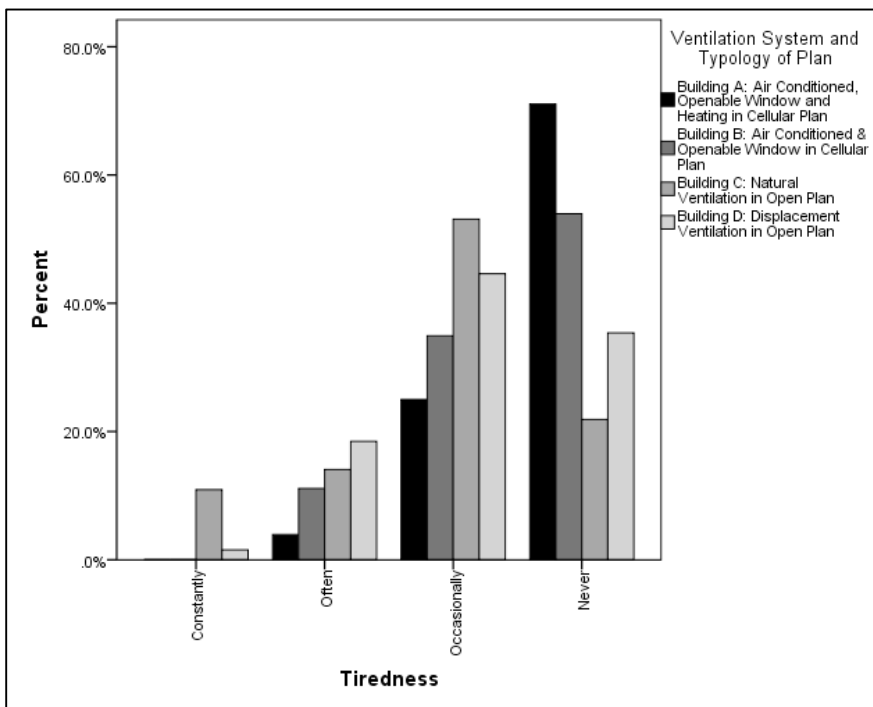


Figure 290: Comparison of tiredness symptom across the four case study buildings

The overall analysis of sick building syndrome shows that the occupants of the two cellular plan offices with high levels of thermal control suffer much less from the symptoms compared to the occupants of the two open plan offices with limited levels of thermal control. During the interviews, an occupant of Building B identified the out of order air conditioning in her room as the result of her headache and tiredness. The air conditioning in her room had

stopped working for two weeks, and she complained that her room had been too hot causing her headache and tiredness. Several occupants of the open plan offices mentioned that because of their symptoms sometimes they stay and work at home. However, when their presence in the office is necessary they have to tolerate suffering because they are not provided with other options or thermal control to regulate the thermal condition. They identified the temperature, humidity, air movement, and air quality in the open plan office as the main reason for their symptoms.

9.2.4. Perceived Productivity

Participants' productivity level is recorded through a survey questionnaire based on McCartney's transverse questionnaire (McCartney and Nicol, 2002). In this method, respondents compare their immediate productivity level to their normal productivity status. This is a seven point scale survey, where -3 is much lower, 0 is the same and +3 is much higher than normal productivity level. The SPSS linear regression analysis is applied to examine the relationship between productivity and low and high levels of thermal control, presented in Appendix M. Although the P value (i.e. 0.045) shows a significant relationship between productivity and type of plan, the extent of this association is not significant. The following table presents the SPSS frequency analysis of productivity in the four case study buildings. It indicates that majority of the respondents have 'the same' perceived productivity level at the time of the survey.

Ventilation System and Typology of Plan		Frequency	Percent	Valid Percent	Cumulative Percent
Building A: Air Conditioned, Valid Openable Window and Heating in Cellular Plan	Slightly lower	8	8.4	8.4	8.4
	The same	76	80.0	80.0	88.4
	Slightly higher	10	10.5	10.5	98.9
	Higher	1	1.1	1.1	100.0
	Total	95	100.0	100.0	
Building B: Air Conditioned & Valid Openable Window in Cellular Plan	Lower	2	2.6	2.6	2.6
	Slightly lower	11	14.3	14.3	16.9
	The same	46	59.7	59.7	76.6
	Slightly higher	17	22.1	22.1	98.7
	Higher	1	1.3	1.3	100.0
Building C: Natural Ventilation Valid in Open Plan	Much lower	1	1.4	1.4	1.4
	Lower	1	1.4	1.4	2.7
	Slightly lower	14	19.2	19.2	21.9
	The same	51	69.9	69.9	91.8
	Slightly higher	5	6.8	6.8	98.6
	Much higher	1	1.4	1.4	100.0
Building D: Displacement Valid Ventilation in Open Plan	Slightly lower	9	13.2	13.2	13.2
	The same	49	72.1	72.1	85.3
	Slightly higher	9	13.2	13.2	98.5
	Higher	1	1.5	1.5	100.0
	Total	68	100.0	100.0	

Figure 291: SPSS, frequency analysis of perceived productivity level compared to the normal state

Based on this analysis, the percentage of respondents with ‘the same’ or higher productivity levels in every building is calculated as follows:

- Building A: 95% respondents have the same or higher perceived productivity level, and 12% have higher rate than normal
- Building B: 83% respondents have the same or higher perceived productivity level, and 25% have higher rate than normal
- Building C: 78% respondents have the same or higher perceived productivity level, and 7% have higher rate than normal
- Building D: 87% respondents have the same or higher perceived productivity level, and 14% have higher rate than normal

The results are similar while the personal offices of Building A have the highest normal and higher perceived productivity level. The perceived productivity level of Building B falls between the two open plan offices. However, 25% of the respondents in Building B have a higher perceived productivity level than their normal status, which is much more than the other buildings. This comparison can be seen more clearly in Figure 292.

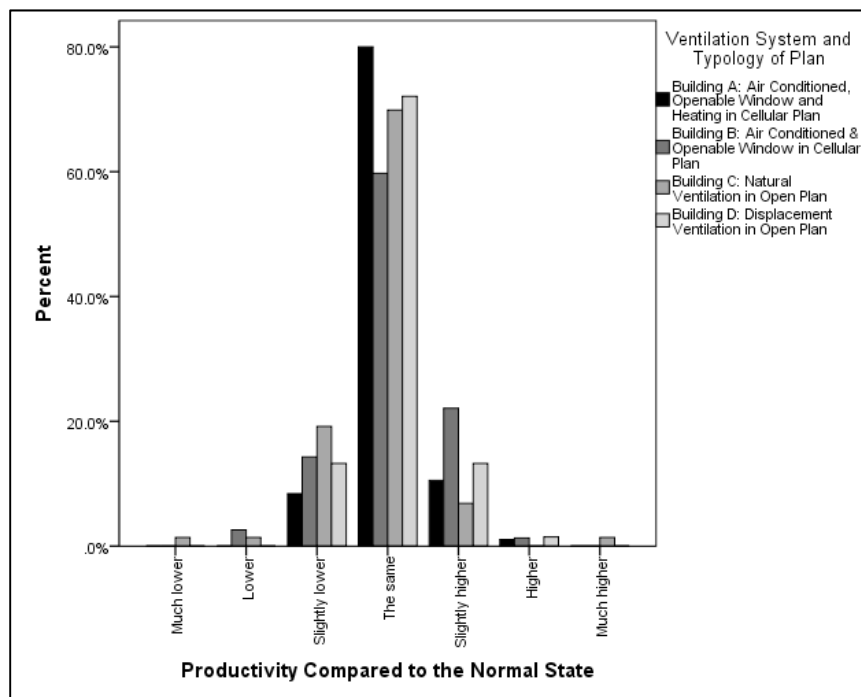


Figure 292: Perceived productivity level in the four case study buildings

Overall 88% of the cellular plan respondents have the same or higher perceived productivity level, while there are 82% in the open plan offices. 17% of the respondents of the personal offices have higher than normal productivity levels, while there are 11% in the open plan

offices. The overall productivity level is higher in the cellular plan offices compared to the open plan offices, although the difference is not so significant. In addition, the SPSS linear regression analysis shows a significant relationship between productivity and type of plan. However, the extent of this association is not significant (i.e. 1.3%). Moreover, there is an inconsistency in the detailed comparison between the four case study buildings as Building B has a lower productivity level compared to Building D. Therefore it is difficult to draw conclusions about the productivity level and further research is recommended. Furthermore, at the time of the survey many participants did not quite understand the question regarding the productivity status and an explanation was required for the 'normal productivity level'. Many respondents found this question difficult to answer. Therefore, further research and other methods are recommended to record and analyse occupants' productivity level. For instance, Kroner's method to monitor users' productivity level before and after moving to the building may be useful (Kroner, 2006), explained in section 3.3.2.4. In this method no questionnaire is required and the productivity level is simply measured based on users' efficiency and productivity regarding the actual workload. Oseland presents other methods like a sophisticated survey and control groups to measure the productivity level (Oseland, 2004), presented in section 5.2.2.4.3. However, none of these methods are applicable to this research, since only a post occupancy survey was possible rather than a pre-occupancy survey. In addition, the company management of the buildings rejected the use of a sophisticated survey, as explained in section 6.1.4.

9.2.5. Satisfaction, Comfort, Health and Productivity: Open vs. Cellular Practices

Overall, the results suggest higher levels of user satisfaction, comfort and health in the cellular plan offices with high levels of thermal control compared to the open plan offices with limited thermal control. Intensive interviews reveal a strong connection between the availability of thermal control and the variables, satisfaction, comfort and health. Although results show that productivity level is slightly higher in the personal offices, it is difficult to draw a conclusion due to the complexities of measuring productivity in this study. Further research is recommended to investigate productivity level in the workplace by applying other methods.

Overall, based on the SPSS linear regression analysis there is a significant relationship between satisfaction and type of plan: open and cellular offices. The satisfaction level is higher (i.e. 30% difference) in the cellular plan offices compared to the open plan offices. The in depth interviews confirm users' satisfaction with the thermal control in the cellular plan

offices. They do not want to share an office because they prefer to adjust the thermal environment in their personal rooms according to their needs. On the contrary, occupants of the open plan offices complained about the lack of thermal control and the universal 'comfort zone'. They explained that no particular temperature satisfies them all. For this reason they preferred not to control the temperature of the office, since they did not like the responsibility of satisfying everyone, considering it impossible. In addition, the results suggest a strong relationship between comfort and type of plan. The frequency analysis shows higher levels of comfort in the personal offices (i.e. at least 20% difference) compared to the open plan workplaces. Furthermore, the analysis of sick building syndrome shows fewer symptoms amongst the occupants of the cellular plan offices compared to the open plan offices, suggesting higher levels of health in the personal offices. Occupants of the open plan offices identified lack of control over the temperature, humidity, air movement, and air quality in their office as the main cause for their symptoms, with an emphasis on the temperature.

The productivity level is overall higher in the cellular plan offices compared to the open plan offices, although the difference is not so significant, 88% compared to 82%. The SPSS linear regression analysis shows a significant relationship between productivity and type of plan, but the extent of this association is not significant (i.e. 1.3%). There is an inconsistency in the detailed comparison between the four case study buildings. Furthermore, respondents did not fully comprehend the productivity question and the 'normal productivity state' at the time of survey. As explained, it is difficult to draw conclusions on the productivity level and further research is recommended using other methods, further explained in section 10.3.

9.3. Summary

This chapter investigated the application of ‘individual thermal control’ in the workplace and its influence on users’ satisfaction, comfort, health, and productivity. The results indicate that when participants’ desire to adjust the thermal environment increases, their satisfaction and comfort decreases. This suggests that occupants with a thermal control intention are more likely to be dissatisfied and uncomfortable. In addition, the results indicate that occupants of the two Norwegian cellular plan offices with high levels of individual thermal control are more comfortable, satisfied and healthy compared to the occupants of the two British open plan offices with limited thermal control. The high quality of the indoor environment of all four buildings as well as the interview results suggest that availability of individual thermal control is the main reason for this difference between the Norwegian and British contexts. This suggests that occupants, who are provided with individual thermal control, are more likely to be satisfied, comfortable and healthy. These results are further discussed in the next chapter, which is the discussion chapter.

CHAPTER 10

DISCUSSION

10. Discussion

This chapter presents the main discussion of the application of ‘individual thermal control’ in the context of the Norwegian and British workplaces. The discussion of the results and findings from the previous chapter is followed by that of the qualitative approach to analyse the data in regard to the context and meaning, rather than the traditional quantitative approach in the field of thermal comfort. The qualitative method is the basis of the analysis and findings in this research. Finally, the research limits are presented.

10.1. Individual Thermal Control in the Workplace

In this thesis, the research question is ‘does thermal control improve user satisfaction in cellular and open plan offices? Norwegian vs. British practices’. This is based on the challenge in the field of thermal comfort between the steady state and adaptive comfort theories, expressed respectively as the ‘comfort zone’ and ‘thermal control’. This research challenges the concept of the standard ‘comfort zone’ and explores the application of ‘individual thermal control’ in the context of the Norwegian and British workplace practices with respectively high and low levels of individual thermal control. The results indicated that the current widely used standard comfort zone and its basis, ‘neutral thermal sensation’, do not apply to the case study buildings in this research, as explained in Chapter Eight. In addition, most respondents preferred a variety of thermal settings throughout the day. This is in further contrast with the concept of the ‘comfort zone’ that aims at providing a steady thermal condition constantly for everyone. Furthermore, respondents with an intention to adjust the thermal environment were more dissatisfied and uncomfortable, which is in line with the active role of the user. Finally, the main finding in the research indicated that occupants of the Norwegian cellular plan offices with high levels of thermal control were more satisfied, comfortable and healthy compared to the occupants of the British open plan offices with limited thermal control. This suggests that workplace environments that provide occupants with the opportunity of ‘individual thermal control’ are more likely to improve their satisfaction, comfort and health.

In this research, two Norwegian cellular plan offices with high levels of thermal control were compared with two British open plan offices with limited thermal control. In the Norwegian offices, every occupant has access to an openable window, blinds, light switches, door, and a thermostat. However, in the British offices only occupants sitting at the perimeter of the building are provided with limited openable windows and blinds. Occupants, who sit closer to the centre and away from the windows, are not provided with any opportunity to adjust their thermal environment.

10.1.1. Findings

The view of ‘comfort zone’ was challenged by examining the following:

- The accuracy of the ASHRAE predictions of comfort zone, as the most widely used standard to predict thermal comfort conditions
- The application of the ‘neutral thermal sensation’ to indicate comfort, as the basis of thermal comfort studies and standards

- The consistency of overall thermal preference of every individual occupant throughout the day

The application of ‘individual thermal control’ was investigated through the following:

- Examining the impact of thermal intention of the user on their satisfaction and comfort
- Examining satisfaction, comfort and health in comparison between two office layouts, the Norwegian cellular plan with high and the British open plan with low levels of thermal control

10.1.1.1. Comfort Zone

10.1.1.1.1. The ASHRAE Comfort Predictions

This research examined the accuracy of the most widely used standard comfort zone, which is the ASHRAE Standard 55-2010 in a summer day in four case study buildings in two contexts. Based on the environmental measurements, the thermal condition of every workstation was predicted using the ASHRAE Thermal Comfort Tool, explained in section 7.2.3. This tool predicts comfort conditions based on PMV and adaptive models and according to the ASHRAE Standard 55-2010. These predictions were compared to the occupants’ survey questionnaires at the time of the measurements. Quantitative and qualitative analysis were applied. The SPSS regression analysis showed a significant relationship between thermal sensation and both PMV and adaptive comfort prediction models, as presented in sections 8.1.1.1.1 and 8.1.2.1.1. However, it indicated that the ASHRAE PMV model could explain only 5%, and the adaptive model only 2.2% of the thermal sensation responses. In addition, the SPSS regression analysis showed no significant relationship between either of the prediction models and occupants’ actual satisfaction and comfort responses.

In the qualitative analysis, the combination of thermal sensation and thermal intention was considered to be the occupant’s thermal comfort response, explained in section 10.1.1.1.2. The results of the qualitative analysis using the visual recording technique indicate that there is:

- No consistency between the ASHRAE PMV prediction model and occupants’ thermal sensation response (i.e. 75%)

- No consistency between the ASHRAE PMV prediction model and occupants' overall thermal preference (i.e. 84%)
- No consistency between the ASHRAE adaptive prediction model and occupants' thermal sensation response (i.e. 63%)
- No consistency between the ASHRAE PMV and adaptive prediction models in predicting comfort status (i.e. 88%)

The results showed that the predicted comfort conditions of the most widely used standard, the ASHRAE Standard 55-2010, does not apply to the case study buildings in the Norwegian and British contexts in this research. This suggests that current worldwide standard comfort zones are less likely to be accurate. This confirms the findings of other researchers, who report inaccuracy in the comfort standards (Humphreys and Nicol, 2002b, Baker and Standeven, 1997, de Dear and Brager, 1998, de Dear and Brager, 2001, Schellen et al., 2013). For instance, Baker reports the inconsistency between international standards and user satisfaction in the real context of offices (Baker and Standeven, 1995), explained in section 3.2.2.1.

10.1.1.1.2. Neutral Thermal Sensation

This research examined the association of the 'neutral thermal sensation' and comfort status of the occupants with regard to the thermal environment. The 'neutral thermal sensation' is the basis of the ASHRAE thermal comfort standard (ASHRAE, 2009, ASHRAE, 2010) and thermal comfort studies (van Marken Lichtenbelt and Kingma, 2013, Schellen et al., 2013, Indraganti et al., 2013, Leyten et al., 2013). Simultaneous thermal measurements and survey questionnaires were applied. The former evaluated the building performance and the quality of the indoor environment at the time of the survey. The analysis showed that the temperature (i.e. optimum temperature between 20°C to 26 °C) and humidity (i.e. between 10 to 70 RH) are within the acceptable range in all four case study buildings, presented in section 7.2.2. In addition, the ASHRAE adaptive model predicted a comfortable status for over 90% of the workstations, presented in section 7.2.3.2. This suggested high levels of neutral thermal sensation that indicate good qualities of indoor thermal environment in the four case studies. Here the question is not whether the building was hot or cold, as the empiric building performance showed that all four buildings provided good qualities of thermal environment. Rather, the question is 'Do participants want to feel neutral?'

The survey questionnaire included questions regarding thermal sensation and intention indicating occupants' immediate feeling about the thermal environment and their desire to

adjust the temperature. In addition, the questionnaire included user satisfaction and comfort. The thermal sensation responses of the occupants were compared against their satisfaction, comfort and thermal intention responses. Quantitative and qualitative analysis were applied to analyse the results. The quantitative analysis using SPSS regression analysis showed a strong relationship between thermal sensation and variables, satisfaction, comfort and thermal intention, as presented in section 8.2.1. 16.9% of the satisfaction responses, 13.2% of the comfort responses, and 46.4% of the thermal intention responses can be explained by the occupant's thermal sensation status.

The qualitative analysis using the visual recording technique indicates:

- 45% of the comfortable respondents did not feel neutral
- 20% of the respondents with a neutral thermal sensation did not feel comfortable
- 38% of the satisfied respondents did not feel neutral
- 36% of the respondents with a neutral thermal sensation did not feel satisfied
- 18% of the respondents with a neutral thermal sensation preferred a change in the temperature
- 28% of the respondents, who wanted no change in the temperature, did not feel neutral
- 35% of the occupants preferred thermal sensations other than neutral

Many occupants, who felt neutral, were uncomfortable, dissatisfied or wanted a change in temperature. On the contrary, many respondents, who felt comfortable and satisfied, did not feel neutral. These results show that the 'neutral thermal sensation' does not indicate user comfort and satisfaction in the case study buildings in this study. In addition, occupants (i.e. 35%) are likely to prefer thermal sensations other than neutral. These results suggest that the 'neutral thermal sensation' is less likely to indicate thermal comfort. This confirms Humphreys' finding that in '57% of occasions the desired sensation was other than "neutral"' (Humphreys and Nancock, 2007). He indicates that 'there were significant differences among the respondents in the thermal sensations they desired, confirming that some characteristically preferred to feel warmer than others' (Humphreys and Nancock, 2007). De Dear also questions the notion of 'neutral thermal sensation' in the PMV model (de Dear, 2011).

Although Humphreys published these results in 2007, the 'neutral thermal sensation' is still the basis of the standard 'comfort zone' (ASHRAE Standard 55-2010). Although recently some researchers have considered sensations other than neutral in their research (Rijal et al., 2009, Arens et al., 2010, Humphreys et al., 2011, de Dear, 2011, Bos and Love, 2013), still

the majority of research on thermal comfort is based on the ‘neutral thermal sensation’ (Liu et al., 2012, Cigler et al., 2012, van Marken Lichtenbelt and Kingma, 2013, Schellen et al., 2013, Indraganti et al., 2013, Leyten et al., 2013). Zhang states that ‘the comfort literature tends to focus on neutral and optimal temperatures’ (Zhang et al., 2011). The new thermal comfort scale includes ‘much too cool, too cool, comfortably cool, neutral, comfortably warm, too warm and much too warm’ (Nicol and Humphreys, 2009b). However, this new scale does not include a combination of too cool and comfortable, or too warm and comfortable. The results of this thesis show that some respondents preferred extreme thermal conditions, such as cold or hot.

10.1.1.1.3. Consistency in Thermal Preference

This research investigated the consistency of individual thermal preference throughout the day. Every participant responded to a survey questionnaire three times a day, morning, early and late afternoon. The combination of two of these questions about thermal sensation and thermal intention indicated the overall thermal preference of a particular individual at a particular time. Thermal preferences of every individual during the day were compared in order to examine their consistency applying qualitative visual recording analysis. The results indicate:

- Inconsistency in the individual’s thermal preferences throughout the day (i.e. 55%)
- Extreme cases of inconsistency in the individual’s thermal preferences throughout the day (i.e. 13%)
- 86% of the respondents wanted to feel neutral at least at one point in the day, however 60% of them preferred to have a thermal sensation other than neutral at another time in the day.
- 14% of the respondents did not want to feel neutral at any time in the day
- 65% of the respondents did not want to feel neutral at least at some point in the day

The results indicate that over half of the respondents in this research did not have a steady thermal preference during the day, as their thermal preference changed at different times. In some cases, there was an extreme change in individual’s thermal preferences, such as from cold in the morning to warm in the late afternoon.

In addition, over half of the respondents, who felt neutral at least once, experienced a different preference at another time in the day. This suggests that if the survey questionnaire was applied only once and their preference at that particular time was ‘neutral’ (i.e. 86%

chance), there would be a risk of misjudgement in concluding that ‘people want to feel neutral’. On the contrary, this research shows that there is a 60% chance that the particular individual has a thermal preference other than neutral at a different time in the day. The results suggest that even if the thermal preference of an individual is neutral, there is a good chance that it will change. Overall, the results indicate that the thermal preference of the occupants is subject to change. This finding is in contrast with the aim of the steady state theory, which is to provide a steady thermal condition at all times for everyone.

10.1.1.2. Individual Thermal Control

10.1.1.2.1. Thermal Intention

This research examined the impact of users’ thermal intention on their satisfaction and comfort. The results of the survey questionnaire were analysed using quantitative and qualitative analysis, as presented in section 9.1. The quantitative analysis showed a significant relationship between thermal intention and the two variables. 27.7% of variance in satisfaction and 18.9% in comfort can be explained by users’ intention to change the thermal environment. In addition, the qualitative analysis indicates:

Satisfaction:

- 89% of the satisfied respondents wanted either no change or a slight adjustment in the temperature, air quality or air movement
- 100% of the dissatisfied participants wanted to adjust the temperature or ventilation
- 85% of the dissatisfied respondents wanted more than a slight change in the temperature, air quality or air movement

Comfort:

- 77% of the comfortable respondents wanted either no change or a slight adjustment in the temperature, air quality or air movement
- 100% of the uncomfortable participants wanted to adjust the temperature, air quality or air movement
- 73% of the uncomfortable respondents wanted more than a slight change in the temperature, air quality or air movement

The results indicate that users’ desire to adjust the thermal environment, including temperature, air quality and air movement, has a great impact on their satisfaction and comfort. The results suggest that occupants with an intention to adjust the thermal

environment are more likely to be dissatisfied and uncomfortable. This confirms the adaptive principle that when people are uncomfortable, they actively apply change (Nicol and Humphreys, 1973b, Nicol et al., 2012). However, the results are in contrast with the passive role of the user, which is considered in the steady state theory. Occupants' decision to change the thermal environment and their active role in applying this change is overlooked in the steady state theory (Nicol et al., 2012). In addition, the standard 'comfort zone' is simply based on the 'neutral thermal sensation' (ASHRAE, 2010). Occupants' desire to adjust the thermal environment is not considered in the comfort standards. This is likely to lead to a misjudgement when indicating occupants' comfort status, as explained in section 10.1.1.1.2.

10.1.1.2.2. Individual Thermal Control

The Norwegian cellular and British open plan practices were compared regarding user satisfaction, comfort and health using the survey questionnaires. Quantitative analysis using SPSS frequency analysis was applied to the information with the following results:

Satisfaction:

- Approximately 60% in the two Norwegian cellular plan offices
- Approximately 30% in the two British open plan offices
- As a result, satisfaction level in the two Norwegian cellular plan offices is approximately 30% higher than the two British open plan offices

Comfort:

- Approximately 75% in the two Norwegian cellular plan offices
- Approximately 55% in the two British open plan offices
- As a result, comfort level in the two Norwegian cellular plan offices is approximately 20% higher than the two British open plan offices

Health:

- Number of respondents never suffering from headaches is larger in the Norwegian buildings (i.e. Building A: 75% and Building B: 75%) compared to the British buildings (i.e. Building C: 40% and Building D: 49%)
- Number of respondents never suffering from tiredness is larger in the Norwegian buildings (i.e. Building A: 56% and Building B: 44%) compared to the British buildings (i.e. Building C: 18% and Building D: 34%)

The results indicate that occupants of the two Norwegian cellular plan offices with high levels of individual thermal control are more comfortable, satisfied and healthy compared to the occupants of the two British open plan offices with limited thermal control. This suggests that occupants, who are provided with individual control over the thermal environment, are more likely to be satisfied, comfortable and healthy. The results confirm the relationship between thermal control and user satisfaction (Leaman and Bordass, 2005, Lee and Brand, 2005, Wagner et al., 2007, Brager and Baker, 2009, Newsham et al., 2009), comfort (Bordass et al., 1993, Bordass et al., 1994) and health (Marmot, 2010, Rayner, 1997, Rollins and Swift, 1997).

10.1.2. Discussion: Comfort Zone vs. Individual Thermal Control

The previous discussion feeds into the challenge of the concept of ‘comfort zone’ and the application of ‘individual thermal control’.

10.1.2.1. The Steady State Theory and Comfort Zone

The steady state theory emerged after the invention of the refrigerator. Engineers managed to find an ‘optimum temperature’ to keep meat and food fresh for longer periods in the refrigerator. Their success led them to apply the same principle (i.e. optimum temperature) to office buildings, where people work (Nicol et al., 2012). They overlooked the decision-making and active role of the user. Through experimental research they managed to find the ‘comfort zone’ that minimises the heat exchange between the human body and the thermal environment (Bluyssen, 2009). Although it is useful to experiment in the controlled environment of the laboratory with limited variables, useful information associated with context and non-physical factors, can be overlooked (Nicol et al., 2012).

The aim of experimental research is to provide a steady thermal condition that satisfies over 80% of the occupants. Their main finding is the universal ‘comfort zone’. This is applied in workplace practices to regulate the thermal environment through building facilities and centrally controlled thermal systems. The universal ‘comfort zone’ is applied in the British open plan offices to provide a uniform thermal environment for all the occupants. In this research, the thermal environment of the case study buildings is regulated according to the ASHRAE comfort zone. So over 80% of the occupants are expected to be thermally comfortable. However, the results of the survey questionnaire did not match the ASHRAE’s predicted comfort, explained in section 10.1.1.1.1. This finding in addition to other researchers’ findings stating that comfort standards do not apply to real world situations (Baker and Standeven, 1997, de Dear and Brager, 1998, de Dear and Brager, 2001, Schellen et al., 2013) suggest that current worldwide comfort standards are less likely to be accurate.

In addition, the interviews indicate the importance of individual differences in perceiving the thermal environment. The majority of respondents acknowledged that no particular temperature would satisfy all, discussed in section 9.2.1. This is in line with the findings of other researchers stating that no fixed temperatures are universally accepted (Baker and Standeven, 1997, Humphreys, 1972, Nicol et al., 1995, Humphreys, 1996), discussed in section 3.2.2.1.

In the view of 'comfort zone', thermal comfort is considered as a 'product' (Fanger, 1970). This final polished product is presented to the occupant, who is expected to receive it passively without interfering with the process. In this view, the users' ability to adjust the thermal environment is replaced by a pre-set thermal setting according to the standard 'comfort zone'. The occupants' active role is overlooked, such as the ability and desire to think, make decisions and actively apply change. However, one of the findings in this thesis shows that when users feel uncomfortable, they are more likely to desire to adjust the thermal environment, explained in section 10.1.1.2.1. This confirms the active role of the user (Ackerly and Brager, 2013), which is the basis of the adaptive comfort theory stating: 'If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort' (Nicol and Humphreys, 1973b, Nicol et al., 2012). Black reports that when occupants are actively involved with decision makings, their satisfaction level increases (Black, 2006).

10.1.2.2. Contradiction: Definition vs. Application

Meir suggests that the ASHRAE Standard 55, 2004 has a contradiction in specifying the comfort zone and defining thermal comfort (Meir et al., 2009). On the one hand, a standard comfort zone that satisfies 80% of people is demonstrated with clear boundaries, on the other hand it defines comfort as 'the state of mind that expresses satisfaction with the surrounding environment' (ASHRAE, 2004). Based on this definition, Meir states that 'things may not be so clear cut' (Meir et al., 2009). The ASHRAE (ASHRAE, 2009) does not specify the meaning of 'condition of mind' and 'satisfaction' and leaves this open (ASHRAE, 2004). Nicol explains that although the ASHRAE relates comfort to the state of mind in its definition, this is not considered in estimating comfort (Nicol et al., 2012). One of the findings in this thesis confirms this contradiction, as it suggests that occupants' intention to adjust the thermal environment has a great influence on their satisfaction and comfort, presented in section 10.1.1.2.1.

10.1.2.3. The 'Neutral Thermal Sensation'

Another finding questions the basis of thermal comfort standards. The ASHRAE standard 'comfort zone' is based on the 'neutral thermal sensation' (ASHRAE, 2004, ASHRAE, 2009). As Hawkes states, when the user is neither cold nor warm, they are thermally comfortable (Hawkes, 2002). The results of this thesis reveal that the 'neutral thermal sensation' does not indicate user comfort with regard to the thermal environment. Over half of the participants preferred thermal sensations other than neutral in order to feel comfortable,

explained in section 10.1.1.1.2. This outcome confirms Humphreys' finding stating that 'on 57% of occasions the desired sensation was other than neutral' (Humphreys and Nancock, 2007). Humphreys suggests that the thermal comfort status should be based on a combination of the thermal sensation and thermal intention (Humphreys and Nancock, 2007). This may suggest further research in order to improve the accuracy of the standard comfort zone. As in the past, when similar results were achieved indicating that the previous ASHRAE comfort zone was not accurate (Baker and Standeven, 1997, de Dear and Brager, 1998, de Dear and Brager, 2001), further research was carried out in order to refine the ASHRAE comfort zone and increase its accuracy (Humphreys and Nicol, 2002a, McCartney and Nicol, 2002).

10.1.2.4. Fixed vs. Dynamic

The results of this research demonstrated the inconsistency in thermal preference of individuals throughout the day, explained in section 10.1.1.1.3. The results propose that the thermal preference of a particular individual is subject to change. 55% of the respondents did not have a steady thermal preference during the day, preferring different thermal settings at different times. This suggests that a steady state thermal setting with a fixed temperature is less likely to satisfy an individual occupant all the time. Therefore when a particular thermal setting from the standard comfort zone is applied to the office constantly, there is no guarantee that every individual occupant is going to be comfortable constantly. This poses a difficulty to the concept of comfort zone, as it suggests that the thermal preference of every individual is dynamic rather than fixed. This finding is in contrast with the view of a steady state thermal setting that satisfies over 80% of the occupants constantly. It suggests that no matter how much the standard comfort zone is refined, it is less likely to be applied in real world situations because thermal comfort is dynamic and a fixed temperatures is less likely to provide thermal comfort.

10.1.2.5. Adaptive Opportunity

The standard 'comfort zone' is mainly introduced and used by steady state researchers although adaptive comfort researchers have also contributed to the field, such as naturally ventilated buildings in the ASHRAE Standard 55-2010 (de Dear and Brager, 1998). As explained, the view of 'comfort zone' is in contrast with adaptive principle, as the latter is based on the active role of the user. The solution that adaptive comfort researchers presented was the 'adaptive opportunity' for occupants to adjust their thermal environment according to their requirements. Adaptive opportunity is mainly 'an attribute of the building' (Baker and Standeven, 1995). 'An environment with high adaptive opportunity is likely to prove more

comfortable than one with low opportunity, because people will take advantage of the actual and potential variations in room temperature' (Humphreys, 1996, Baker and Standeven, 1995), and occupants are given more choices.

The difference between these two views is that the 'comfort zone' presents comfort to occupants as a product and occupants are expected to receive it with satisfaction and no intention of changing it. In contrast, the 'adaptive opportunity' allows occupants to find their own comfort, as thermal comfort is achieved through a process of adjustment, in which users are actively involved.

10.1.2.6. Adaptive Opportunity in the British Context

In the British context, the design of offices is based on organisational goals rather than users' satisfaction and the vague regulations do not support workers' rights, as explained in section 4.2.2.2. According to the British workplace regulations, sufficient temperature, ventilation and light should be provided for occupants (HSE, 1992), as explained in section 4.2.2.2. This regulation is vague and it does not specify which conditions are considered to be 'sufficient'. Furthermore, thermal control is not mentioned in the regulations, as it is not considered necessary to provide every occupant with the ability to adjust the thermal environment. This is reflected in the design of the office layout, which is the open plan office. The main approach to provide thermal comfort in the open plan office is still the provision of a uniform thermal environment that is centrally controlled based on the comfort standards. Some open plan offices do not have any source of thermal control, such as openable windows. When openable windows and blinds are provided, they are not the main source of adjusting the thermal environment. For instance, a naturally ventilated open plan office is less likely to only rely on the manually controlled windows, as occupants may not open the window in the wintertime when ventilation is still required. Therefore 'adaptive opportunity' in the British context is applied as a secondary option. In case occupants were uncomfortable, they have an option to adjust the thermal environment (Bordass et al., 1993).

The 'adaptive opportunity' in an open plan office is usually limited to a few windows and blinds around the perimeter of the building. This 'adaptive opportunity' is not provided for everyone, as only occupants seated around the perimeter of the building can access the windows and blinds. Occupants seated away from the window and closer to the centre are not provided with any thermal control and they are expected to simply accept the condition. In this context, the occupant is considered somewhere between 'active' and 'passive'. Most of the time they are expected to passively accept the thermal environment. However, when the

system fails to provide them with comfort, occupants become active and apply limited change to the thermal environment.

10.1.2.7. Adaptive Opportunity to Set a Uniform Temperature

The two British case study buildings in this study have an open layout with openable windows and blinds as an adaptive opportunity provided for limited occupants. Occupants seated away from the windows complained that when they are uncomfortable, they cannot do anything about it other than tolerate the situation. Sometimes they preferred to stay and work at home if their physical appearance was not required in the office. In addition, the occupants, who had access to openable windows and blinds, reported the impact of the 'other' colleagues in making their decision to adjust a window or blind. Thus they did not freely use the 'adaptive opportunity'.

In this research, many respondents explained their lack of desire to access a thermostat in the open plan office, because the responsibility of setting the uniform temperature would be passed on to the occupants. According to their previous experiences and acknowledging individual differences, they explained that each individual wants to set the temperature based on their individual needs, which may not be in line with other individuals. Therefore they had observed arguments about which person has the right to set the uniform temperature for all. Consequently they preferred a centrally controlled system to avoid such conflicts. However, their initial desire was to be able to adjust the thermal environment according to their needs when their decision would not impact on 'others'.

10.1.2.8. Individual Thermal Control in the Norwegian Context

In the Norwegian context according to the regulations and workers' demand, every occupant has the right to access an openable window that provides an outside view, natural light and ventilation, as well as being able to adjust the temperature (Arbeidstilsynet, 2003, Van Meel, 2000). Therefore 'individual thermal control' is a requirement in the design of the office layout, which is reflected in the cellular plan offices with high levels of individual thermal control. In this context, the centrally controlled thermal system is treated as a secondary or background system. If the occupant does not apply thermal control for any given reason, the central system regulates the thermal environment within an acceptable range. However, it is expected that the occupant actively sets the thermal environment according to their requirements, as the occupant is considered active rather than passive. In the Norwegian context, rather than presenting comfort to the occupant, the means to provide a comfortable

condition is provided for every occupant so that they find their own comfort by actively using those means according to their immediate thermal needs.

10.1.2.9. Personal Thermal Settings and Individual Differences

The Norwegian context of traditional cellular plan offices recognises the differences in individuals. Therefore every occupant is provided with a personal room, in which they can regulate their office environment without interfering with thermal settings of ‘other’ occupants. The two Norwegian case study buildings in this study are designed based on Norwegian workplace regulations that originated from users’ demands. Therefore every occupant is provided with various opportunities to fine-tune their thermal environment in their personal room. The provided individual thermal control includes an openable window, blind, door, light, and the ability to adjust the temperature.

During the interviews, the participants reported their lack of interest in moving into an open plan layout, mainly because of individual thermal control and privacy. They stated that the availability of thermal control for every occupant allows them to adjust the thermal environment according to their instant thermal preference and requirements, which may be very different from their ‘other’ colleagues. They explained that they find thermal settings of their ‘other’ colleagues inconvenient, therefore they preferred not to share a room. The individual thermal control also allows individuals with warm or cool thermal preferences to adjust the thermal environment accordingly. This is in line with Humphreys finding stating that ‘if there is sufficient adaptive opportunity, people who feel ‘slightly warm’ perhaps desire at that time to feel ‘slightly warm’, while people who feel ‘slightly cool’ perhaps desire to feel ‘slightly cool’, and so on’ (Humphreys and Nancock, 2007).

Thermal control is more sophisticated and provided for every individual through the building layout and facilities in the cellular plan offices in this study. However, these two buildings are less sustainable and efficient in terms of use of energy and space. The Norwegian case studies consume much more energy compared to the two British practices, discussed in section 7.2.4. In addition, the Norwegian practices in this research are less efficient in terms of use of space compared to the two British practices, presented in section 7.1. This thesis compares the impact of availability of high levels of thermal control on users’ comfort and satisfaction, however more sustainable techniques are recommended. As Hitchings explains ‘instead of talking about what temperatures feel neutral in particular places when we have already accepted this to be dynamic, the ambition may now be to reveal which techniques people are willing to employ to get through particular periods more sustainably’ (Hitchings, 2009).

10.1.2.10. Satisfaction, Comfort and Health: Norwegian vs. British Context

The main finding in this research suggests that occupants of the two Norwegian cellular plan offices with higher levels of individual thermal control are more satisfied, comfortable and healthy compared to the two British open plan offices with limited thermal control. This is in line with workers' demands in the 1970s regarding openable windows and individual thermal control (Van Meel, 2000). The satisfaction and comfort levels of the Norwegian offices are respectively 30% and 20% higher than the British offices. The thermal environment of the four buildings was within the acceptable range and the major difference between these two offices is the availability of thermal control for users. This suggests that availability of thermal control increases user satisfaction, comfort and health. In addition, the interview results confirm this finding, as the Norwegian respondents explained the significant influence of individual thermal control in their personal offices on their satisfaction, comfort and health. In contrast, the British respondents complained about lack of thermal control and its undesirable influence on their satisfaction, comfort and health. The majority of them had to tolerate the situation when they were uncomfortable with the thermal environment. Sometimes they found it so difficult to cope with the thermal condition at their workstations that they put on inconvenient layers, such as a sleeping bag, or they stayed at home. In addition, this finding is in line with other research in the field, which report that thermal control increases satisfaction (Wagner et al., 2007, Brager and Baker, 2009, Newsham et al., 2009), comfort (Bordass et al., 1993) and health (Rayner, 1997, Rollins and Swift, 1997, Marmot, 2010).

10.1.3. Conclusion

This research challenges the view of the 'comfort zone' and investigates the application of 'individual thermal control' in the Norwegian and British workplace contexts. This thesis suggests that current worldwide 'comfort zones' and their basis are less likely to be accurate and indicate user comfort. In addition, it is proposed that thermal comfort is dynamic rather than fixed so that a particular thermal setting is less likely to satisfy a particular individual at all times. This is in contrast with providing a steady state thermal setting according to the standard 'comfort zone'. In addition, this research proposes that occupants with a desire to change the thermal settings are more likely to be dissatisfied, uncomfortable and suffer from building related symptoms. This thesis suggests that occupants, who are provided with 'individual thermal control', are more likely to be satisfied, comfortable and healthy.

The case studies in this study are either energy efficient or comfortable through providing thermal control for individuals. Energy efficient constructions are essential, due to climate change, energy and economic crises. However, user comfort, satisfaction and health are also important and providing a pleasant environment for individuals is essential, due to rising expectations and reducing absenteeism. The researcher suggests a balance between energy efficiency and providing comfort for individuals, as either extreme is not sufficient and causes difficulties for the other end. Therefore, providing sustainable thermal control for individuals is recommended. The thesis suggests that a comfort zone that satisfies all is less likely to apply to the real world context of offices. It is suggested that buildings provide a degree of flexibility in a sustainable way to allow users to adjust their thermal environment according to their immediate requirements.

10.2. Qualitative Visual Analysis

This section explains the new visual recording technique that is introduced in this thesis, presented in sections 5.2.3 and 6.1.6, and it highlights its significance in extracting meanings that influence the findings of the research. It is proposed that ‘the quantitative appraisal could be associated with a risk of misjudgement’ (Shahzad, 2013b).

10.2.1. Traditional Analysis in Thermal Comfort

Traditionally, mainly quantitative analysis is used in the field of thermal comfort, since the aim of most of thermal comfort studies is to generalise and to refine the comfort zone. In the field studies of thermal comfort, the collected information is analysed using quantitative analysis methods in order to produce algorithms (McCartney and Nicol, 2002), computer software, such as CBE Thermal Comfort Tool (Hoyt et al., 2013) or general guidelines to predict comfort conditions (Nicol et al., 2012). For example, Nicol and McCartney introduced an ‘adaptive control algorithm’ to calculate the comfort conditions required to control air conditioned buildings. They used Excel/SPSS databases to present and analyse the collected data by computer software (McCartney and Nicol, 2002). In addition, steady state theory, which takes place in experimental chambers, investigates the heat exchange between the human body and the physical environment. Therefore quantitative analysis is applied to produce complicated equations that explain this physical phenomenon, such as Fanger’s heat balance equation, presented in section 3.2.1.1 (Fanger, 1973). In order to make it possible for other researchers to use these complicated equations, computer tools, such as the ASHRAE Thermal Comfort Tool, have been introduced. In this case, the environmental measurements are given to the computer tool and it evaluates the comfort condition. However, except the final result, the analysis process is not known to the user. The quantitative analysis is useful to understand the physical reactions and to refine the standard comfort zone. However, it overlooks the context and meaning, which are highlighted in this research, as they influence the interpretation and findings.

Thermal comfort is often researched by engineers (Meir et al., 2009), who apply mainly quantitative analysis methods. Nicol explains that ‘Architects have gradually passed responsibility for building performance to service engineers, who are largely trained to see comfort as a “product”, designed using simplistic comfort models’ (Nicol et al., 2012). Engineers’ research outcomes are based on ‘mathematical language and logic’ (Gaucherel et al., 2011), which may not appear so convenient to architects. In order to encourage architects to contribute to the field of thermal comfort, the use of a familiar language is useful. ‘Visual tools are commonly used in the field of architecture to apply information on plans and

sections. They add a different value and perspective by putting together different information regarding a specific aspect in a visual way' (Shahzad, 2013b).

10.2.2. Innovative Visual Analysis Technique

The aim of this thesis is to investigate the application of thermal control in the workplace. The real life context and users' daily experience of using thermal control are particularly highlighted. Therefore grounded theory as a qualitative methodology and a semi-structured interview as a qualitative method are conducted to explore the field in depth. Careful consideration is given to keep the connection between the collected data and its context through recording the precise time, location, situation, and observations. It is essential to maintain the connection between different items of information about every occupant, such as thermal sensation, intention, comfort, satisfaction, health, clothing, occupant's instant comments and environmental measurements. Therefore a qualitative analysis technique is introduced to analyse the data bringing in the contextual information, such as location and observations, without losing connections, presented in sections 5.2.3 and 6.1.6.

10.2.3. Quantitative vs. Qualitative: Neutral Thermal Sensation

The quantitative and qualitative analysis, which are applied to examine the application of the 'neutral thermal sensation' as the basis of thermal comfort standards, demonstrate the difference between these two analytic approaches, presented in section 8.2.3. The statistics, using SPSS linear regression analysis, showed a significant relationship between thermal sensation and variables such as satisfaction, comfort and thermal intention. In addition, although the number of comfortable respondents is slightly high (i.e. 68%), the other variables are closely related, sections 8.2.2.1 and 8.2.3. These statistics show a significant relationship between the neutral thermal sensation and the variables confirming the neutral thermal sensation as the basis of thermal comfort. However, this is in contrast with the findings of the qualitative analysis method, also discussed in sections 8.2.2 and 8.2.3.

Based on the meaning, the combination of the thermal sensation and thermal intention were considered as the overall thermal preference of the respondent. The results indicated that 45% of the respondents with thermal sensations other than neutral felt comfortable. Further qualitative analysis revealed that thermal preference of the user is more likely to change throughout the day, discussed in section 8.3. It suggests that if a respondent expresses their desire for a neutral feeling, there is a 60% chance that the particular individual has a thermal preference other than neutral at a different time in the day. Based on these qualitative analysis

using the visual recording technique, it is proposed that neutral thermal sensation is less likely to indicate the comfort status of the user. This shows the importance of meanings and connections between variables, which could be overlooked in a quantitative analysis. This suggests that quantitative analysis is limited when interpreting and extracting meanings.

Using the visual recording technique led to four of the main findings in this research. In fact, the only finding in this study that did not require the qualitative analysis is the comparison of the two office layouts regarding satisfaction, comfort and health of the occupants, discussed in section 10.1.1.2.2.

10.2.4. Conclusion

This thesis suggests that ‘the quantitative approach is more suited for general understanding of a situation, such as the overall satisfaction level’ (Shahzad, 2013b), in addition to comparing two variables, such as users’ satisfaction level between two buildings. ‘However, the interpretation of the connection between information through a quantitative approach could drive to a misjudgement’ (Shahzad, 2013b). For instance, it can overlook the importance of users’ decision in changing the temperature, which is related to meaning. As Brennan explains ‘the significance of often straightforward mathematical relationships becomes talismanic’ (Brennan, 2013). ‘Therefore, user competence is required as to where to apply the quantitative or qualitative method. The qualitative analysis of the collected information reveals connections between the data regarding a particular person that changes the meanings and influences the findings of the research’ (Shahzad, 2013b). ‘This research suggests that the qualitative analysis reduces the risk of misjudging the information, so the results are more likely to be accurate and applicable’ (Shahzad, 2013b).

10.3. Conflict: Perceived Productivity

In this research, there was an obstacle in comparing the productivity level among the four case study buildings. The results suggest that the adopted data collection technique to record the productivity level of the occupants is not suited for this study. The question that is presented in Figure 293 was adopted from Rijal and Humphreys' survey questionnaire (Rijal et al., 2009) to record occupants' instant productivity level, explained in section 5.2.2.4.3 and presented in section 6.3.6.



9. Compared to normal, currently my productivity is

Much higher Higher Slightly higher The same Slightly lower Lower Much lower No strong opinion

Figure 293: Productivity question, based on (Rijal et al., 2009)

There is an inconsistency in comparing the productivity level between the four case study buildings. The SPSS linear regression analysis shows a significant relationship between the productivity level and type of plan. Nevertheless, there is an inconsistency in detailed comparison between the four buildings. The productivity level of Building A, which is a cellular plan office, is lower than Building D, which is an open plan office, as explained in section 9.2.4. Furthermore, many respondents had difficulties in understanding the question about productivity status and an explanation was required for 'normal productivity level'. They found this question difficult to answer.

In this thesis, the adopted method to measure the productivity level was unsuccessful. Perceived productivity is used to justify individual adaptive comfort. However, in some ways this is subjective and difficult to investigate, although some researchers claim substantial measurable improvements and they apply different methods to research perceived productivity. Further research applying other methods is recommended to investigate the productivity level of occupants. Kroner and Oseland apply other methods that may be more successful (Kroner, 2006, Oseland, 2004), discussed in section 9.2.4.

10.4. Limits

Two main difficulties limit this research and its findings: an obstacle regarding this particular research and a complexity that is associated with the field studies of thermal comfort. Accessing the building and the complexities of the context, which leads to a difficulty in generalising the findings are respectively the main constraints in this research.

Accessing the case study buildings was extremely difficult so that over a year was spent on it, as managements preferred not to participate in the research, due to publicity, sensitivity or time-consuming reasons. This limited the selection of the buildings, as most of the preferred buildings were not available. Therefore it was not possible to have control of some of the building characteristics, such as the ventilation system and energy use. However, the main characteristics of the selected case study buildings are based on the selection criteria, presented in section 6.5. Other researchers in the field also report difficulties in accessing the buildings (Leaman, 1996, Baird et al., 1996, McCartney and Nicol, 2002, Meir et al., 2009, Bos and Love, 2013). Leaman explains that buildings are usually offered rather than being selected, therefore there is less control over the sampling design and building conditions (Leaman, 1996). In this study, in order to gain access to the buildings, management were offered the option of anonymising their building, which is the case in the Building A. Furthermore, careful consideration was applied to make the site visit and user participation as concise as possible (Roaf et al., 2004). For instance, the general questionnaire was replaced by a semi-structured interview, explained in section 6.1.4. Also, one of the research methods, the ethnographic video recording technique, was not permitted, as explained in section 6.1.5.

Another obstacle is a general criticism associated with field studies of thermal comfort, which is the complexity of the context and the various factors that influence the thermal comfort of occupants (Roaf et al., 2004, Bluysen, 2009).

Although the experimental chambers have the advantage of control over the condition of the experiment and it is possible to limit the variables, their findings do not apply to the context of daily life (Nicol et al., 2012). In addition, the results of a particular context may not apply to other contexts, which makes generalising of the findings difficult (Humphreys and Nicol, 2002a). Nicol suggests that more research in various contexts is required to unfold the complexities of thermal comfort (Nicol and Roaf, 2005, Nicol et al., 2012). In this study, air temperature, relative humidity, mean radiant temperature, clothing, activity, location in the room, and outdoor air temperature are included in the calculations of the ASHRAE adaptive and PMV prediction models. The qualitative analysis is based on the questions of the general

survey questionnaires applied in thermal comfort, including user comfort, satisfaction, thermal sensation and thermal intention (ASHRAE, 2009), discussed in section 3.1.5. Still many factors are not included, such as contextual and psychological factors, and this is the limit of the study. Nicol reports the complexity of measuring thermal comfort, due to numerous variables influence the field (Nicol et al., 2012) such as psychological factors (ASHRAE, 2009), presented in section 3.1.5.

In this research, two distinct contexts, Norwegian and British, were compared and all case studies have high quality of indoor environment, presented in Chapter Seven. In the semi-structured interviews devised to limit various factors, presented in section 6.3.5. Occupants recognised the temperature as the main factor that influenced their satisfaction, comfort and health in over 80% of the cases. This is in line with other research results in the field, which indicate that the temperature is the most influential factor (Leaman and Bordass, 2005). When participants responded to the health-related questions, they were asked whether they experience the symptoms during the weekend and how much the symptoms were related to the environment at their workstation. Accordingly the symptoms that were not associated with the thermal environment were eliminated in the analysis. When participants responded to the instant questionnaire, they were asked to respond according to the current thermal conditions at their workstation in order to reduce the impact of other factors, such as psychological issues or job satisfaction. Despite these measured steps to reduce the influence of other factors, they cannot be completely eliminated, as this is the complexity in the field studies of thermal comfort. Due to the limited number of case study buildings and respondents, in addition to the influence of their contexts, the results of this study cannot be generalised.

10.5. Wider Context

In a wider context, the findings of this research highlight the role of the architect in designing the office layout. Architects are recommended to include opportunities to increase thermal control for individual occupants in the workplace design in order to increase occupants' satisfaction, comfort and health. As Nicol explains, architects have passed the responsibility to engineers to provide thermal comfort in the building (Nicol et al., 2012). This thesis shows the significant influence of office layout and availability of thermal control on user satisfaction, comfort and health, as presented in sections 10.1.1.2.2 and 10.1.2.5. The history of the workplace shows the importance of workplace legislations regarding thermal control followed by architectural design for occupants (Van Meel, 2000). However, currently user satisfaction with cellular plan offices (Axéll and Warnander, 2005) and individual thermal control are overlooked (Roaf et al., 2004).

This thesis demonstrates the difficulties of the current thermal standards and questions the possibility of predicting occupant comfort accurately, as suggested to be associated with a dynamic quality. However, the importance of a good standard is valued, as Nicol and Humphreys state 'thermal comfort standards are required to help building designers to provide an indoor climate that building occupants will find thermally comfortable' (Humphreys and Nicol, 2002a). It is proposed that the building designer and architect follow the comfort standards so that their design is not too far away from acceptable comfort conditions. However, there is a risk of misjudgement and over-expectation in relying too much on the comfort standards and providing a uniform thermal environment, as presented in section 6.1.1. The results of this research suggest that a thermal setting that is based on comfort standards does not guarantee user comfort. In addition, a universal 'optimum temperature' may not satisfy all (Baker and Standeven, 1997, Humphreys, 1972, Nicol, 1995, Humphreys, 1996). Nicol and Humphreys recommend the future standards to assess 'the characteristics of a building, in terms of controls and building management, in relation to the local climate', rather than 'specifications of the indoor thermal climate' (Humphreys and Nicol, 2002a).

This thesis highlights the individual differences in perceiving the thermal environment, in addition to the active role of users and their intention to change the thermal environment when they are uncomfortable. On these bases, this research emphasises the application of individual control over the thermal environment in regard to the architecture and office layout. Therefore architects are recommended to design building layouts and opportunities to increase thermal control for individual occupants in the workplace. It is possible to combine

this quality with sustainable criteria (Hitchings, 2009, Nicol et al., 2012), as Bordass suggests that thermal control reduces energy use (Bordass et al., 1993).

10.6. Summary

The findings propose that a 'comfort zone' that satisfies everyone is less likely to apply to the real world context of offices. This thesis suggests that workplace design provides a degree of flexibility to allow users to adjust their thermal environment according to their requirements.

This research is based on the challenge in thermal comfort between the steady state and adaptive comfort theories, which are followed by respectively comfort zone and adaptive opportunity. This thesis challenges the concept of the standard 'comfort zone', which is the aim of the experimental comfort studies and investigates the application of thermal control. The Norwegian and British workplace contexts with respectively high and low levels of thermal control were compared. In the Norwegian cellular plan offices, individual differences and the active role of the user are recognised, therefore they are provided with an opportunity to find their own comfort regarding the thermal environment. In contrast, in the British open plan offices, these qualities are overlooked and a uniform thermal environment is provided to the user as a product, according to the comfort standards, endeavouring to satisfy the majority of the occupants. The former provides every user with various opportunities to adjust their thermal environment, while the latter is based on setting the thermal environment according to the standard comfort zone.

The results indicate that the ASHRAE comfort zone and its basis do not apply to the case study buildings. In addition, it is proposed that thermal comfort is dynamic, thus a steady thermal setting is less likely to satisfy everyone constantly. This thesis suggests that occupants are more likely to feel comfortable when they are provided with an opportunity to adjust their thermal environment according to their requirements in the workplace. Thus it is proposed to recognise the active role of the user as well as individual differences in perceiving the thermal environment in the design of offices. The thesis suggests providing the opportunity of thermal control for every occupant in their workstation, as it is more likely to improve user satisfaction, comfort and health.

CHAPTER 11

CONCLUSION

11. Conclusion

This thesis is based on the challenge in the field of thermal comfort between the steady state and adaptive comfort theories. It challenges the concept of the standard ‘comfort zone’ and investigates the application of ‘individual thermal control’ in the workplace. The key research question being examined is: ‘Does thermal control improve user satisfaction in cellular and open plan offices? Norwegian vs. British practices’.

An innovative qualitative analysis method, which is called the visual recording technique, is introduced in this thesis to analyse the information in regard to the context and meaning. On this basis, the research outcomes derived five different findings, the key ones being:

- A particular steady state thermal setting based on the comfort standards is less likely to satisfy a particular individual at all times. This is in contrast with the concept of the standard ‘comfort zone’.
- Occupants, who are provided with individual thermal control, are more likely to be satisfied, comfortable and healthy.

In this chapter, the research theme and findings are addressed. Finally, further research in the field of thermal comfort based on the findings of this thesis is recommended.

11.1. Individual Thermal Control in Norwegian and British Contexts

The aim of this thesis is to show how satisfaction, comfort and health of the user can be improved in the workplace. This research is based on the challenge between the steady state and adaptive comfort theories. Eventually, the key research question in this thesis was formed as ‘does thermal control improve user satisfaction in cellular and open plan offices? Norwegian vs. British practices’.

The challenge in the field of thermal comfort between steady the state and adaptive comfort theories was approached. Experimental researchers aim to find a steady ‘optimum temperature’ to minimise the heat exchange between the human body and the thermal environment. This physical state is considered to be comfortable. In this view, occupants are considered passive and they receive comfort as a ‘product’ (Fanger, 1970), which is designed and presented by engineers (Nicol et al., 2012). In contrast, adaptive comfort theory considers occupants active, as they actively apply a change when they are uncomfortable (Nicol and Humphreys, 1973b). Adaptive comfort theory is mainly based on users’ ability to adjust themselves to the changes of the thermal environment, such as seasonal changes.

Based on these different views, two different approaches were proposed in order to provide users with thermal comfort in the workplace. The steady state theory presented the universal ‘comfort zone’, while the adaptive comfort theory proposed the ‘adaptive opportunity’, explained in section 3.2. The ‘comfort zone’ is based on the ‘neutral thermal sensation’ (ASHRAE, 2010), in which the user feels ‘neither cold nor warm’ (Hawkes, 2002). Therefore when the occupant feels neutral in regard to the thermal environment, the user is assumed to be thermally comfortable (ASHRAE, 2009, ASHRAE, 2010). The comfort zone presented in the ASHRAE Standard 55-2010, the most widely used comfort standard, claims to satisfy over 80% of the occupants (ASHRAE, 2009, ASHRAE, 2010), discussed in section 3.2.2.1. Adaptive comfort researchers have also contributed to refine the ‘comfort zone’ in naturally ventilated buildings (Nicol et al., 2012), but their main approach is the ‘adaptive opportunity’. This is mainly the building attribute that allows users to adjust the thermal environment when they are inconvenienced (Baker and Standeven, 1995). As discussed in sections 3.2.2 and 10.1.2, in the view of standard ‘comfort zone’, thermal comfort is presented to occupants and they are expected to passively receive it with satisfaction. In contrast, in the notion of ‘adaptive opportunity’, users actively adjust the thermal environment to meet their requirements when they are uncomfortable.

In this research, it was important to investigate case study buildings that reflect these two distinct approaches in the office layout: a centrally controlled uniform thermal environment with low levels of thermal control and an office layout with high levels of individual thermal control. In the 1970s and 1980s the UK and Norway followed two separate paths regarding workers' demands and consequently office design. In the UK, organisational goals were the main criteria, which led to the design of the open plan office layout. In contrast, workers' rights and demands, such as control over the thermal environment, were the main criteria in Norway, which were reflected in the design of the cellular plan offices with high levels of thermal control.

The British open plan office, which represents the Anglo-Saxon model, is generally regulated as a uniform thermal environment based on the standard 'comfort zone' and the adaptive opportunity is applied as a secondary option in case the user is uncomfortable. Only occupants seated around the perimeter of the building are provided with a limited number of windows and blinds. In contrast, individual thermal control is the main approach in the Norwegian cellular plan office, which represents the Northern European office layout. Every individual is provided with various opportunities to regulate the thermal environment, such as a window, blind, door and the ability to adjust the temperature. The users are expected to regulate the thermal environment in their personal rooms. However, the centrally controlled mechanical ventilation operates in the background to ensure the thermal environment is within the acceptable range stated in the work regulations in case the user does not apply any thermal control.

The comparison of the application of thermal control in the Norwegian cellular plan and the British open plan office layouts was applied to examine occupants' satisfaction, comfort and health. Two mechanically ventilated Norwegian cellular plan offices with high levels of individual thermal control were compared against two mechanically and naturally ventilated British open plan offices with limited thermal control. The Norwegian cases provide every occupant with control over blinds, door, light and an openable window, which provides natural light and natural ventilation, in addition to the ability to adjust the temperature. In contrast, the British cases provide limited control over the windows and blinds for occupants seated around the perimeter of the building. Occupants seated farther from the windows are not provided with any means to control their thermal environment.

11.2. Research Methodologies

To investigate the challenge between the two approaches as manifested in the case studies, a combination of quantitative and qualitative methodologies was applied with a particular emphasis on grounded theory. Through a process of initial pilot studies, the research objectives, methods, plan, and analytical tools were defined. Occupants' perceptions of their thermal environment were recorded through a questionnaire and empirical building performance was evaluated through thermal measurements. These traditional techniques were further reinforced with semi-structured interviews to investigate thermal control more intensively.

Traditional quantitative analysis as well as innovative qualitative analysis methods were applied on the collected data. A visual recording technique was introduced to analyse the information according to the context and meaning.

The research objectives were refined through the pilot studies and two main objectives were recognised, challenging the notion of 'comfort zone' and investigating the application of 'individual thermal control'. They correspond to the two distinct approaches to providing thermal comfort for occupants according to the steady state and adaptive comfort theories. The application of 'comfort zone' was challenged by examining the followings:

- The accuracy of the comfort zone presented in the ASHRAE Standard 55-2010, as the most widely used standard
- The application of the 'neutral thermal sensation' to predict comfort, as the basis of thermal comfort studies and standards
- The consistency of overall thermal preference of individual users throughout the day

The application of 'individual thermal control' was investigated through examining the following:

- The impact of thermal intention on satisfaction, comfort and health
- User satisfaction, comfort and health in comparing two office layouts with high and low levels of thermal control

11.3. Research Findings

The building performance analysis of the case study buildings in this research validated good qualities of indoor environment, which were expected to be satisfactory for users according to standards and benchmarks. The energy use of the two Norwegian practices was much higher and therefore less efficient compared to the two British case studies, but the quality of the indoor environment of all four case studies was similar and within the acceptable range, presented in Chapter 7. The interviews revealed that the temperature is the main factor in influencing the satisfaction, comfort and health of the user, which confirms other research in the field (Auliciems and Szokolay, 1997, Leaman and Bordass, 2005). The major difference between the British and Norwegian case studies is the availability of individual thermal control. The results indicate the following findings in regard to challenging the ‘comfort zone’:

- The ASHRAE comfort zone does not indicate user comfort in the case studies, which operate in the zone of the ASHRAE predictions, and individual thermal comfort relies on factors more nuanced than the ASHRAE predicts. This suggests that universal comfort standards are less likely to be accurate. This confirms other research in the field (Baker and Standeven, 1997, de Dear and Brager, 1998, de Dear and Brager, 2001, Schellen et al., 2013).
- In addition, the ‘neutral thermal sensation’, which is the basis of thermal comfort studies and standards, does not apply to the case study buildings in this research. This suggests that the ‘neutral thermal sensation’ is less likely to indicate user comfort. This confirms Humphreys’ findings (Humphreys and Nancock, 2007).
- The majority of respondents in this study prefer different thermal settings at different times. This suggests that a particular thermal setting is less likely to satisfy a particular individual at all times.

These findings propose that the most widely used comfort zone and its basis are less likely to apply to real world context of offices. In addition, comfort standards define the steady state thermal condition that satisfies all, while this thesis suggests that individuals are more likely to prefer different thermal settings at different times. This is in contrast with providing a steady state thermal setting constantly as the optimum comfort condition. These three findings challenge the concept of a comfort zone that is expected to satisfy all.

The results indicate the following findings in regard to investigating the application of 'individual thermal control:

- The intention of the user to adjust the thermal environment is the main cause of the reduction of user satisfaction, comfort and health in this study. Therefore this research suggests that occupants with a thermal control intention are more likely to be dissatisfied, uncomfortable and suffer from Sick Building Symptoms. This is in line with the adaptive comfort principle (Nicol and Humphreys, 1973b, Nicol et al., 2012).
- In this study, occupants of the Norwegian cellular plan offices with high levels of individual thermal control are more satisfied, comfortable and healthy compared to the occupants of the British open plan offices with limited thermal control. This suggests that occupants, who are provided with individual thermal control, are more likely to be satisfied, comfortable and healthy.

These two findings indicate that when occupants want to change the thermal settings, they are more likely to be dissatisfied and uncomfortable. However, if they are provided with individual thermal control, they are more likely to restore their satisfaction and comfort. The researcher suggests a balance between energy efficiency and providing individual thermal comfort and control.

11.4. Discussion

There is a body of research investigating the influence of the adaptive opportunity on user satisfaction (Leaman, 1996, Bauman, 1999, Huizenga et al., 2006a, Wagner et al., 2007, Newsham et al., 2009), comfort (Bordass et al., 1993, Bordass et al., 1994, Leaman, 1996, Melikov, 2004, Arens et al., 2010), health (Rayner, 1997, Rollins and Swift, 1997, Marmot, 2010), and productivity (Bordass et al., 1993, Kroner et al., 1992, Kroner, 2006). (Olgyay, 1992, Carnevale and Rios, 1995, Seppänen and Fisk, 2004) . In addition, different means of thermal control are explored, such as openable windows (Brager et al., 2004, Tuohy et al., 2007, Rijal et al., 2007, Huizenga et al., 2006b) and lights (Mahdavi and Proglhof, 2008). However, Bordass reports a lack of knowledge in the field of thermal control (Bordass et al., 1994). Still the majority of researchers in the field of thermal comfort concentrate on comfort standards, such as the ASHRAE Standard 55, explained in section 3.2.2.1. Even the adaptive comfort researchers are searching to improve the comfort zone presented in the standards (de Dear and Brager, 1998, McCartney and Nicol, 2002).

Lack of knowledge regarding thermal control in addition to technological advances, organisational changes and economic challenges influence the thermal systems in the workplace. Consequently, centrally controlled systems replace individual control over the thermal environment (Bordass et al., 1993, Roaf et al., 2004). In addition, the Workers' Council is losing its power to protect workers' rights in Europe (Van Meel and de Jonge, 2006). Regardless of workers' demands for thermal control and personal offices, currently even the Scandinavian cellular plan offices with high levels of thermal control are being replaced by open plan layouts with limited thermal control (Axéll and Warnander, 2005, Gadsjö, 2006).. Furthermore, the necessity of thermal control in future offices has been questioned (Harris, 2006). This thesis highlighted the importance of individual thermal control compared to the uniform thermal environment of the open plan offices.

This thesis suggests that thermal comfort is dynamic rather than fixed, as the thermal preference of the user is subject to change. This is in contrast with the steady state theory that aims to provide a steady state thermal condition constantly for everyone, as occupants are more likely to prefer different temperatures at different times. This reveals a difficulty in satisfying occupants in an open plan office with a constant uniform thermal condition. The interviews revealed the importance of individual differences and it was highly acknowledged by occupants in both cellular and open plan offices. Individual differences are valued in the design of the cellular plan offices in Norway, while overlooked in the open plan offices. This

thesis proposes to provide means of controlling the thermal environment for the user so that they can make adjustments any time they want, according to their immediate requirements.

Workplace history shows that one of the greatest demands of the user is ‘individual thermal control’ (Van Meel, 2000, Hookway, 2009). This thesis shows the significant difference between a workplace context, which is built entirely based on users’ demand regarding ‘individual thermal control’ and a different workplace context that overlooks this demand. The Norwegian cellular plan offices, which are designed based on users’ demand and workers’ rights, have much higher user satisfaction, comfort and health compared to the British open plan layouts with limited thermal control. Although the latter is designed based on organisational goals, it overlooks the influence of user satisfaction, comfort and health on the performance of the organisation. For instance, users who suffer from the building related symptoms are more likely to be absent from work (Eaton, 1997). The interviews in this study confirms this, as several occupants of the British open plan offices preferred to stay home as they could not tolerate the thermal environment of their office and suffered from building related symptoms. Although organisations benefit from efficiency of use of space and communication in an open plan layout, the low rate of user satisfaction, comfort and health is a disadvantage, which affects the organisation.

Kroner reports high user satisfaction levels in providing individual thermal control in an open plan office. Although the organisation under the study spent money on providing every individual with thermal control, it saved money as the productivity level of the staff increased up to 16%. This financial benefit was more than the cost of providing individual thermal control. In addition, providing users with a pleasant environment increased users’ attachment to their workplace and organisation. The employees did not leave their organisation even with the offer of higher income from another company (Kroner, 2006). This is in line with Kapetanakis’ prediction that in the future organisations will rely on a talented workforce so how to attract them will be a challenge (Katsikakis, 2006). Duffy states that offices with higher qualities rather than quantity are required (Duffy, 2008). Furthermore, Moezzi explains that ‘comfort quickly becomes “about nearly everything”’ (Moezzi, 2009). He also states that people’s expectations for a refined and controlled thermal environment is increasing (Moezzi, 2009). In addition, Nicol explains four principles to tackle climate change, energy and economic challenges, in which two of them are related to adaptive opportunity and availability of thermal control in the buildings (Nicol and Stevenson, 2013). He highlights the role of architects and designers in providing thermal comfort and tackling these current worldwide challenges through building design and application of adaptive comfort.

This thesis highlights the importance of individual thermal control for users. The results reveal a significant difference in the satisfaction level between the Norwegian cellular and the British open plan offices (i.e. 30%). Overall, the findings of this thesis suggest that rather than presenting thermal comfort to occupants according to the steady state theory and the standard comfort zone, buildings are recommended to provide occupants with the opportunity to find their own comfort. Finally, this thesis indicates that a 'comfort zone' that satisfies all is less likely to apply to the real world context of offices. It suggests that office buildings provide a degree of flexibility to allow users to adjust their thermal environment according to their requirements.

11.5. Constraints and Further Research

The results of this research cannot be generalised, due to the limited number of case study buildings and number of participants, in addition to the complexities of the context based information, discussed in more detail in section 10.4.

Further research on individual thermal control in the workplace with an emphasis on sustainable criteria is encouraged, in addition to more intensive qualitative research in the field of thermal control. Research is encouraged in both cellular and open plan office layouts, since the future of the workplace is more likely to be a combination of both layouts (Duffy, 1997, Duffy, 1992, Laing, 2006, Van Meel et al., 2010). The energy use of the two Norwegian practices is much more than the two British open plan offices. Therefore researching the Northern European cellular plan offices with a more sustainable approach is recommended and will provide valuable information regarding users' behaviour and satisfaction. German offices such as projects by Behnisch and Sauerbruch Hutton architects provide high degrees of thermal control in cellular plan offices using sustainable methods. There is also a possibility that providing thermal control for every individual in an open plan office increases comfort and satisfaction of the occupants. Currently research is undergoing in Berkeley University on other types of thermal control in the open plan office, such as the Personal Control System (Bauman et al., 1993, Zhang et al., 2008) is likely to increase user satisfaction. In addition, modern thermal control systems have the potential to reduce the overall energy consumption of the building (Hawkes, 1982, Bordass et al., 1993). For instance, rather than heating the building as a whole, workstations are adjusted individually according to the occupant's needs (Zhang et al., 2008).

Further investigation from the point of view of occupancy in the workplace is encouraged. This thesis shows the difficulty to predict how buildings will be used and the difference

between predicted and perceived comfort of occupants. It also shows that difference between individuals is underestimated and encourages more focus on this area. Therefore further research is required to compare other office buildings that provide different qualities to the case study buildings in this thesis. As explained, both open and cellular plan offices that provide sustainable methods of individual thermal control are recommended for further research and cross comparison. The methodology, methods and qualitative analysis technique of this thesis are recommended for investigating the field qualitatively and from the point of view of occupancy. The graphic presentation in the form of the visual recording technique as well as the boxplots that focus on the context of separate buildings are useful to explore the field qualitatively. This cross comparison in a broaden context of various buildings is also useful to investigate the challenge between comfort and energy efficiency in buildings.

In addition, the author recommends the application of two qualitative methods in particular, including the visual analysis method and the ethnographic video recording technique, presented in sections 5.2.3, 6.1.6 and 6.1.5. The qualitative analysis method introduced in this research allowed further intensive context based qualitative investigation. The pictograms provide an opportunity to demonstrate all of the collected information at once using colour codes. This allows an overall and instant understanding of the thermal condition, comfort situation and user behaviour in regard to the context as well as meaning. Since the data is presented on the plan, it gives a special understanding of the climatic conditions and user behaviour in different parts of the building and workstations in a particular area of the office (e.g. Figure 64). The author is interested in analysing the current data from this research to discover further qualitative findings. For instance, it is possible to examine the pattern of user behaviour and use of thermal control opportunities throughout the day as well as their impact on their satisfaction and comfort. Although it was not possible to apply the ethnographic video recording technique in the main case study buildings in this research, this method is highly recommended. This is an easy and accurate way to observe the natural behaviour of the user towards the thermal environment. A follow up interview would be useful to discuss the motivation of particular behaviours. The main difficulty is in obtaining permission to apply this method in the building.

11.5.1. Potential for a Qualitative Analysis

The visual recording technique that has been introduced in this thesis, section 6.1.6, allows an intensive qualitative ethnographic analysis according to the context and meaning. This section presents a sample of this analysis for a respondent in Building B, presented in Figure 294, and all the information is presented on the plan using colour codes, presented in Figure 295 and

Figure 297. Figure 296 shows how to read the pictogram in Figure 297. This male participant responded to the survey questionnaire three times a day.

- Location: Figure 294 shows the location of this personal office in Building B. The office has two windows facing east so it receives more sunlight in the morning hours.
- Thermal environment: the PMV model predicts that the occupant feels 'slightly cool' and adaptive model predicts a 'neutral' feeling regarding the thermal environment of the workstation all day. So there is a contradiction between these two prediction models. The temperature reading shows 24°C in the morning and 22°C in the afternoon. The concentration of carbon dioxide is slightly higher in the morning, however it is within a very good range as it stays well below 600 ppm. The noise level did not change throughout the day. The light is stronger in the morning and early afternoon, which matches the solar gain as the room is facing east.
- His view of the thermal environment: The changes of the thermal sensation shows that he feels 'slightly warm' in the morning and 'slightly cool' in the early and late afternoon. However, the thermal intention shows that he does not want any change in the temperature throughout the day. There is no consistency in his overall thermal preference throughout the day, as it changes from 'slightly warm' in the morning to 'slightly cool' in the early and late afternoon. His satisfaction level is constantly 'satisfied' and his comfort level changes from 'comfortable' in the morning to 'very comfortable' in the early and late afternoon.
- Other facts: he is not suffering from any sick building symptoms and his productivity level is the same as normal throughout the day. His hands and face feel neutral all day, while the thermal feeling in his feet changes from warm to slightly warm and neutral during the day. This is in line with his thermal sensation and solar gain throughout the day.
- Behaviour: Figure 297 shows that he is wearing summer clothes (i.e. 0.5 clo) with no change all day. He opened the large window and closed the blinds (half closed) in the morning, and did not change anything else the rest of the day. The door and corridor blinds are open all day. So he applied thermal control only in the morning.
- Interview: in the follow up interview he explains that he is not sensitive towards the changes of the thermal environment. He has a good knowledge of the availability of

thermal control in his office, he applies them when required and he is satisfied with it. He is relaxed and no particular work or psychological matter influences his comfort level in this particular day.

- Interpretation: there seems to be a connection between his comfort level and overall thermal preference suggesting the possibility that he feels more comfortable when feeling 'slightly cool', although he reports to be comfortable in both situations. Although this slightly affects his comfort level, he is quite comfortable and satisfied. The survey questionnaire and the follow up interview suggest that the occupant is not sensitive towards the changes of the thermal environment and he can tolerate a range of temperature changes. The adaptive and PMV predictions are contradictory, adaptive model could not predict his thermal sensation, while the PMV model could predict his thermal sensation in the afternoon. The PMV model recommends warmer temperature for the occupant, however the occupant does not want any change in the temperature and he feels 'very comfortable' and 'satisfied'. Overall, the occupant is not sensitive regarding the temperature, still he uses the available control to adjust the thermal environment according to his needs and he is satisfied with it.

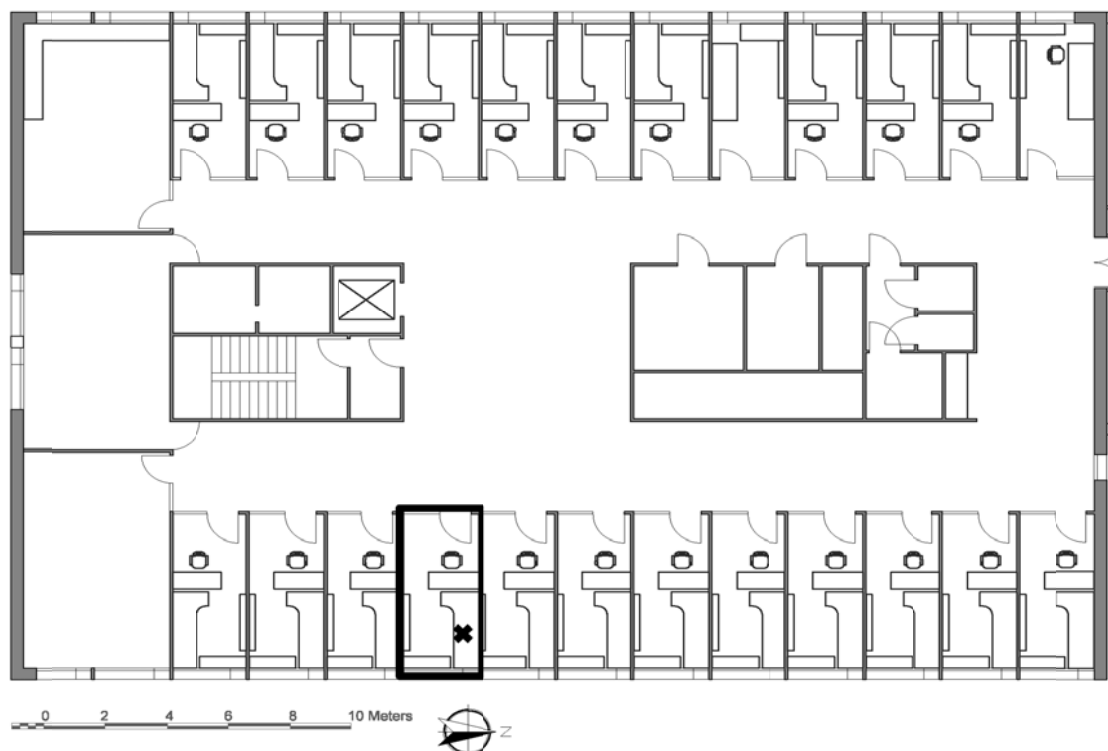


Figure 294: Location of the personal office in Building B

Do the occupant want to feel neutral? during a day: morning, early and late afternoon?			Consistency in thermal preference
Morning	Early afternoon	Late afternoon	
			Not Consistent at all
Slightly warm	Slightly cool	Slightly cool	

Figure 295: Overall thermal preference of the occupant throughout the day, extracted from Figure 251

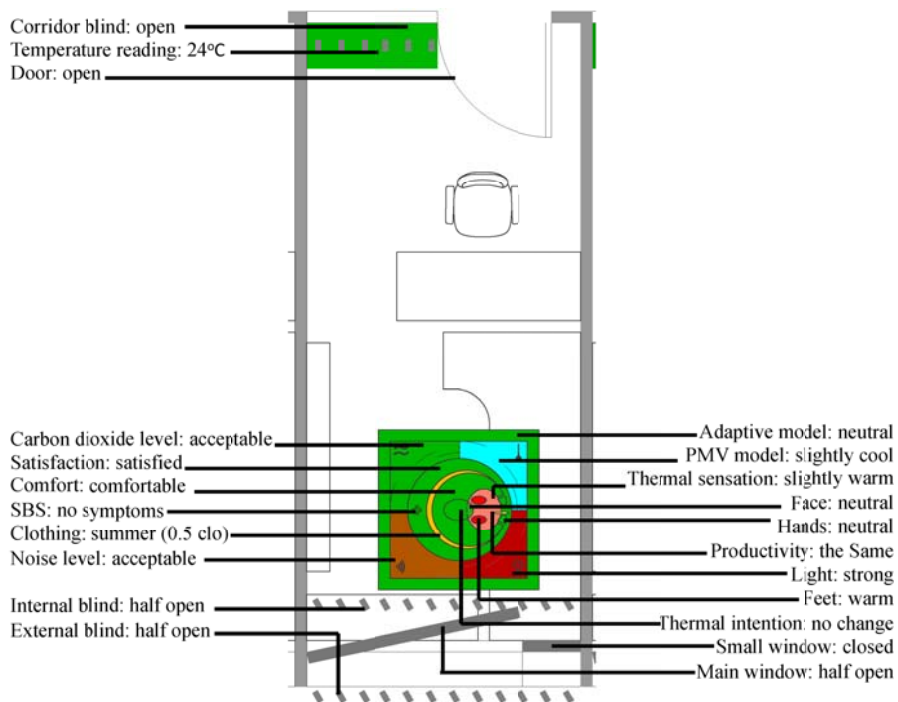


Figure 296: A sample on how to read the pictogram in Figure 297

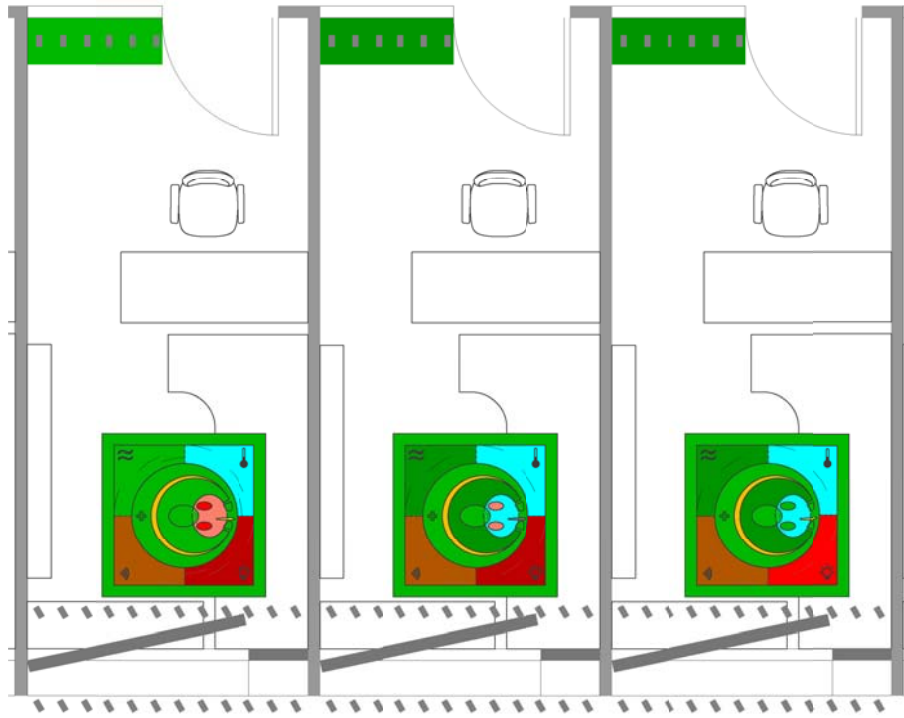


Figure 297: All the information mapped on the pictograms: morning (left), early (middle) and late afternoon (right)

Solar radiation is possibly the reason the person feels warmer in the morning and less comfortable.

11.6. Summary

The thesis supports the adaptive comfort theory and its approach, adaptive opportunity, while it challenges the steady state theory and universal comfort zone. An innovative qualitative analysis method was introduced in this thesis. The main findings suggest that thermal comfort is dynamic rather than fixed, as the thermal preference of an individual changes throughout the day. This suggests that a steady state thermal condition according to the standard comfort zone is less likely to satisfy everyone constantly, as individuals are more likely to desire different thermal conditions at different times. In this research, the Norwegian cellular plan offices with high levels of individual thermal control have higher user satisfaction, comfort and health (i.e. up to 30%) compared to the British open plan offices with limited thermal control. This suggests that the availability of individual thermal control is more likely to increase satisfaction, comfort and health of the user in the workplace.

This research suggests that rather than providing a uniform thermal condition according to the standard 'comfort zone', office buildings are recommended to provide a degree of flexibility to allow users to find their own comfort by adjusting their thermal environment according to their immediate requirements.

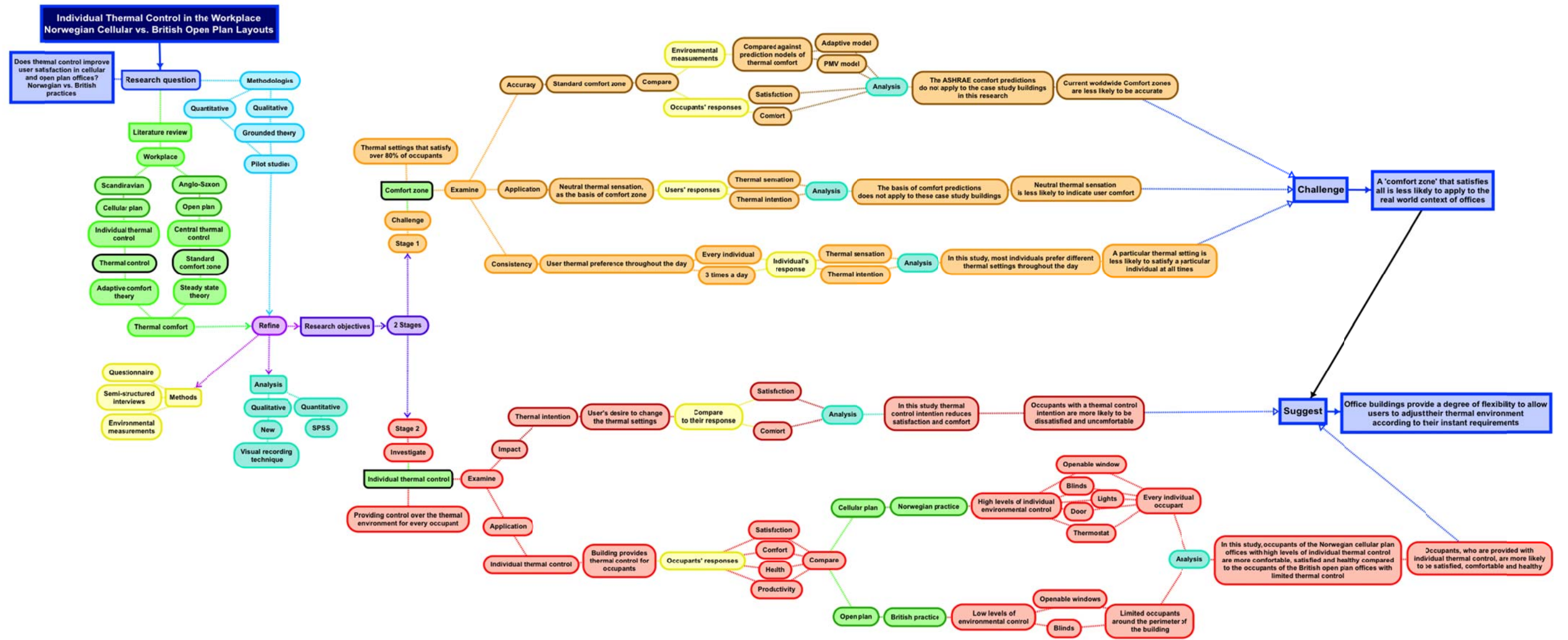


Figure 298: The thesis diagram

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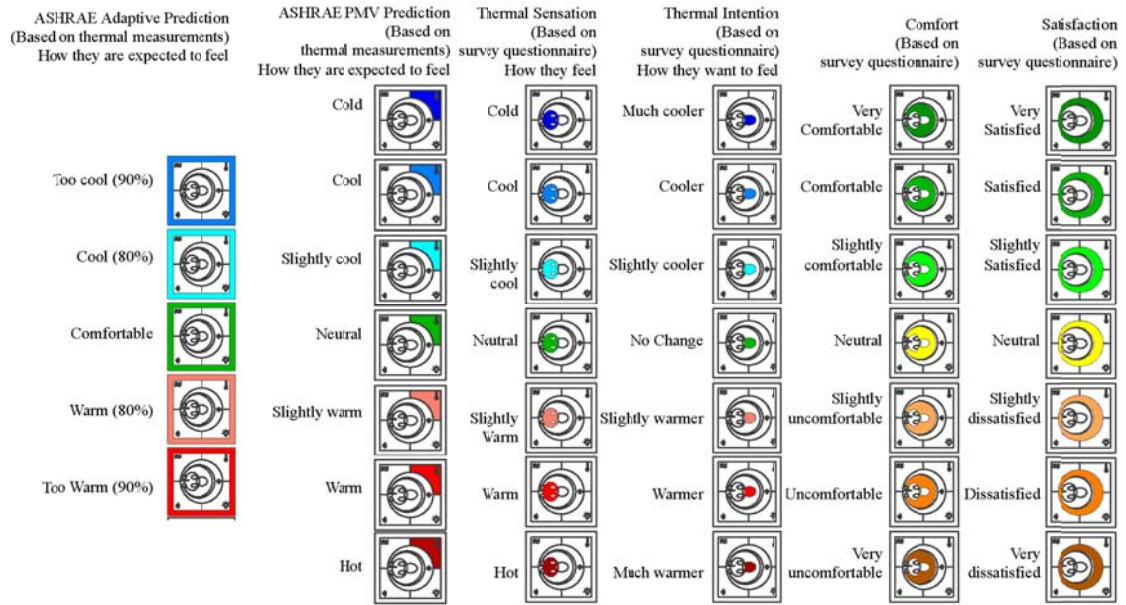
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APPENDIX

Appendix A: Pictograms



Building A: Morning, Early and Late Afternoon Analysis



Figure 299: Building A: Morning visual analysis

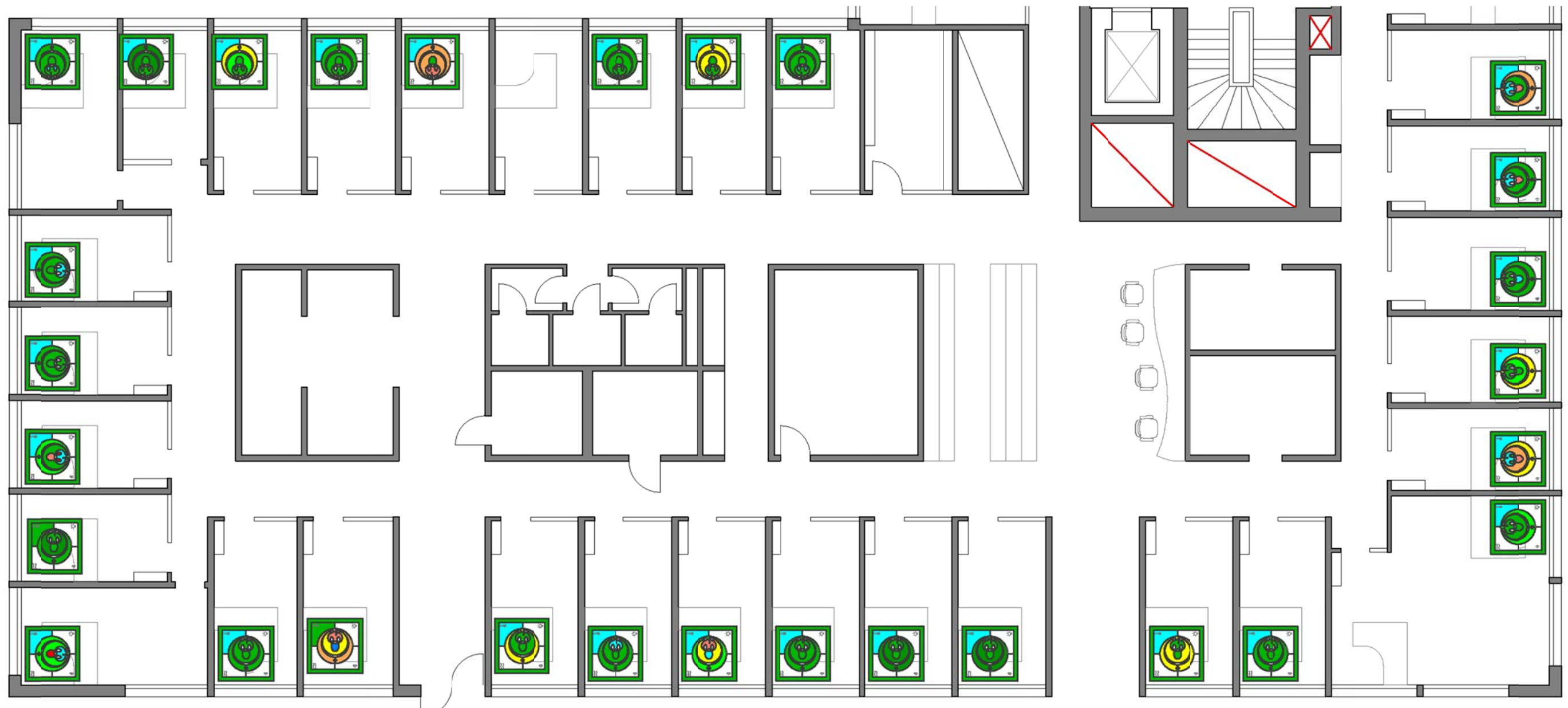


Figure 301: Building A: Late afternoon visual analysis

Building B: Morning, Early and Late Afternoon Analysis

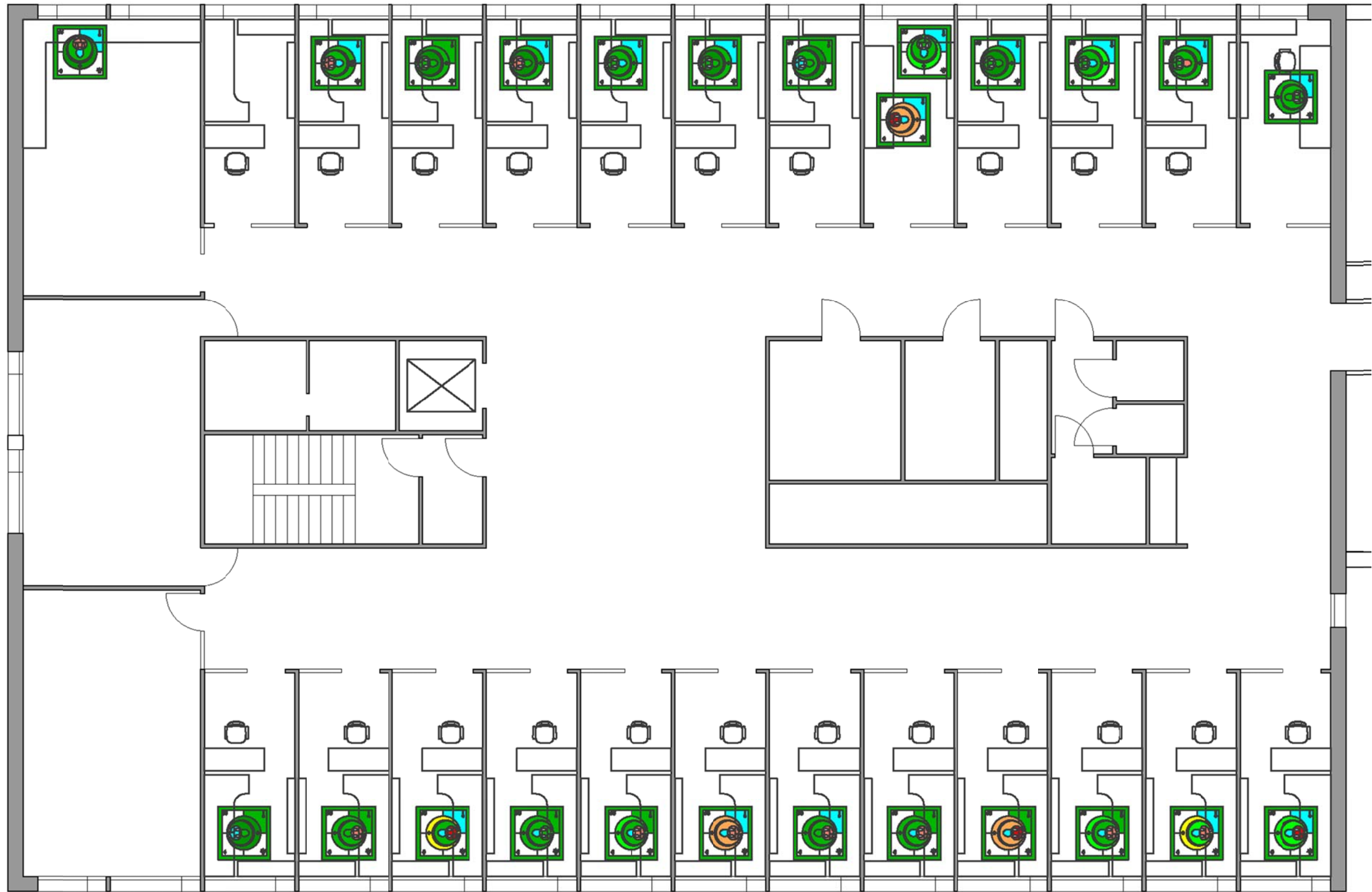


Figure 302: Building B: Morning visual analysis

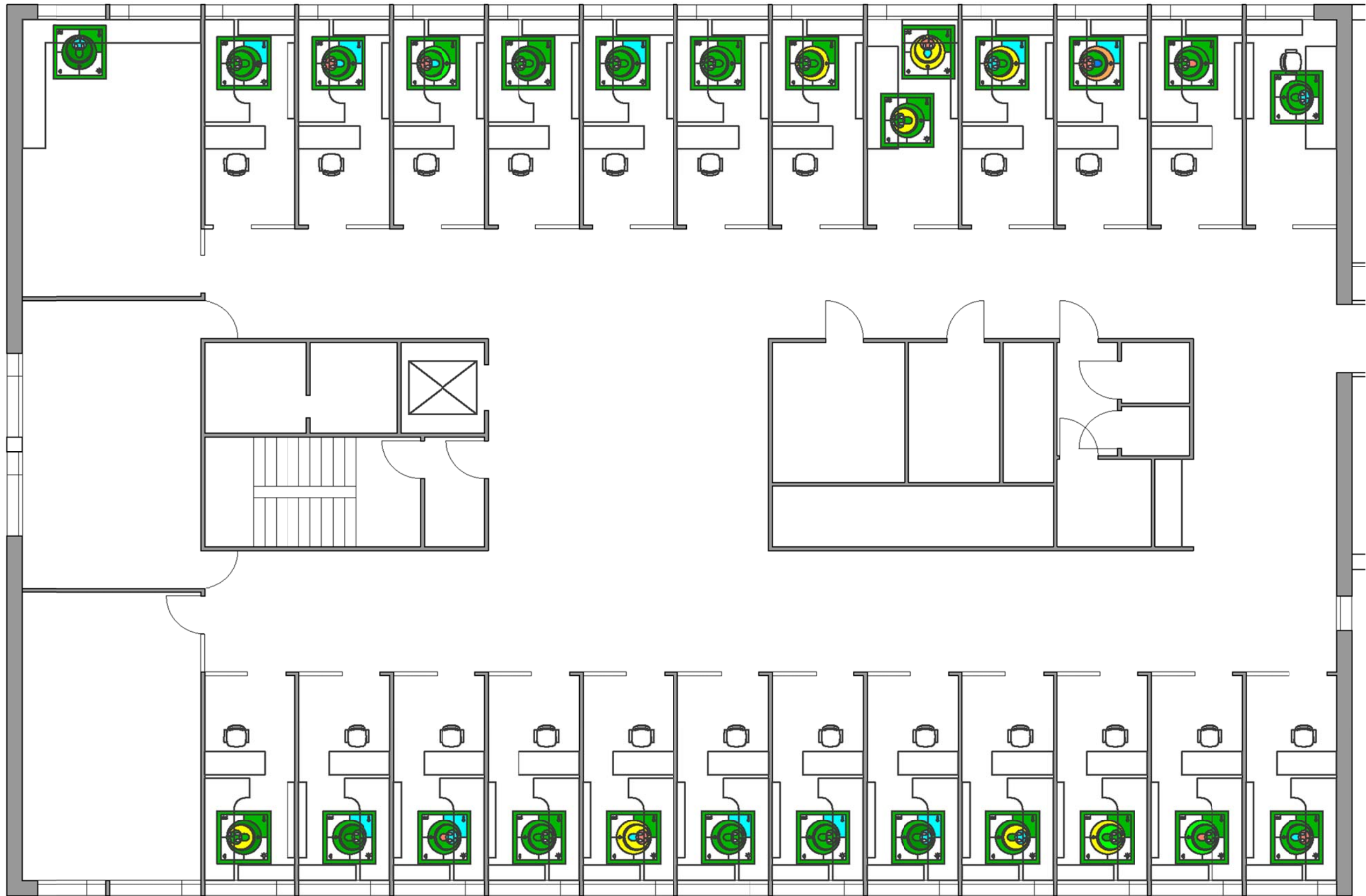


Figure 303: Building B: Early afternoon visual analysis

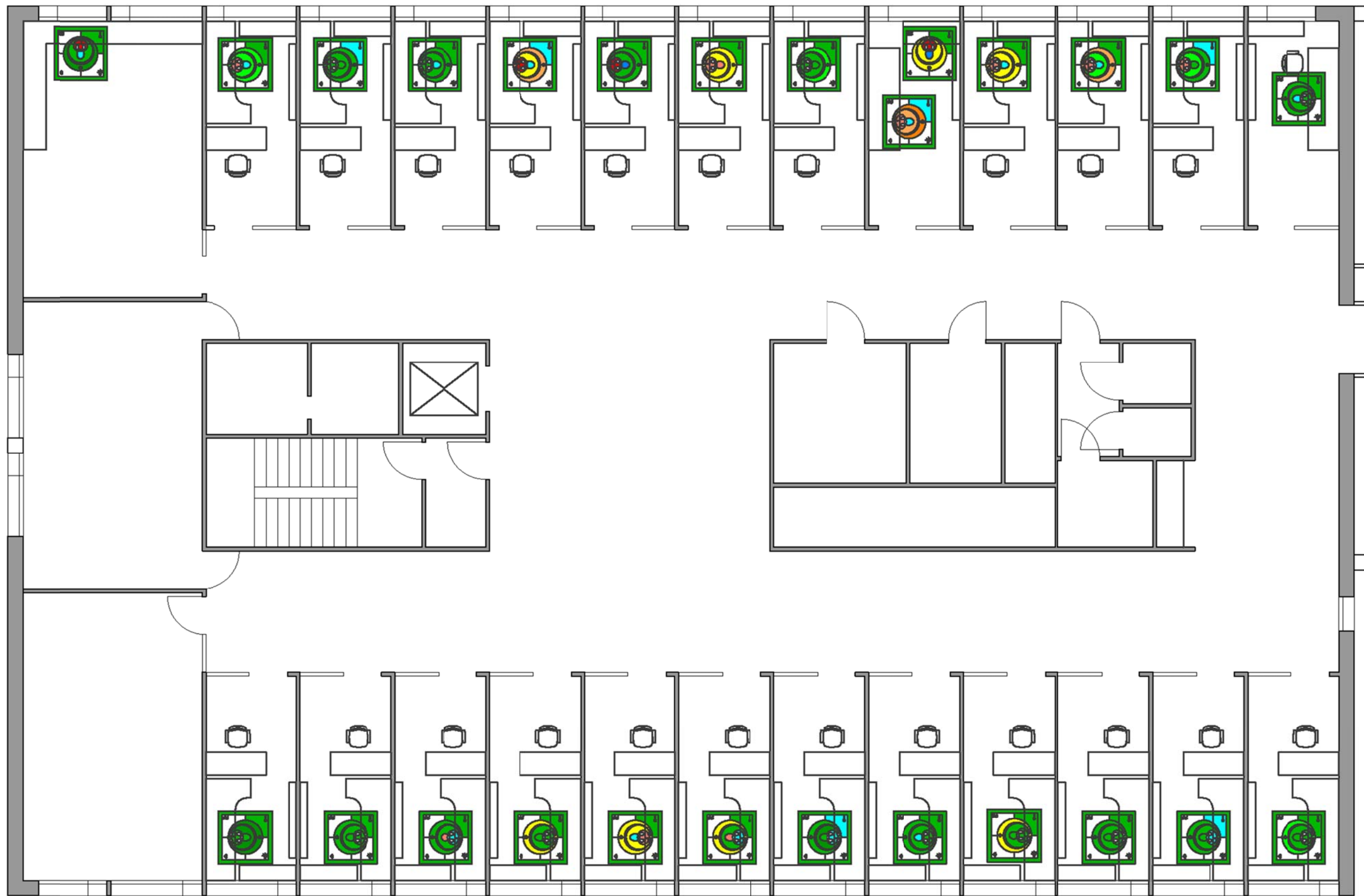


Figure 304: Building B: Late afternoon visual analysis

Building C: Morning, Early and Late Afternoon Analysis

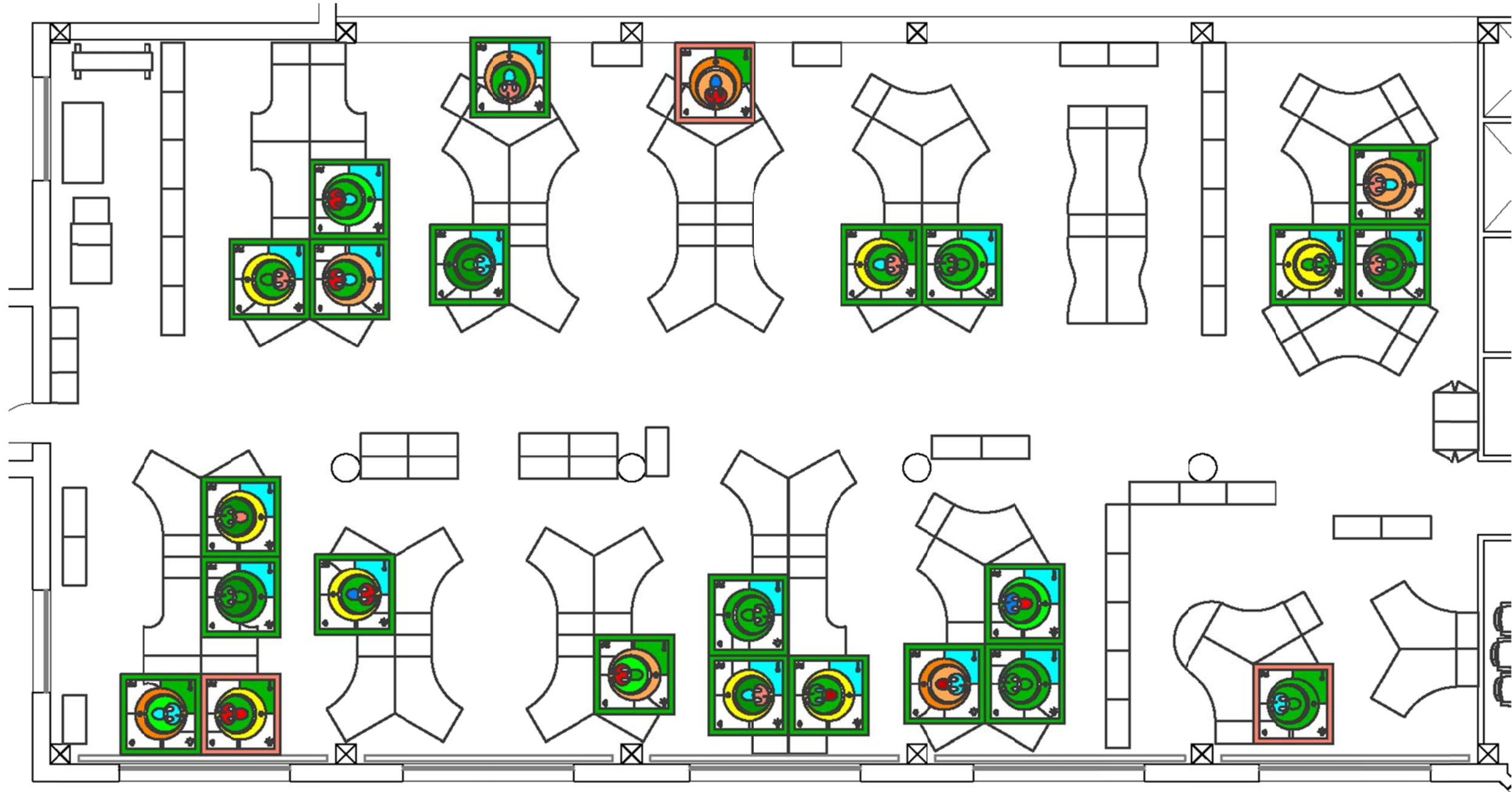


Figure 305: Building C: Morning visual analysis

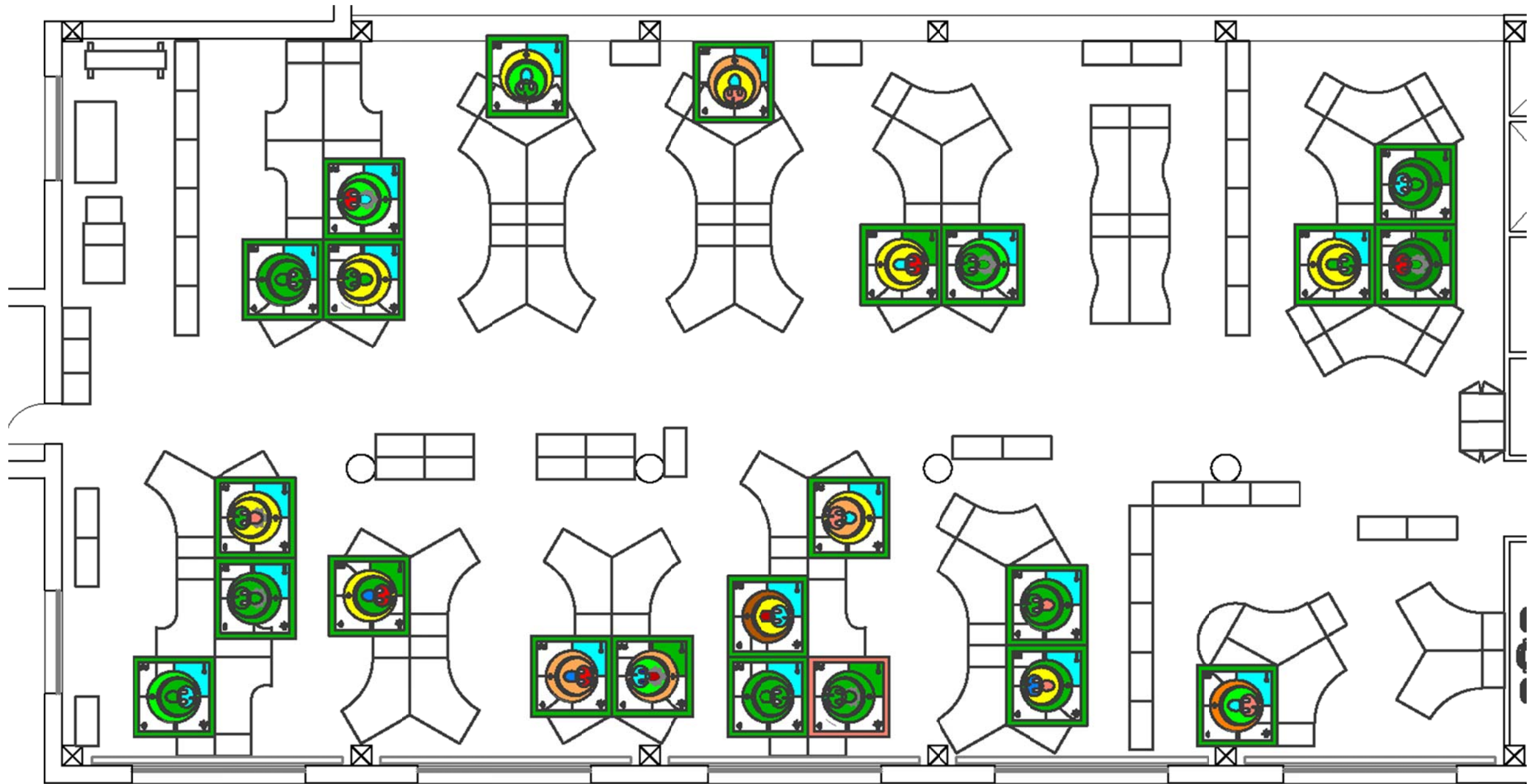


Figure 306: Building C: Early afternoon visual analysis

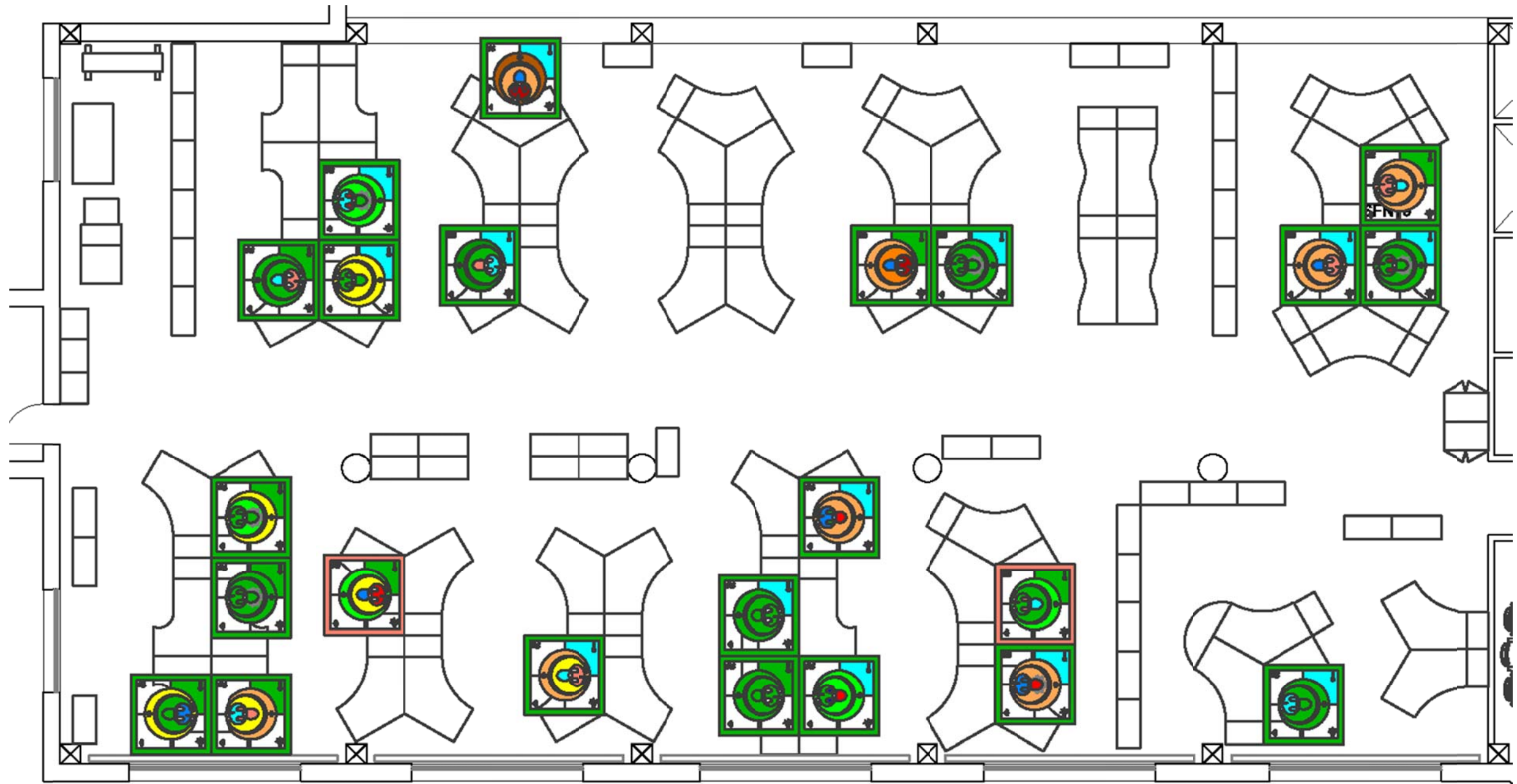


Figure 307: Building C: Late afternoon visual analysis

Building D: Morning, Early and Late Afternoon Analysis

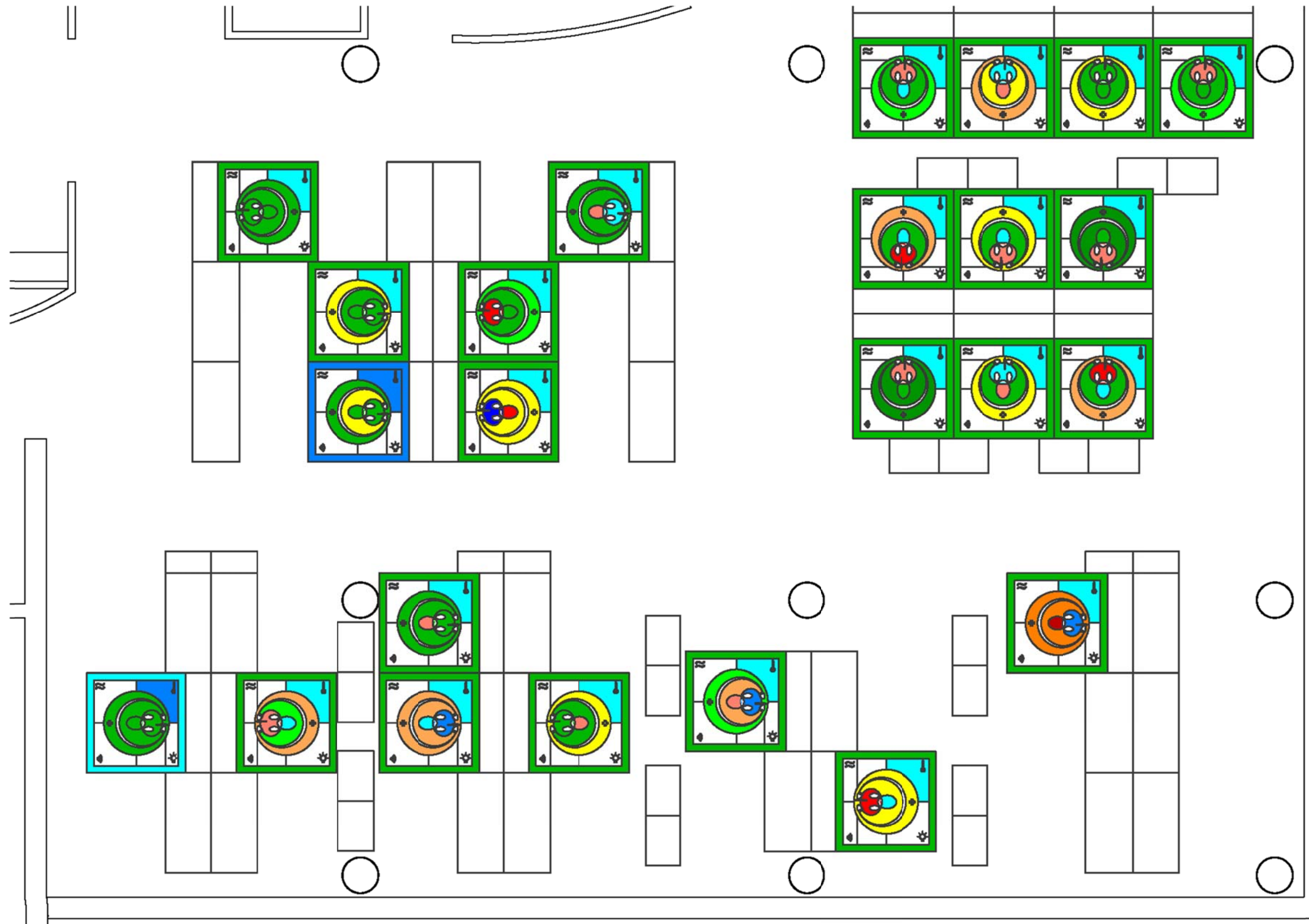


Figure 308: Building D: Morning visual analysis

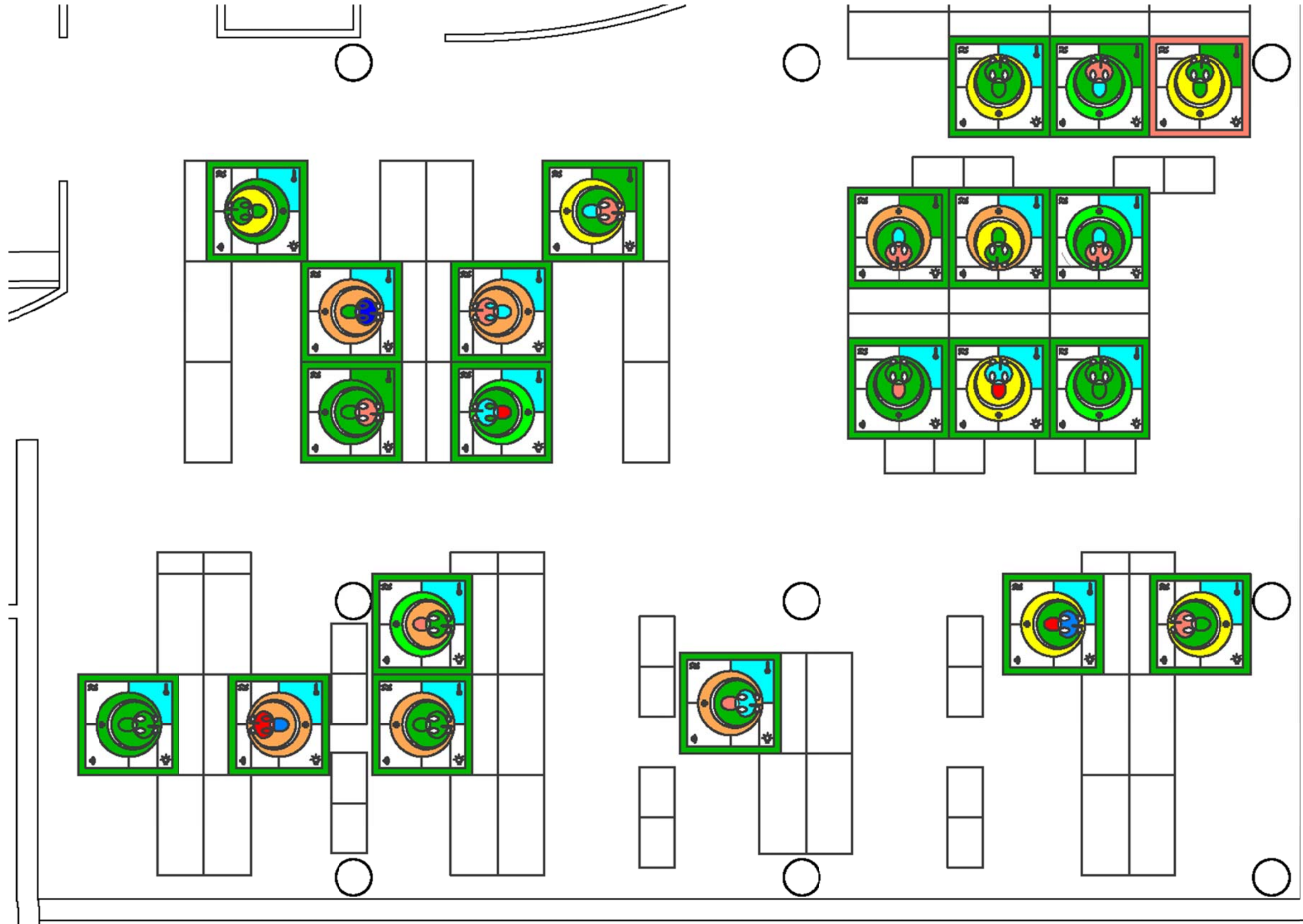


Figure 309: Building D: Early afternoon visual analysis



Figure 310: Building D: Late afternoon visual analysis

Appendix B: Questionnaires

Initial Paper-Based Questionnaire

Questionnaire for Individual Comfort

Building: G2G3 Office

Date:

Please kindly attempt to answer all the questions. It is important that you record your own views, without talking to colleagues. Do not take too much time over your answers. Just give your initial response at this point in time and space.

Please note that all of your information is confidential, as it is for research purposes only.

I. General Information

1. Surname: _____ First Name: _____

2. Tell (Optional): _____

3. Email address (Optional): _____

4. Sex: Female Male

5. Year of birth: 19 ____

6. What is the main part of the work you do? Please tick a box:

Managing people or resources

Using special skills (e.g. legal, medical, engineering, scientific)

Doing clerical, secretarial or administrative work

Other, please describe: _____

7. How long have you been working in this company? _____ years & _____ months

8. How long have you been working at your current workstation (desk)? _____ years & _____ months

9. How many days per week do you normally spend in the building? _____ days

10. How many hours per day do you normally spend at your desk? _____ hours

11. How many hours per day do you normally operate a PC at work? _____ hours

II. General Thermal Comfort. Please tick a box:

12. The temperature level in the office is usually acceptable:

Strongly agree Agree Slightly agree No strong opinion Slightly disagree

Disagree Strongly disagree

13. The humidity level in the office is usually acceptable:

Strongly agree Agree Slightly agree No strong opinion Slightly disagree

Disagree Strongly disagree

14. The light level in the office is usually acceptable:

Strongly agree Agree Slightly agree No strong opinion Slightly disagree

Disagree Strongly disagree

15. The noise level in the office is usually acceptable:

Strongly agree Agree Slightly agree No strong opinion Slightly disagree

Disagree Strongly disagree

16. The source of distracting noise is:

Outside Traffic Inside Computers Printers and other equipments

Colleagues talking together Colleagues talking on the phone Toilets Other

Questionnaire for Individual Comfort

II. Thermal comfort. Please tick a box:

Note: Please respond to this set of questions based on the exact condition of current time and space.

17. Overall, I feel:

- Very uncomfortable Uncomfortable Slightly uncomfortable No strong opinion
 Comfortable Slightly comfortable Very comfortable

18. The current temperature at my desk is:

- Cold Cool Slightly cool Neutral Slightly warm Warm Hot

19. I prefer the temperature at my desk to be:

- Much colder Colder Slightly colder No change Slightly warmer
 Warmer Much warmer

20. I prefer to be able to change the temperature at my desk :

- Strongly agree Agree Slightly agree No strong opinion Slightly disagree
 Disagree Strongly disagree

21. I prefer the temperature to be automatically set fine without my effort:

- Strongly agree Agree Slightly agree No strong opinion Slightly disagree
 Disagree Strongly disagree

22. I prefer to have a small heater at my desk:

- Strongly agree Agree Slightly agree No strong opinion Slightly disagree
 Disagree Strongly disagree

23. I prefer to have a small fan at my desk:

- Strongly agree Agree Slightly agree No strong opinion Slightly disagree
 Disagree Strongly disagree

24. The current air movement at my desk is:

- Very sufficient Slightly sufficient Sufficient No strong opinion
 Insufficient Slightly insufficient Very insufficient

25. I prefer the air movement at my desk to be:

- Much more More Slightly more No change Slightly less Less Much less

26. I prefer to be able to change the air movement at my desk:

- Strongly agree Agree Slightly agree No strong opinion Slightly disagree
 Disagree Strongly disagree

27. I prefer the air movement to be automatically set fine without my effort:

- Strongly agree Agree Slightly agree No strong opinion Slightly disagree
 Disagree Strongly disagree

28. Currently, the air at my desk is:

- Too dry Dry Slightly dry No strong opinion Slightly humid
 Humid Too humid

29. Currently, my feet are:

- Cold Cool Slightly cool No strong opinion Slightly warm Warm Hot

30. I prefer my feet to be:

- Much colder Colder Slightly colder No change Slightly warmer
 Warmer Much warmer

31. Currently, the floor surface feels:

- Cold Cool Slightly cool No strong opinion Slightly warm Warm Hot

32. Currently at my desk I smell:

- Strongly bad smell Bad smell Slightly bad smell No strong opinion
 Slightly pleasant smell Pleasant smell Strongly pleasant smell

Questionnaire for Individual Comfort

II. Thermal comfort. Please tick a box:

33. If there is a bad smell, the source of the smell is:
 Outside Inside Kitchen Toilets ceiling Equipments in the office
 Heating system Other
34. Currently at my desk the natural light level is:
 Too Strong Strong Adequate No Strong Opinion Inadequate
 Low Too low
35. I prefer to close the blinds:
 Strongly agree Agree Slightly agree No strong opinion Slightly disagree
 Disagree Strongly disagree
36. Currently at my desk the artificial light level is:
 Too Strong Strong Adequate No Strong Opinion Inadequate
 Low Too low
37. I prefer to be able to change the lighting levels:
 Strongly agree Agree Slightly agree No strong opinion Slightly disagree
 Disagree Strongly disagree
38. I prefer to sit next to a window at work:
 Strongly agree Agree Slightly agree No strong opinion Slightly disagree
 Disagree Strongly disagree
39. I prefer to have an outside view at my desk:
 Strongly agree Agree Slightly agree No strong opinion Slightly disagree
 Disagree Strongly disagree
40. Outside view distracts me while working:
 Strongly agree Agree Slightly agree No strong opinion Slightly disagree
 Disagree Strongly disagree

III. Building related symptoms. Please tick a box:

	Very Strongly	Strongly	Slightly	Not at all
41. Currently at my desk, I have dry or watery eyes	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
42. Currently at my desk, I have blocked or runny nose	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
43. Currently at my desk, I have dry or irritated throat	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
44. Currently at my desk, I have chest tightness	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
45. Currently at my desk, I have dry or irritated skin	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
46. Currently at my desk, I have headaches	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
47. Currently at my desk, I have lethargy or tiredness	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
48. Currently at my desk, I have pain in neck, shoulders or back	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>


Thank you very much.

Figure 311: Initial paper-based questionnaire

Initial Online Questionnaire: General Questions

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General Questionnaire on Thermal Comfort at the Victoria Quay Building



Welcome

I am a PhD candidate in architecture at the University of Edinburgh. I am researching the internal environment of workplaces in terms of thermal environment and individual comfort. The aim of this research is to improve the future development of workplaces in order to increase users' health, comfort, productivity and satisfaction by providing a more pleasant, comfortable and sustainable internal environment. A survey of the Victoria Quay Building is part of this research and I would be very grateful if you kindly participate in the research by answering this online questionnaire.

This questionnaire seeks to gain a general understanding of the Victoria Quay building in terms of thermal comfort. Please record your own views and do not take too much time over your answers; just give your initial response. The survey takes around 15 minutes to complete.


Many thanks for participating in this research.
Kind regards,
Sally

Note that once you have clicked on the CONTINUE button at the bottom of each page you can not return to review or amend that page

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General Questionnaire on Thermal Comfort at the Victoria Quay Building



Data Protection

All data collected in this survey will be held anonymously and securely. I would stress that this work is for academic purposes only as part of my research for the University of Edinburgh, therefore all of your personal information is confidential.

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General Questionnaire on Thermal Comfort at the Victoria Quay Building



Part I

Questions are **mandatory** unless marked otherwise.

Note that once you have clicked on the CONTINUE button your answers are submitted and you can not return to review or amend that page.

1. Initials

2. Are you

Male

Female

3. Year of birth

Select an answer

4. Country of birth

Select an answer

5. What is the main part of the work you do?
(select all that apply)

Managing people or resources

Using special skills (e.g. legal, medical, engineering, scientific)

Clerical, secretarial or administrative work

Other (please specify):

6. How long have you been working in this building?

Select an answer

7. How many days per week do you normally spend in the building?

Select an answer

8. How long have you been working at your current workstation (desk)?

Select an answer

9. How many hours per day do you normally spend at your desk?

Select an answer

10. How often have you changed your workstation?

Never Every few years Every year Every few months Every month Every day Every few hours

Other (please specify):

12. Do you usually work in a team?

Yes No

Do you sit next to your team members?

Yes No

13. Have you ever suffered from

	Yes	No
a. Hay fever or other allergic reactions	<input type="radio"/>	<input type="radio"/>
b. Asthmatic problems	<input type="radio"/>	<input type="radio"/>
c. Eczema	<input type="radio"/>	<input type="radio"/>

Continue >

General Questionnaire on Thermal Comfort at the Victoria Quay Building



Part II

14. Generally, which climatic environment do you prefer?

- Very cold
- Cool
- Slightly cool
- Neutral
- Slightly warm
- Warm
- Hot
- No strong opinion

15. How do you usually feel at your work station in the

	Very cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot	No strong opinion
a. Summertime	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
b. Wintertime	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

16. Generally when you are in a stressful situation, how do you feel?

(How does your body react? Does your body become warmer or colder? Do you feel warmer or colder than usual?)

- Much colder than usual
- Colder than usual
- Slightly colder than usual
- The same as usual
- Slightly warmer than usual
- Warmer than usual
- Much warmer than usual
- No strong opinion

17. Generally when you are in a stressful situation, how do you prefer the environment to be?

- Very cold
- Cool
- Slightly cool
- Neutral
- Slightly warm
- Warm
- Hot
- No strong opinion

Continue >

General Questionnaire on Thermal Comfort at the Victoria Quay Building



Part III

18. At work how often do you have

	Constantly	Very often	Often	Occasionally	Rarely	Never	No strong opinion
a. Dry or watery eyes	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
b. Blocked or runny nose	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
c. Dry or irritated throat	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
d. Chest tightness	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
e. Dry or irritated skin	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
f. Headaches	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
g. Lethargy or tiredness	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Continue >

General Questionnaire on Thermal Comfort at the Victoria Quay Building



Part IV

19. Overall, do you rate this building as sustainable?

- Strongly agree Agree Slightly agree No strong opinion Slightly disagree Disagree Strongly disagree

20. Overall, are you happy with the performance of the building?

- Strongly agree Agree Slightly agree No strong opinion Slightly disagree Disagree Strongly disagree

If you are not happy with the performance of the building, could you briefly explain why? (Optional)

21. Overall, how do you feel at the office?

- Very comfortable Comfortable Slightly comfortable Neutral Slightly uncomfortable Uncomfortable Very uncomfortable No strong opinion

22. Would you prefer to be able to change the temperature at your desk?

- Strongly agree Agree Slightly agree No strong opinion Slightly disagree Disagree Strongly disagree

23. Do you actually change the temperature at your desk?

If your answer is Slightly agree, Agree or Strongly agree please answer questions a and b, otherwise please go to question 24.

- Strongly agree Agree Slightly agree No strong opinion Slightly disagree Disagree Strongly disagree

a. At the office, how often do you personally change the temperature? (Optional)

- Every few hours Every day Every week Every month Every season Never

Other (please specify):

b. At the office, how do you actually change the temperature?

Please go to question 25. (Optional) (select all that apply)

- Open/close a window
 Change the nearest thermostat
 Turn on/off a small heater at my desk
 Turn on/off a small fan at my desk
 Change the central control system for the temperature in the office
 Ask the facilitator manager/others to change the temperature
 I don't change the temperature
 Other (please specify):

24. Why don't you want to change the temperature at the office? (Optional) (select all that apply)

- The temperature is fine
 I don't know how to change the temperature
 I don't want to worry or think about it
 I don't want to lose my concentration
 It takes energy/effort
 It takes time
 Whatever I do is not effective and I cannot change the actual temperature at my work station
 We are not allowed
 Other (please specify):

25. Do you prefer the following to be automatically set without your effort at the office?

	Strongly agree	Agree	Slightly agree	No strong opinion	Slightly disagree	Disagree	Strongly disagree
a. Temperature	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
b. Air movement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
c. Light levels	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

26. At your desk, do you prefer to have a small

	Strongly agree	Agree	Slightly agree	No strong opinion	Slightly disagree	Disagree	Strongly disagree
a. Heater	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
b. Fan	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
c. Cooler	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
d. Desk lamp	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

27. Do you prefer to be able to change the air movement at your desk?

Strongly agree Agree Slightly agree No strong opinion Slightly disagree Disagree Strongly disagree

28. Usually at your desk, is there a bad smell?

Strongly agree Agree Slightly agree No strong opinion Slightly disagree Disagree Strongly disagree

If there is a bad smell, which is the source of the smell? (Optional) (select all that apply)

Outside Inside Kitchen/Pantry Toilets Ceiling Equipments in the office Heating/cooling system Stuffy air

Other (please specify):

29. Usually at your desk, are you satisfied with the light level?

Strongly agree Agree Slightly agree No strong opinion Slightly disagree Disagree Strongly disagree

30. Usually at your desk, how is the natural light level?

Very adequate Adequate Slightly adequate Neutral Slightly inadequate Inadequate Very inadequate No strong opinion

31. Usually in the office, do you prefer to close the blinds?

Strongly agree Agree Slightly agree No strong opinion Slightly disagree Disagree Strongly disagree

32. Do you prefer to be able to change the light levels?

Strongly agree Agree Slightly agree No strong opinion Slightly disagree Disagree Strongly disagree

33. Is your current workstation next to a window?

Yes No

Are you happy with it?

Strongly agree Agree Slightly agree No strong opinion Slightly disagree Disagree Strongly disagree

34. Does your current workstation have an outside view?

Yes No

Are you happy with it?

Strongly agree Agree Slightly agree No strong opinion Slightly disagree Disagree Strongly disagree

35. At work, do you prefer to

	Strongly agree	Agree	Slightly agree	No strong opinion	Slightly disagree	Disagree	Strongly disagree
a. Have an outside view	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
b. Sit next to a window	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
c. Face the window	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

36. Does an outside view distract you while working?

Strongly agree Agree Slightly agree No strong opinion Slightly disagree Disagree Strongly disagree

37. Do you usually feel closed-in at your workstation?

Strongly agree Agree Slightly agree No strong opinion Slightly disagree Disagree Strongly disagree

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General Questionnaire on Thermal Comfort at the Victoria Quay Building



Part V

38. What do you do when you feel hot in the office in summertime?
(select all that apply)

- I drink cold water/drinks
- I take off my extra clothes
- I turn on a small fan
- I change the central temperature control
- I open a window
- I open a door
- I tolerate it
- I move to another place
- I inform the facilitator manager/person in charge
- Other (please specify):

39. What do you do when you feel cold in the office in wintertime?
(select all that apply)

- I drink warm coffee/tea
- I put on a pullover/jumper
- I put on a scarf
- I put on gloves
- I turn on a small heater
- I change the central temperature control
- I close the windows
- I close the door
- I tolerate it
- I move to another place
- I inform the facilitator manager/person in charge
- Other (please specify):

40. What do you do when the air is stuffy in the office in summertime?
(select all that apply)

- I open a window
- I open a door
- I turn on a small fan
- I tolerate it
- I move to another place
- I inform the facilitator manager/person in charge
- Other (please specify):

41. What do you do when the air is stuffy in the office in wintertime?
(select all that apply)

- I open a window
- I open a door
- I turn on a small fan
- I tolerate it
- I move to another place
- I inform the facilitator manager/person in charge
- Other (please specify):


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 Supervisor: 28
 22 October 2011
 PhD in Architecture
 University of Ed.
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General Questionnaire on Thermal Comfort at the Victoria Quay Building



Part VI

42. Would you like to participate in this academic research to improve internal environments of workplaces to increase comfort, health and satisfaction of users? The participants are required to answer a single sheet questionnaire, which includes 12 questions and will take approximately three minutes. They are required to answer this questionnaire four times. These questions include the instant feeling and satisfaction of the temperature, air movement and light levels. The researcher will measure the temperature, humidity, light levels and CO2 levels while the occupant is answering the questionnaire.

Yes No

a. First Name
If you intend to participate, please enter your name in order to contact you. I would stress that your personal information is confidential.

b. Surname

c. Tel. (Optional)


d. Email address (Optional)

43. Please kindly write your comments or add any information you would like the researcher to know. (Optional)

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General Questionnaire on Thermal Comfort at the Victoria Quay Building



Final Page

Thank you very much to fill in the questionnaire.

Kind regards,
Sally

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Figure 312: Initial online questionnaire, general questions

Appendix C: Collected Data

Building	Date	Time	Comfort	Thermal_Sensation	Thermal_Intention	Ventilation_Intention	Fresh_Air	Light_Intention	Productivity	Satisfaction	Temperature	Humidity	CO2	Light	Noise=	Clothes
A	23-Jul-2012	1	-1	2	-2	-3	-3	1	-1	-2	24.90	43.40	396	1085	68.90	1
A	23-Jul-2012	2	0	1	-1	1	-1	0	0	-1	24.80	40.00	376	1092	49.80	1
A	23-Jul-2012	2	0	0	0	0	0	2	0	0	24.30	40.90	181	282	59.70	3
A	23-Jul-2012	3	-1	1	-2	-2	-2	0	0	-1	24.70	41.10	95	238	100.70	3
A	24-Jul-2012	1	2	0	0	-1	0	3	0	2	21.60	62.40	302	582	42.60	3
A	24-Jul-2012	2	2	0	0	1	2	2	0	2	26.50	44.90	554	628	60.40	3
A	24-Jul-2012	3	-1	-2	2	1	1	2	0	-1	24.20	50.00	507	398	88.00	3
A	24-Jul-2012	1	2	2	-1	-1	-1	2	-1	1	21.60	62.40	302	397	36.40	2
A	24-Jul-2012	2	1	2	-1	-1	-1	2	-1	1	25.00	48.80	895	419	68.90	3
A	24-Jul-2012	3	1	-1	0	1	1	2	0	1	24.10	50.80	388	412	32.40	3
A	24-Jul-2012	1	2	2	-1	-2	-2	2	0	-1	25.40	57.40	486	375	67.80	2
A	24-Jul-2012	2	0	0	0	2	2	2	0	0	23.30	50.20	441	448	40.79	2
A	24-Jul-2012	3	0	0	0	2	2	2	-2	0	24.00	50.90	532	444	78.90	2
A	22-Jul-2012	1	2	1	-1	-2	-1	0	0	0	24.80	47.20	551	427	51.10	2
A	22-Jul-2012	2	0	2	-1	-1	-1	0	0	0	25.60	43.40	578	423	86.60	2
A	22-Jul-2012	3	-2	3	-2	-2	-2	0	-1	-1	24.70	43.60	390	499	71.90	2
A	23-Jul-2012	1	1	-1	-1	2	3	3	0	-2	24.30	45.30	299	1378	72.00	1
A	23-Jul-2012	2	2	-1	0	3	3	3	0	1	24.10	42.20	123	539	74.40	1
A	23-Jul-2012	3	2	-2	0	2	-1	3	0	0	24.90	41.10	354	307	66.80	1
A	23-Jul-2012	2	-1	1	-1	-2	-2	-1	-1	0	25.00	40.70	196	240	71.00	1
A	23-Jul-2012	3	-1	-2	2	-1	-1	0	1	-1	25.00	42.00	126	201	67.00	2
A	23-Jul-2012	2	0	-2	1	0	1	-1	0	2	24.70	41.00	136	889	88.60	1
A	23-Jul-2012	3	2	-1	0	2	2	2	0	2	24.40	41.20	83	1044	67.09	1
A	23-Jul-2012	1	2	-1	0	3	3	0	0	2	25.80	41.30	425	427	91.80	1
A	24-Jul-2012	1	2	1	-1	0	-1	-1	0	-1	21.60	62.40	302	378	84.30	3
A	24-Jul-2012	2	1	0	-1	-1	-1	2	1	0	24.90	48.90	461	238	79.70	3
A	24-Jul-2012	3	-3	3	-2	-2	-2	2	-1	-3	24.10	50.80	388	358	40.70	1
A	22-Jul-2012	1	3	-1	0	2	2	2	0	3	21.90	55.20	241	298	82.00	1
A	22-Jul-2012	3	2	-1	1	2	2	-1	0	3	24.60	42.40	320	205	73.50	1
A	23-Jul-2012	1	3	1	0	2	2	2	0	2	25.00	48.40	438	385	87.90	3
A	24-Jul-2012	1	2	1	0	2	2	2	0	2	25.40	47.90	615	277	79.20	3
A	24-Jul-2012	2	3	2	0	2	2	2	0	3	24.40	51.40	330	326	73.09	1
A	24-Jul-2012	3	2	0	0	3	2	2	0	2	21.60	62.40	302	483	77.00	3
A	22-Jul-2012	1	2	0	0	2	2	0	0	2	22.40	53.70	273	356	80.40	2
A	22-Jul-2012	2	2	0	0	0	2	2	0	2	25.30	46.70	578	414	74.80	2
A	22-Jul-2012	3	2	0	0	2	2	2	0	2	23.90	43.40	324	487	83.30	2
A	23-Jul-2012	1	3	1	-1	1	-1	2	-1	0	24.30	43.20	337	2630	95.80	3
A	23-Jul-2012	3	2	0	0	-1	-1	-2	0	2	25.60	41.30	299	422	71.80	3
A	23-Jul-2012	1	2	0	3	1	2	2	1	0	21.70	54.10	317	585	89.00	1
A	23-Jul-2012	2	0	-1	1	-1	0	0	-1	-1	26.20	45.00	461	438	73.00	3
A	24-Jul-2012	1	2	0	3	1	2	2	1	0	24.10	50.80	388	344	44.50	3
A	24-Jul-2012	2	1	-1	3	0	1	2	0	-1	24.30	42.70	311	1328	85.70	2
A	23-Jul-2012	1	2	1	0	2	2	0	0	0	23.10	51.90	308	365	87.60	1
A	23-Jul-2012	2	2	0	0	2	2	2	0	2	24.60	41.70	315	314	110.00	1
A	23-Jul-2012	3	2	1	-1	1	1	2	0	2	25.40	40.50	373	330	102.00	1
A	23-Jul-2012	1	2	0	0	2	-1	-1	0	1	21.60	62.40	302	357	87.70	3
A	24-Jul-2012	2	2	0	0	0	-1	2	0	1	24.60	50.70	427	177	86.50	1
A	24-Jul-2012	3	2	0	0	1	0	1	-1	2	24.40	50.30	503	240	85.90	3
A	22-Jul-2012	1	3	0	1	0	0	0	0	0	23.80	50.20	385	538	90.10	1
A	22-Jul-2012	2	0	0	1	0	0	1	3	0	24.50	44.90	578	266	73.20	1
A	22-Jul-2012	3	1	0	0	-1	-1	0	0	0	24.60	43.90	370	634	71.70	2
A	22-Jul-2012	1	3	0	0	2	0	2	0	2	23.90	50.50	399	458	90.00	2
A	22-Jul-2012	2	2	0	0	2	1	2	0	2	23.80	49.50	355	513	48.00	2
A	22-Jul-2012	3	2	0	0	2	0	2	0	2	24.60	44.20	383	645	71.70	2
A	23-Jul-2012	1	2	2	2	1	0	1	-1	0	25.60	43.80	446	732	87.60	2
A	23-Jul-2012	3	0	-1	1	-1	0	2	-1	1	25.70	40.00	266	1911	102.20	2
A	23-Jul-2012	2	2	2	-2	-1	-1	1	0	0	24.90	41.30	214	222	72.09	1
A	23-Jul-2012	3	0	2	-2	-1	-1	1	0	1	26.10	38.90	293	362	91.30	1
A	23-Jul-2012	2	-1	2	-2	-1	-1	2	-1	-1	24.60	43.00	336	361	70.30	1
A	23-Jul-2012	3	0	1	-1	-1	-1	2	0	-1	24.30	42.80	169	359	77.20	1

Building	Date	Time	Comfort	Thermal_Sensation	Thermal_Intention	Ventilation_Intention	Fresh_Air	Light_Intention	Productivity	Satisfaction	Temperature	Humidity	CO2	Light	Noise=	Clothes
A	23-Jul-2012	1	1	2	0	-2	-2	-1	0	-1	24.80	44.20	389	539	78.40	1
A	23-Jul-2012	2	0	-1	3	0	0	-1	0	-3	24.30	50.90	437	953	47.40	1
A	24-Jul-2012	1	2	-2	3	2	2	2	0	1	21.20	60.50	320	470	43.70	1
A	24-Jul-2012	2	2	0	1	0	0	0	0	2	24.60	50.00	445	1303	81.00	1
A	24-Jul-2012	1	-1	-2	3	-1	-2	2	-1	-2	21.60	62.40	302	609	51.90	3
A	24-Jul-2012	2	1	1	-1	-2	-2	0	-3	-2	24.60	48.80	435	859	81.80	2
A	22-Jul-2012	1	2	2	-1	-2	-2	0	0	1	24.40	46.60	313	2440	487.00	1
A	22-Jul-2012	3	2	0	-1	1	1	2	0	1	25.90	43.60	578	3870	75.80	1
A	22-Jul-2012	2	2	1	-1	-2	-3	2	0	-1	25.20	41.90	346	3270	73.59	1
A	22-Jul-2012	1	-1	1	-1	0	1	2	0	-1	24.30	43.30	445	533	76.30	2
A	22-Jul-2012	2	2	-1	0	2	2	2	0	3	24.50	48.20	578	360	80.40	2
A	22-Jul-2012	3	-1	1	-1	-1	0	2	-1	-1	25.20	41.60	357	572	77.30	2
B	30-Aug-2012	1	2	0	1	0	0	0	1	2	23.40	33.80	429	355	79.90	3
B	30-Aug-2012	2	2	-1	1	0	0	0	-1	-1	24.20	29.10	577	334	84.30	3
B	30-Aug-2012	3	2	0	0	0	0	0	-1	1	24.00	26.10	470	298	74.20	2
B	30-Aug-2012	2	-1	-3	0	2	2	0	-1	-1	23.60	28.40	455	321	70.90	3
B	30-Aug-2012	3	0	-1	2	2	2	0	0	0	23.80	25.80	460	391	74.20	3
B	30-Aug-2012	1	-1	-2	1	0	0	0	1	1	23.40	38.90	516	585	89.10	1
B	30-Aug-2012	2	2	0	0	2	2	0	0	-1	23.90	29.80	500	546	82.90	1
B	30-Aug-2012	3	0	2	-1	2	2	0	-1	-2	24.40	30.30	528	543	88.70	1
B	29-Aug-2012	1	2	-1	1	0	0	0	0	2	23.60	52.10	480	508	76.80	2
B	31-Aug-2012	1	2	2	0	0	2	0	0	1	23.10	33.30	491	463	111.00	3
B	31-Aug-2012	2	-1	1	-1	1	1	0	0	-1	23.80	34.20	472	520	84.80	3
B	31-Aug-2012	3	0	0	0	1	1	0	0	0	23.40	32.50	481	413	86.20	1
B	31-Aug-2012	1	0	-3	2	0	0	0	0	0	23.50	33.10	551	668	83.80	1
B	31-Aug-2012	2	2	-1	2	0	0	0	0	1	24.30	29.20	451	589	78.40	1
B	31-Aug-2012	3	2	-1	2	0	0	0	-1	0	24.60	29.80	481	509	80.20	1
B	29-Aug-2012	1	2	0	0	0	0	0	0	2	23.50	48.70	373	505	85.80	1
B	29-Aug-2012	2	0	0	0	0	0	0	0	2	24.70	43.70	409	498	86.10	1
B	29-Aug-2012	3	0	0	0	0	0	0	0	2	23.50	46.70	394	477	84.80	1
B	30-Aug-2012	1	-1	-2	-1	1	2	1	0	-1	23.20	37.70	567	415	63.50	1
B	30-Aug-2012	2	-1	0	1	1	0	0	1	1	23.70	29.90	707	363	70.70	1
B	31-Aug-2012	2	0	0	0	1	1	0	0	0	25.20	30.40	423	898	70.00	3
B	30-Aug-2012	1	3	1	0	0	0	0	0	3	22.20	44.30	464	675	67.60	2
B	30-Aug-2012	2	2	0	1	0	0	0	1	2	24.40	31.50	562	594	75.80	3
B	30-Aug-2012	3	2	0	1	0	0	0	0	2	23.90	29.20	488	561	70.80	3
B	30-Aug-2012	1	2	-1	1	0	1	0	0	0	24.00	36.50	531	523	87.30	3
B	30-Aug-2012	2	0	-1	2	0	0	0	0	0	24.30	32.00	657	534	74.00	3
B	30-Aug-2012	3	2	0	0	1	0	0	0	0	23.30	33.30	385	476	75.30	3
B	28-Aug-2012	1	2	2	-1	1	1	0	0	-1	24.30	50.70	389	612	81.80	2
B	28-Aug-2012	2	2	0	0	1	0	0	0	1	24.50	43.30	420	477	54.20	2
B	28-Aug-2012	3	1	0	0	1	0	0	0	0	24.80	37.30	516	848	152.80	2
B	28-Aug-2012	1	2	1	-1	0	1	0	0	0	22.90	50.60	373	528	78.70	3
B	28-Aug-2012	2	2	1	-1	1	1	0	1	-1	26.40	38.70	426	504	55.20	3
B	28-Aug-2012	3	2	-1	0	0	0	0	1	2	24.40	37.90	520	494	114.10	3
B	29-Aug-2012	1	2	-2	2	0	2	0	0	0	23.50	49.30	424	503	88.50	1
B	29-Aug-2012	2	-2	-2	3	0	0	0	0	-2	24.50	44.90	573	630	82.90	3
B	29-Aug-2012	3	0	0	0	0	0	0	0	0	23.60	48.30	372	848	80.80	1
B	30-Aug-2012	2	2	1	0	2	3	0	-1	0	23.60	32.00	416	1044	84.30	3
B	30-Aug-2012	3	1	1	-1	2	3	0	0	-1	24.00	27.40	386	501	69.40	3
B	31-Aug-2012	1	0	2	-1	1	1	0	0	0	23.80	31.90	607	466	93.90	2
B	29-Aug-2012	1	1	1	-1	1	3	0	0	-1	23.30	54.10	508	354	82.70	1
B	29-Aug-2012	2	-1	2	-2	1	3	0	0	-1	24.20	47.20	384	470	86.50	1
B	29-Aug-2012	3	1	1	-1	2	2	1	0	-1	24.10	46.60	411	275	79.70	1
B	31-Aug-2012	1	2	0	0	0	0	0	0	2	22.60	33.90	599	1016	73.80	1
B	31-Aug-2012	2	2	0	0	0	0	0	0	2	24.50	30.00	423	927	93.60	1
B	31-Aug-2012	3	2	0	0	0	0	0	0	2	24.30	32.00	457	459	125.70	1
B	31-Aug-2012	1	0	0	0	0	0	0	0	2	20.80	41.40	518	751	73.90	1
B	31-Aug-2012	2	2	1	0	0	0	0	1	2	25.50	30.00	414	532	87.80	1
B	31-Aug-2012	3	2	1	0	0	0	0	0	2	24.50	31.50	433	508	85.60	1
B	29-Aug-2012	1	2	1	0	0	1	0	0	1	22.90	51.00	383	276	90.40	2
B	29-Aug-2012	2	0	0	0	2	3	2	0	-1	25.00	46.20	602	367	78.20	1
B	28-Aug-2012	1	2	2	-1	3	3	0	0	-1	24.60	45.80	631	555	93.30	1
B	28-Aug-2012	2	2	1	-1	1	1	0	0	-1	24.40	53.70	512	568	78.10	1

BuildinB	Date	Time	Comfort	Thermal_Sensation	Thermal_Intention	Ventilation_Intention	Fresh_Air	Light_Intention	Productivity	Satisfaction	Temperature	Humidity	CO2	Light	Noise=	Clothes
B	28-Aug-2012	3	0	0	0	1	1	0	0	0	24.10	40.40	468	464	90.20	1
B	29-Aug-2012	1	2	0	0	1	2	1	0	0	23.40	49.80	416	441	81.20	2
B	29-Aug-2012	2	2	1	-1	0	1	1	0	0	25.20	43.30	689	397	85.50	2
B	29-Aug-2012	3	0	1	-1	0	1	1	0	0	23.90	46.80	379	409	53.30	2
B	28-Aug-2012	1	2	1	-1	0	1	0	2	1	24.20	45.10	426	460	78.80	3
B	28-Aug-2012	2	2	1	-1	1	1	0	-1	1	25.00	40.40	480	384	53.80	1
B	28-Aug-2012	3	2	0	0	1	1	0	1	2	25.00	38.50	363	299	95.50	2
B	29-Aug-2012	1	2	0	0	1	2	0	0	0	25.30	45.00	449	381	82.60	3
B	29-Aug-2012	3	0	0	0	1	1	0	-1	0	24.80	45.60	555	398	76.00	3
B	29-Aug-2012	1	2	0	1	3	0	0	-1	0	23.20	49.70	436	845	75.80	3
B	29-Aug-2012	3	0	0	0	0	1	0	1	0	23.70	47.30	420	523	85.30	3
B	31-Aug-2012	1	3	1	0	0	1	0	0	3	23.60	31.40	470	433	103.30	3
B	31-Aug-2012	2	3	1	0	0	1	0	0	3	25.30	33.10	478	372	80.00	3
B	31-Aug-2012	3	3	1	0	0	0	0	0	3	24.50	30.50	493	403	78.30	3
B	31-Aug-2012	1	0	-1	1	0	3	1	0	-1	24.00	30.50	788	475	90.60	2
B	31-Aug-2012	2	2	0	0	0	3	1	0	0	24.90	32.00	517	448	144.00	1
B	31-Aug-2012	3	1	-1	1	0	3	1	0	0	24.40	30.30	439	403	81.50	1
C	24-May-2012	1	-1	2	-1	-1	-1	-2	0	-1	24.60	46.00	425	284	84.00	2
C	24-May-2012	2	2	0	0	2	2	2	1	2	24.60	42.50	225	1609	44.80	2
C	24-May-2012	3	2	0	0	-1	-1	2	0	0	24.50	35.90	370	1094	94.00	2
C	24-May-2012	1	2	0	-1	0	0	0	0	2	24.60	44.60	302	300	71.60	1
C	24-May-2012	1	2	1	-1	-1	0	3	1	2	24.00	45.20	280	780	82.90	2
C	24-May-2012	2	2	0	0	2	2	2	1	2	24.10	41.30	302	684	37.80	2
C	24-May-2012	3	2	0	1	3	2	2	1	3	24.30	38.90	253	580	94.10	1
C	24-May-2012	3	1	1	-1	2	2	1	-1	2	24.20	34.80	304	710	94.00	2
C	24-May-2012	1	2	-1	0	3	3	3	1	3	23.80	45.80	435	1226	85.60	1
C	24-May-2012	2	3	0	0	3	2	2	0	3	23.90	39.60	741	1017	94.10	1
C	25-May-2012	3	3	0	0	3	3	3	1	3	24.40	34.60	342	872	94.00	1
C	24-May-2012	2	2	0	1	2	2	2	0	1	24.80	39.20	419	947	94.10	2
C	24-May-2012	3	2	-1	0	2	2	2	0	2	24.70	33.70	366	347	94.00	2
C	25-May-2012	1	2	1	-1	-1	2	2	0	2	25.50	39.40	311	1589	85.40	1
C	25-May-2012	2	0	-1	0	0	-1	0	-1	2	25.50	37.70	407	908	94.00	1
C	25-May-2012	3	2	0	-1	-1	-1	2	0	2	25.40	32.30	327	924	90.20	1
C	24-May-2012	1	2	1	0	0	2	2	0	2	23.80	45.40	471	2035	84.60	1
C	24-May-2012	2	3	-1	0	2	2	2	0	2	24.00	38.20	238	1134	94.10	1
C	24-May-2012	3	3	-1	0	2	2	2	0	2	24.20	34.00	343	883	94.00	1
C	25-May-2012	2	2	1	-1	2	2	2	0	2	24.30	39.20	326	763	94.00	2
C	25-May-2012	3	2	0	0	2	2	2	0	2	24.30	39.20	326	763	94.00	2
C	22-May-2012	1	1	2	-1	0	1	1	0	1	24.80	38.00	354	150	67.00	2
C	22-May-2012	2	2	1	-1	1	1	2	1	2	24.60	39.70	452	740	67.00	1
C	22-May-2012	3	2	0	0	1	0	2	0	1	25.00	32.90	472	897	66.90	1
C	24-May-2012	1	2	1	-1	-1	0	2	0	1	23.70	44.90	498	2060	41.70	2
C	24-May-2012	2	1	0	0	1	1	0	0	0	25.30	40.50	505	387	90.20	2
C	24-May-2012	3	2	0	0	1	1	2	0	2	24.10	34.10	348	768	70.80	1
C	22-May-2012	2	2	0	0	2	2	2	0	2	24.00	39.50	352	670	66.80	2
C	23-May-2012	1	1	1	-1	2	1	2	0	0	24.00	37.80	353	1071	41.80	1
C	23-May-2012	2	2	0	0	2	2	1	0	2	23.60	42.70	336	890	46.20	1
C	23-May-2012	3	2	-1	1	0	2	2	0	0	24.10	43.30	309	1209	42.30	1
C	25-May-2012	2	0	1	-1	-1	-1	0	-1	0	25.30	34.50	299	1435	94.00	1
C	25-May-2012	3	0	1	-1	-1	-1	0	-1	0	25.70	32.70	220	1256	90.10	1
C	24-May-2012	1	2	2	-1	0	-1	2	-1	0	24.30	44.20	252	348	41.10	2
C	24-May-2012	2	2	-1	1	2	2	2	0	2	24.20	37.70	286	724	94.10	2
C	24-May-2012	3	2	-1	1	2	2	2	0	2	24.70	33.60	325	728	69.40	2
C	22-May-2012	1	2	1	0	1	1	2	-2	2	25.10	36.10	336	120	67.00	1
C	22-May-2012	2	3	0	0	2	2	2	0	2	24.00	39.50	356	833	67.00	1
C	22-May-2012	3	2	0	0	0	0	1	1	2	24.80	34.00	348	883	67.90	1
C	25-May-2012	1	3	-1	0	3	3	3	0	3	25.30	41.10	351	304	86.40	1
C	25-May-2012	2	0	0	0	0	0	0	0	3	26.10	37.40	400	428	94.00	1
C	25-May-2012	3	3	0	0	0	0	0	0	3	25.50	31.70	315	378	90.00	1
C	25-May-2012	1	2	1	-1	1	3	2	0	3	24.60	40.60	285	300	82.70	2
C	25-May-2012	2	3	-1	0	3	3	3	1	3	25.90	33.90	345	90	85.20	1
C	25-May-2012	3	2	2	-1	3	3	3	0	3	26.30	31.80	337	386	90.00	1

Building	Date	Time	Comfort	Thermal_Sensation	Thermal_Intention	Ventilation_Intention	Fresh_Air	Light_Intention	Productivity	Satisfaction	Temperature	Humidity	CO2	Light	Noise=	Clones
C	25-May-2012	1	3	0	0	2	2	2	1	2	24.50	34.00	288	1695	94.00	1
C	25-May-2012	2	2	1	-1	-1	2	2	2	1	25.00	33.50	311	1765	94.00	1
C	25-May-2012	3	2	0	-1	2	2	2	0	2	26.00	31.00	490	2480	90.20	1
C	22-May-2012	1	3	1	0	2	2	2	1	2	24.30	37.90	245	112	72.00	1
C	22-May-2012	2	2	0	0	2	2	3	1	3	25.00	38.60	348	1065	66.90	1
C	22-May-2012	3	0	2	-1	-2	-1	-1	-1	-1	24.30	35.80	365	328	68.20	1
C	23-May-2012	1	2	0	-1	0	2	2	0	2	24.40	39.20	274	134	43.50	2
C	23-May-2012	2	2	0	0	2	2	2	-1	2	24.30	42.10	348	1138	41.40	2
C	23-May-2012	3	2	2	-2	-1	-1	2	-2	2	24.70	43.60	463	1736	44.70	2
C	22-May-2012	1	3	0	0	0	0	0	0	2	23.20	39.60	270	815	50.00	2
C	22-May-2012	2	2	0	0	1	1	0	0	2	25.00	37.90	325	902	66.90	1
C	22-May-2012	3	0	1	1	-1	-1	0	0	0	24.70	35.90	470	1250	66.50	1
C	24-May-2012	2	2	0	0	0	0	0	1	0	25.60	33.10	468	860	94.00	1
C	24-May-2012	3	2	0	0	2	2	2	1	1	24.70	36.60	385	935	75.20	1
C	24-May-2012	1	2	0	-1	2	2	0	0	1	23.70	42.70	305	1078	35.90	1
C	24-May-2012	2	0	1	-1	1	1	-1	0	0	25.30	36.80	504	1900	94.00	1
C	24-May-2012	3	0	2	-2	-1	-1	0	0	0	25.30	36.80	504	1900	94.00	1
C	24-May-2012	1	-1	2	-1	0	2	2	0	-1	23.70	42.70	305	880	35.50	1
C	24-May-2012	2	0	0	0	2	2	2	1	2	25.20	37.20	450	64	94.10	1
C	24-May-2012	3	-1	1	-1	0	2	2	1	-2	23.80	34.60	305	199	73.80	1
C	23-May-2012	1	3	0	0	2	2	1	0	2	24.10	39.50	402	626	44.80	1
C	23-May-2012	2	2	-1	0	2	2	2	0	0	24.00	41.50	435	370	45.50	1
C	23-May-2012	3	0	1	-1	2	2	1	0	0	24.30	44.60	307	1542	43.10	1
C	23-May-2012	1	2	0	-1	2	2	2	0	1	24.30	38.70	559	432	41.20	1
C	25-May-2012	2	2	1	-2	-1	0	2	-1	-1	23.70	33.40	471	1032	90.30	1
C	25-May-2012	3	2	1	-2	-1	0	2	-1	-1	25.00	33.40	471	1032	90.30	1
C	24-May-2012	1	2	0	1	2	2	1	0	2	23.80	43.90	210	122	37.30	1
C	24-May-2012	2	2	0	1	2	2	2	0	2	25.30	37.30	263	505	81.00	1
C	24-May-2012	3	1	1	0	2	2	2	-1	2	23.90	36.10	268	1381	94.00	1
C	24-May-2012	1	2	0	0	-1	-2	2	-1	2	24.20	44.10	174	285	51.10	1
C	24-May-2012	2	2	-1	0	0	1	2	1	2	24.80	40.40	364	257	94.10	1
C	24-May-2012	3	2	0	-1	-1	-1	3	1	2	24.50	33.80	284	715	69.90	1
D	30-May-2012	1	2	0	-1	-1	-1	0	0	2	23.50	18.00	430	500	94.10	2
D	31-May-2012	3	-1	1	0	-1	-1	0	0	-1	24.30	24.30	430	616	89.90	2
D	30-May-2012	1	2	0	0	-1	-1	-1	0	2	23.20	17.10	333	569	94.10	3
D	30-May-2012	2	0	0	0	0	-1	0	0	0	24.20	16.90	139	1003	94.10	2
D	30-May-2012	3	0	0	0	-1	-1	0	0	0	24.00	19.50	83	1069	93.90	2
D	01-Jun-2012	1	2	0	0	-1	-1	0	0	2	22.20	18.00	215	1653	86.80	2
D	01-Jun-2012	2	2	0	0	0	0	0	0	2	24.50	11.20	401	1311	87.20	2
D	01-Jun-2012	3	2	0	0	-1	-1	0	0	2	25.00	11.30	447	1827	52.40	2
D	05-Jun-2012	1	2	0	0	-3	-3	2	0	2	23.20	29.90	437	212	75.20	3
D	05-Jun-2012	2	2	0	0	-3	0	2	-1	2	23.50	27.90	514	236	91.90	3
D	01-Jun-2012	1	2	0	10	-1	-1	2	0	1	22.40	15.10	387	451	94.80	1
D	01-Jun-2012	2	2	-1	0	0	1	2	-1	1	23.10	9.40	423	488	74.30	1
D	05-Jun-2012	3	2	0	0	-2	1	2	-1	1	23.70	32.60	461	245	84.40	3
D	04-Jun-2012	1	2	-1	0	0	2	2	0	2	21.40	30.50	278	526	85.20	4
D	04-Jun-2012	2	2	-1	0	0	0	0	-1	0	23.40	27.10	279	578	72.20	4
D	04-Jun-2012	3	-1	-1	1	0	0	0	-1	0	23.40	26.40	151	1145	75.20	4
D	30-May-2012	1	2	0	0	0	1	0	0	2	24.20	16.20	408	740	94.10	1
D	30-May-2012	2	2	0	0	0	1	0	0	2	23.50	16.10	335	1096	94.10	1
D	30-May-2012	1	2	0	0	-1	-1	2	0	2	23.40	16.70	443	576	94.10	2
D	30-May-2012	2	2	0	-1	-1	-1	2	0	2	23.80	20.30	169	1261	94.10	2
D	01-Jun-2012	1	1	-2	2	-1	-1	2	0	1	21.80	16.60	381	896	89.00	3
D	01-Jun-2012	1	2	-1	10	2	1	0	0	2	20.60	20.60	427	210	89.30	2
D	04-Jun-2012	2	2	-1	0	0	1	0	0	2	23.00	28.90	172	243	72.20	3
D	30-May-2012	1	2	-1	1	2	2	2	0	2	23.20	16.70	280	931	94.10	2
D	30-May-2012	2	-1	-1	1	1	1	2	0	-1	24.00	18.70	99	1535	94.10	2
D	31-May-2012	3	2	-1	1	-1	-1	2	-1	-1	24.10	23.60	378	1678	89.90	2
D	31-May-2012	1	2	0	-1	0	2	2	0	2	23.60	26.00	426	176	89.50	2

Building	Date	Time	Comfort	Thermal_Sensation	Thermal_Intention	Ventilation_Intention	Fresh_Air	Light_Intention	Productivity	Satisfaction	Temperature	Humidity	CO2	Light	Noise=	Clothes
D	31-May-2012	2	0	0	0	0	0	1	0	0	23.00	25.10	362	375	89.80	2
D	31-May-2012	3	1	0	0	0	0	0	0	0	23.80	24.50	496	309	90.00	2
D	31-May-2012	1	2	-1	1	2	1	2	0	1	22.90	28.00	321	525	84.70	2
D	31-May-2012	2	2	-1	1	2	2	2	0	2	23.40	24.80	330	222	90.10	2
D	31-May-2012	3	2	-1	1	2	1	2	0	1	22.80	24.10	310	186	90.00	2
D	31-May-2012	1	2	0	0	0	2	2	0	1	23.20	27.90	625	518	89.50	1
D	31-May-2012	2	2	0	0	2	2	2	0	0	23.00	24.90	413	500	90.10	1
D	31-May-2012	3	2	0	0	2	2	2	0	2	23.50	23.80	409	392	89.80	1
D	04-Jun-2012	1	3	1	-1	0	-1	2	0	0	22.10	29.90	408	620	71.00	2
D	04-Jun-2012	2	2	0	0	0	0	2	0	2	23.70	26.30	302	564	78.50	2
D	31-May-2012	1	3	0	0	-1	-1	0	0	0	24.60	24.40	325	1014	89.80	2
D	04-Jun-2012	2	0	0	0	0	-1	0	0	0	24.10	25.60	391	441	89.90	2
D	31-May-2012	1	2	0	0	0	0	0	1	2	23.40	27.20	345	925	89.50	2
D	31-May-2012	2	2	0	0	0	0	0	1	2	24.10	23.50	396	634	89.90	2
D	31-May-2012	3	2	0	0	0	0	0	0	2	24.20	24.10	490	620	89.90	2
D	04-Jun-2012	1	1	-1	1	0	0	2	0	1	22.20	28.70	327	608	72.90	3
D	04-Jun-2012	2	1	-1	1	1	1	2	0	0	23.40	28.30	237	708	76.80	3
D	30-May-2012	1	2	-1	1	0	0	2	0	2	23.20	18.50	360	587	94.10	1
D	30-May-2012	2	1	-2	2	-1	0	1	0	0	23.20	18.60	152	841	94.10	2
D	30-May-2012	3	1	-1	2	-1	1	1	1	1	24.00	19.70	68	663	93.90	2
D	30-May-2012	1	2	0	0	0	2	-1	0	2	23.20	17.80	364	450	94.10	2
D	30-May-2012	2	2	0	0	-1	0	-1	0	2	23.40	19.80	116	251	94.10	2
D	30-May-2012	3	2	0	0	0	0	-1	0	2	23.00	21.60	177	265	93.80	2
D	04-Jun-2012	1	2	-1	0	2	2	2	0	3	23.00	29.30	594	406	72.40	3
D	04-Jun-2012	2	2	-1	0	2	2	2	0	2	23.20	27.20	462	278	71.10	3
D	04-Jun-2012	3	2	-1	0	2	2	2	0	2	24.30	28.10		388	72.50	3
D	30-May-2012	1	2	0	0	0	0	0	0	2	22.20	20.10	372	433	94.10	2
D	30-May-2012	2	0	0	0	0	0	0	0	1	23.90	18.50	344	588	94.10	2
D	30-May-2012	3	0	1	-1	0	0	0	0	1	24.80	18.40	86	309	93.80	2
D	04-Jun-2012	1	2	-1	0	2	2	2	1	2	23.20	26.20	462	576	72.90	3
D	04-Jun-2012	2	2	-1	-1	2	2	2	0	2	23.80	26.70	504	573	82.10	3
D	04-Jun-2012	3	2	0	0	2	2	2	0	2	23.30	29.30	458	484	93.10	3
D	01-Jun-2012	1	3	0	0	2	2	2	1	2	23.40	9.10	463	787	87.00	2
D	01-Jun-2012	2	3	0	0	2	2	2	1	2	23.80	12.40	430	1254	84.50	2
D	01-Jun-2012	1	3	0	0	2	1	2	0	2	24.60	14.70	399	546	82.50	3
D	01-Jun-2012	2	3	0	0	0	0	0	0	3	24.30	14.80	510	510	82.40	2
D	01-Jun-2012	3	3	0	0	0	0	0	0	3	25.50	11.40	355	510	89.50	2
D	05-Jun-2012	1	0	1	-2	2	2	2	0	1	23.30	29.40	389	1158	87.80	2
D	05-Jun-2012	2	3	-1	0	2	2	3	1	2	24.10	26.70	368	1296	85.60	2
D	05-Jun-2012	3	2	-1	0	2	2	2	1	2	24.90	29.10	519	528	86.30	2
D	01-Jun-2012	3	1	0	0	-1	-1	0	0	0	24.60	10.90	469	880	76.80	2
D	05-Jun-2012	2	2	0	0	10	10	0	0	2	24.40	26.30	380	648	79.90	2
D	05-Jun-2012	3	2	0	0	10	10	-1	0	2	25.70	29.80	564	317	96.80	2
D	04-Jun-2012	2	3	0	0	0	0	0	0	3	23.90	29.50	156	549	70.80	3
D	04-Jun-2012	3	3	0	0	0	0	0	0	3	23.30	26.40	170	448	70.80	3
D	05-Jun-2012	1	3	1	-1	0	0	0	0	3	24.30	28.80	373	612	83.60	2
D	05-Jun-2012	1	2	-1	1	2	2	1	0	1	24.70	28.70	476	676	69.20	2
D	05-Jun-2012	2	2	0	1	2	2	1	0	2	25.00	26.10	433	540	91.10	2
D	05-Jun-2012	3	2	0	0	2	1	1	0	2	25.00	30.00	510	340	90.00	2
D	04-Jun-2012	2	2	0	0	-2	-2	1	0	2	25.00	26.40	329	489	71.30	3
D	04-Jun-2012	3	2	0	0	-1	-1	0	0	2	23.30	25.90	556	347	74.20	3
D	05-Jun-2012	1	2	-1	1	0	-1	1	0	2	23.80	29.50	419	472	97.10	2
D	05-Jun-2012	1	2	0	0	0	0	0	0	0	24.60	28.00	455	700	84.70	1
D	05-Jun-2012	2	0	0	0	0	0	0	0	0	24.80	27.10	480	492	77.50	1
D	05-Jun-2012	3	0	0	0	0	0	0	0	0	25.30	29.50	527	372	94.70	2
D	01-Jun-2012	3	3	0	0	3	3	3	1	3	24.60	13.40	503	1349	51.40	2
D	04-Jun-2012	1	2	0	0	2	1	3	2	2	24.00	26.00	420	450	78.00	2
D	04-Jun-2012	2	2	0	0	2	2	3	0	2	24.40	26.00	464	735	73.20	2
D	04-Jun-2012	3	2	-1	1	2	2	3	0	2	24.50	30.30	401	651	95.10	2

Building	Date	Time	Comfort	Thermal_Sensation	Thermal_Intention	Ventilation_Intention	Fresh_Air	Light_Intention	Productivity	Satisfaction	Temperature	Humidity	CO2	Light	Noise=	Clothes
D	05-Jun-2012	1	2	0	0	2	1	2	1	2	24.40	27.30	357	1031	73.60	3
D	05-Jun-2012	2	2	0	0	2	2	2	0	2	24.50	26.10	382	320	81.20	3
D	05-Jun-2012	3	2	0	0	0	-1	2	-1	0	25.00	30.00	510	630	80.20	3
D	05-Jun-2012	1	3	0	0	0	-1	2	0	2	23.70	29.10	502	1022	80.90	2
D	05-Jun-2012	2	0	1	-1	0	-1	2	0	1	24.90	26.60	388	1555	77.50	3
D	05-Jun-2012	3	0	1	-2	-1	-1	1	-1	-1	25.50	39.50	595	716	96.90	2
D	05-Jun-2012	1	2	-1	1	2	2	2	0	2	24.40	28.10	451	910	77.40	1
D	05-Jun-2012	2	3	0	0	2	2	2	0	3	24.70	27.00	385	664	85.50	1
D	05-Jun-2012	3	3	0	0	0	0	0	0	2	25.30	29.60	584	460	101.90	2

Figure 313: Collected data, all four case study buildings

Appendix D: Quantitative Analysis of the ASHRAE Prediction Models

The ASHRAE Adaptive and PMV Thermal Comfort Prediction Models Using the SPSS Regression Analysis

The ASHRAE Adaptive Comfort Prediction and Comfort Survey Questionnaire

Figure 314 is the SPSS regression analysis for the 313 responses. It shows no strong relationship between surveyed comfort and the ASHRAE adaptive prediction model (i.e. P value = 0.711 > 0.05).

	Mean	Std. Deviation	N		
Comfort	1.48	1.163	313		
Adaptive Model-3 Point Scale	2.94	0.4	313		
Descriptive Statistics, SPSS linear regression analysis of the ASHRAE adaptive model and comfort					
Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	0.186	1	0.186	0.137	.711^b
Residual	421.884	311	1.357		
Total	422.07	312			
ANOVA, SPSS linear regression analysis of the ASHRAE adaptive model and comfort					

Figure 314: SPSS linear regression analysis of the ASHRAE adaptive model and comfort

The ASHRAE Adaptive Comfort Prediction and Satisfaction Survey Questionnaire

Figure 315 is the SPSS regression analysis and it shows no significant relationship between surveyed satisfaction level and the ASHRAE adaptive prediction model (i.e. P value = 0.462 > 0.05). The three point scale has been used for the adaptive model, explained in section 8.1.1.1.2.

	Mean	Std. Deviation	N		
Satisfaction	1	1.334	313		
Adaptive Model	2.94	0.4	313		
Descriptive Statistics, SPSS linear regression analysis of the ASHRAE adaptive model and satisfaction					
Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	0.966	1	0.966	0.542	.462^b
Residual	554.031	311	1.781		
Total	554.997	312			
ANOVA, SPSS linear regression analysis of the ASHRAE adaptive model and satisfaction					

Figure 315: SPSS linear regression analysis of the ASHRAE adaptive model and satisfaction

The ASHRAE PMV Comfort Prediction and Thermal Sensation Survey Questionnaire

The statistics presented in Figure 316 reveal as significant relationship between thermal sensation and PMV model (i.e. P value = 0.000 < 0.05). The R square shows that 5% of the thermal sensation responses can be explained by the ASHRAE PMV model, which is not a significant prediction.

	Mean	Std. Deviation	N							
PMV Model	-0.78	0.454	313							
Thermal Sensation	0.09	0.994	313							
Descriptive Statistics, SPSS linear regression analysis of the ASHRAE PMV prediction model and thermal sensation										
Model	Sum of Squares	df	Mean Square	F	Sig.					
Regression	3.221	1	3.221	16.39	.000^a					
Residual	61.124	311	0.197							
Total	64.345	312								
ANOVA, SPSS linear regression analysis of the ASHRAE PMV comfort prediction model and thermal sensation										
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics					
					R Square Change	F Change	df1	df2	Sig. F Change	
1	.224 ^a	0.050	0.047	0.443	0.050	16.390	1	311	0.000	
Model Summary, SPSS linear regression analysis of the ASHRAE PMV prediction model and thermal sensation										

Figure 316: SPSS linear regression analysis of the ASHRAE PMV prediction model and thermal sensation

The ASHRAE PMV Comfort Prediction and Comfort Survey Questionnaire

Figure 317 shows no significant relationship between the two variables (i.e. P value = 0.569 > 0.05).

	Mean	Std. Deviation	N							
Comfort	1.48	1.163	313							
PMV Model-4 Point Scale	3.22	0.454	313							
Descriptive Statistics, SPSS linear regression analysis of the ASHRAE PMV model and comfort										
Model	Sum of Squares	df	Mean Square	F	Sig.					
Regression	0.44	1	0.44	0.325	.569^b					
Residual	421.63	311	1.356							
Total	422.07	312								
ANOVA, SPSS linear regression analysis of the ASHRAE PMV model and comfort										

Figure 317: SPSS linear regression analysis of the ASHRAE PMV model and surveyed comfort level

The ASHRAE PMV Comfort Prediction and Satisfaction Survey Questionnaire

Figure 318 shows no significant relationship between the predicted ASHRAE PMV model and surveyed satisfaction level (i.e. P value = 0.694 > 0.05).

	Mean	Std. Deviation	N		
PMV Model	3.22	0.454	313		
Satisfaction	1	1.334	313		
Descriptive Statistics, SPSS linear regression analysis of the ASHRAE PMV model and satisfaction					
Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	0.032	1	0.032	0.155	.694^a
Residual	64.313	311	0.207		
Total	64.345	312			
ANOVA, SPSS linear regression analysis of the ASHRAE PMV model and satisfaction					

Figure 318: SPSS linear regression analysis of the ASHRAE PMV model and satisfaction

Appendix E: Quantitative Analysis of Thermal Sensation and Variables

Thermal Sensation and Satisfaction

Figure 319 is the SPSS linear regression analysis of surveyed satisfaction and thermal sensation. The R Square indicates that 16.9% of the satisfaction responses can be explained by the thermal sensation status. The coefficients analysis shows that every degree increase in thermal sensation towards 'neutral' improves the satisfaction level by 0.734 degree. The statistics show a strong relationship between the two variables (i.e. P value =0.000 <0.05).

	Mean	Std. Deviation	N								
Satisfaction	1	1.334	313								
Thermal Sensation	3.32	0.747	313								
Descriptive Statistics, SPSS linear regression analysis of satisfaction based on the four scale thermal sensation											
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics						
					R Square Change	F Change	df1	df2	Sig. F Change		
1	.411 ^a	0.169	0.166	1.218	0.169	63.142	1	311	0		
Model Summary, SPSS linear regression analysis of satisfaction based on the four scale thermal sensation											
Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.						
	B	Std. Error	Beta								
1	(Constant)	-1.432	0.314		0						
	Thermal Sensation-4 Point Scale	0.734	0.092	0.411	7.946	0					
Coefficients, SPSS linear regression analysis of satisfaction based on the four scale thermal sensation											
Model	Sum of Squares	df	Mean Square	F	Sig.						
Regression	93.664	1	93.664	63.142	.000^b						
Residual	461.333	311	1.483								
Total	554.997	312									
ANOVA, SPSS linear regression analysis of satisfaction based on the four scale thermal sensation											

Figure 319: SPSS linear regression analysis of satisfaction based on the four scale thermal sensation

Thermal Sensation and Thermal Intention

Figure 320 is the SPSS linear regression analysis between surveyed thermal sensation and thermal intention. 311 out of 313 responses are included in this analysis, since 2 participants had no strong opinion about their thermal intention. The R Square indicates that 46.4% of the thermal sensation variance can be explained by thermal intention, which is quite significant. The analysis also shows that every degree change in thermal intention results in 0.647 degree

change in thermal sensation. The statistics reveal a significant relationship between the surveyed thermal sensation and thermal intention (i.e. P value = 0.000 < 0.05).

	Mean	Std. Deviation	N						
Thermal Intention	4.04	0.946	311						
Thermal Sensation	0.1	0.995	311						
Descriptive Statistics, SPSS linear regression analysis of thermal intention and thermal sensation									
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.681 ^a	0.464	0.462	0.694	0.464	267.367	1	309	0
Model summary, SPSS linear regression analysis of thermal intention and thermal sensation									
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.			
		B	Std. Error	Beta					
1	(Constant)	3.976	0.04		100.576	0			
	Thermal Sensation-7 Point Scale ASHRAE	0.647	0.04	0.681	16.351	0			
Coefficients, SPSS linear regression analysis of thermal intention and thermal sensation									
Model	Sum of Squares	df	Mean Square	F	Sig.				
Regression	128.745	1	128.745	267.367	.000^a				
Residual	148.792	309	0.482						
Total	277.537	310							
ANOVA, SPSS linear regression analysis of thermal intention and thermal sensation									

Figure 320: SPSS linear regression analysis of thermal intention and thermal sensation

Appendix F: The ASHRAE PMV Model

Figure 321 demonstrates the descriptive analysis of the ASHRAE PMV prediction model in the four case study buildings in this study.

		ASHRAE PMV Model			Total
		Cool	Slightly cool	Neutral	
Ventilation System and Typology of Plan	Building A: Air Conditioned, Openable Window and Heating in Cellular Plan	3	90	2	95
	Building B: Air Conditioned & Openable Window in Cellular Plan	0	35	42	77
	Building C: Natural Ventilation in Open Plan	0	47	26	73
	Building D: Displacement Ventilation in Open Plan	2	61	5	68
Total		5	233	75	313

Figure 321: The ASHRAE PMV Model

Appendix G: Analysis of Thermal Sensation and Thermal Intention

Figure 322 shows that 148 out of 313 participants (i.e. 47%) have a neutral thermal sensation and Figure 323 shows that 167 Participants (i.e. 53%) want to no change in the temperature.

Ventilation System and Typology of Plan		Frequency	Percent	Valid Percent	Cumulative Percent
Building A: Air Conditioned, Openable Window and Heating in Cellular Plan	Valid	Cool	2	2.1	2.1
		Slightly cool	27	28.4	28.4
		Neutral	59	62.1	62.1
		Slightly warm	7	7.4	7.4
		Total	95	100.0	100.0
Building B: Air Conditioned & Openable Window in Cellular Plan	Valid	Slightly cool	12	15.6	15.6
		Neutral	36	46.8	46.8
		Slightly warm	21	27.3	27.3
		Warm	8	10.4	10.4
Total	77	100.0	100.0		
Building C: Natural Ventilation in Open Plan	Valid	Cool	6	8.2	8.2
		Slightly cool	12	16.4	16.4
		Neutral	25	34.2	34.2
		Slightly warm	16	21.9	21.9
		Warm	12	16.4	16.4
		Hot	2	2.7	2.7
Total	73	100.0	100.0		
Building D: Displacement Ventilation in Open Plan	Valid	Cold	2	2.9	2.9
		Cool	4	5.9	5.9
		Slightly cool	10	14.7	14.7
		Neutral	28	41.2	41.2
		Slightly warm	18	26.5	26.5
		Warm	6	8.8	8.8
Total	68	100.0	100.0		

Figure 322: Thermal sensation frequency in the four case study buildings

Ventilation System and Typology of Plan		Frequency	Percent	Valid Percent	Cumulative Percent
Building A: Air Conditioned, Openable Window and Heating in Cellular Plan	Valid	Cooler	2	2.1	2.2
		Slightly cooler	8	8.4	8.6
		No change	65	68.4	69.9
		Slightly warmer	15	15.8	16.1
		Warmer	3	3.2	3.2
		Total	93	97.9	100.0
Building B: Air Conditioned & Openable Window in Cellular Plan	Valid	Cooler	4	5.2	5.2
		Slightly cooler	26	33.8	33.8
		No change	39	50.6	50.6
		Slightly warmer	8	10.4	10.4
Total	77	100.0	100.0		
Building C: Natural Ventilation in Open Plan	Valid	Cooler	7	9.6	9.6
		Slightly cooler	20	27.4	27.4
		No change	30	41.1	41.1
		Slightly warmer	7	9.6	9.6
		Warmer	3	4.1	4.1
		Much warmer	6	8.2	8.2
Total	73	100.0	100.0		
Building D: Displacement Ventilation in Open Plan	Valid	Cooler	1	1.5	1.5
		Slightly cooler	16	23.5	23.5
		No change	33	48.5	48.5
		Slightly warmer	11	16.2	16.2
		Warmer	6	8.8	8.8
		Much warmer	1	1.5	1.5
Total	68	100.0	100.0		

Figure 323: Thermal intention frequency in the four case study buildings

Appendix H: Quantitative Analysis of Thermal Control Intention and Comfort

Figure 324 is the SPSS linear regression analysis of comfort against thermal control intention regarding temperature, air quality and air movement of 313 responses. It shows a strong relationship between surveyed comfort and thermal control intention (i.e. P value = 0.000 < 0.05). The R square in the model summary table shows that 18.8% of variance in comfort can be explained by the thermal control intention, including thermal, air movement and indoor air quality intention. The R square in this model is greater than the one regarding thermal sensation (i.e. 13.2%), presented in Figure 215. This suggests that thermal control intention explains comfort better than thermal sensation does. The statistics show that by improving thermal intention towards no change, comfort level improves by 0.546 degree. Air movement intention is less effective (i.e. 0.126 degree), and indoor air quality intention is even less effective (i.e. 0.025 degree). This analysis shows that temperature control improves comfort more than air movement and air quality controls.

	Mean	Std. Deviation	N						
Comfort	1.48	1.163	313						
Thermal Intention	3.41	0.738	313						
Air Movement Intention	0.6	1.52	313						
Indoor Air Quality Intention	0.74	1.546	313						
Descriptive Statistics, SPSS linear regression analysis of comfort and thermal control intention, including temperature, air quality and air movement intention									
Model	Sum of Squares	df	Mean Square	F	Sig.				
Regression	79.203	3	26.401	23.793	.000^b				
Residual	342.867	309	1.11						
Total	422.07	312							
ANOVA, SPSS linear regression analysis of comfort and thermal control intention, including temperature, air quality and air movement intention									
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.433 ^a	0.188	0.18	1.053	0.188	23.793	3	309	0
Model Summary, SPSS linear regression analysis of comfort and thermal control intention, including temperature, air quality and air movement intention									
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.			
		B	Std. Error	Beta					
1	(Constant)	-0.48	0.287		-1.671	0.096			
	Thermal Intention	0.546	0.083	0.346	6.547	0			

Air Movement Intention	0.126	0.073	0.164	1.716	0.087
Indoor Air Quality Intention	0.025	0.071	0.033	0.348	0.728
Coefficients, SPSS linear regression analysis of comfort and thermal control intention, including temperature, air quality and air movement intention					

Figure 324: SPSS linear regression analysis of comfort and thermal control intention, including temperature, air quality and air movement intention

Appendix I: Quantitative Analysis of SBS Symptoms

Headaches

Frequency analysis of the headache symptom in the open and cellular plan offices is presented in Figure 325 and Figure 326. They indicate that this symptom is less common amongst the occupants of the cellular plan offices compared to the open plan offices. The number of the cellular plan respondents, who never suffer from this symptom, is twice as many as the open plan participants (i.e. 130 compared to 63). In addition, none of the respondents in the personal offices constantly suffer from this symptom, while 9 participants reported suffering constantly in the open plan offices.

		Headache				Total
		Constantly	Often	Occasionally	Never	
Open or Cellular Plan Layouts	Open plan	9	1	57	63	130
	Cellular plan	0	0	15	130	145
Total		9	1	72	193	275

Figure 325: Crosstabulation, SPSS descriptive analysis of Headache symptom between open vs. cellular offices

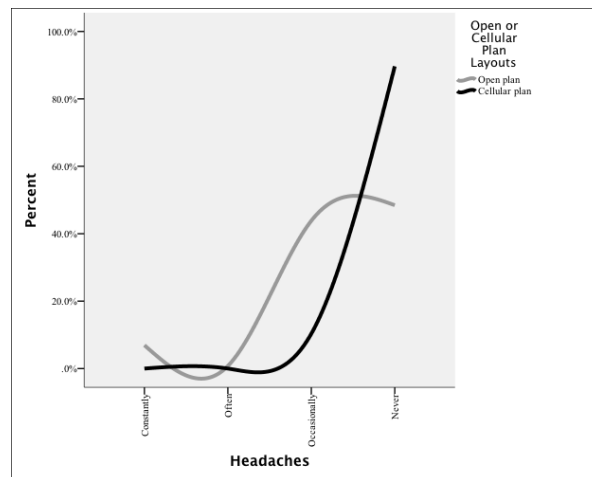


Figure 326: Headache symptom between open vs. cellular plan offices

Figure 327 is the linear regression analysis of the headaches symptom between open and cellular plan offices, based on 275 responses. It shows a strong relationship between the headache symptom and type of plan, including open and cellular offices (i.e. P value = 0.000 < 0.05). Type of plan can explain 13.4% of the variance in the headache and cellular plan offices have 0.712 degree lower headache symptom.

	Mean	Std. Deviation	N						
Headache	2.56	0.974	275						
Open or Cellular Plan Layouts	1.53	0.5	275						
Descriptive Statistics, SPSS linear regression analysis of headache symptom between open vs. cellular offices									
Model	Sum of Squares	df	Mean Square	F	Sig.				
Regression	34.742	1	34.742	42.151	.000^a				
Residual	225.018	273	0.824						
Total	259.76	274							
ANOVA, SPSS linear regression analysis of headache symptom between open vs. cellular offices									
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.366 ^a	0.134	0.131	0.908	0.134	42.151	1	273	0
Model Summary, SPSS linear regression analysis of headache symptom between open vs. cellular offices									
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.			
		B	Std. Error	Beta					
1	(Constant)	1.473	0.176		8.358	0			
	Open or Cellular Plan Layouts	0.712	0.11	0.366	6.492	0			
Coefficients, SPSS linear regression analysis of headache symptom between open vs. cellular offices									

Figure 327: SPSS linear regression analysis of headache symptom between open vs. cellular offices

Appendix J: Satisfaction in Open vs. Cellular Plan Offices

Figure 328 presents the SPSS linear regression analysis of satisfaction level between the two Scottish open plan case studies and the two Norwegian cellular plan offices in this study. It indicates that satisfaction can be explained based on the type of plan (P value = $0.000 < 0.05$). The R Square in this figure suggests that 11.5% of variance in satisfaction level can be explained by the type of plan, which is either open or cellular layout. The R square shows the significance of the association rather than the extent to which the variables are associated. The statistics also reveal that satisfaction level in the two Norwegian cellular plan offices is 0.424 degree higher than in the Scottish open plan offices.

	Mean	Std. Deviation	Number of votes							
Satisfaction	1.03	1.427	313							
Building Type (open vs. cellular)	2.623	1.14286	313							
Descriptive Statistics, SPSS linear regression analysis of satisfaction between open vs. cellular plan offices										
Model	Sum of Squares	df	Mean Square	F	Sig.					
Regression	73.248	1	73.248	40.503	.000^b					
Residual	562.433	311	1.808							
Total	635.681	312								
ANOVA, SPSS linear regression analysis of satisfaction between open vs. cellular plan offices										
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics					
					R Square Change	F Change	df1	df2	Sig. F Change	
1	.339 ^a	0.115	0.112	1.345	0.115	40.503	1	311	0	
Model Summary, SPSS linear regression analysis of satisfaction between open vs. cellular plan offices										
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.				
		B	Std. Error	Beta						
1	(Constant)	-0.08	0.191		-0.42	0.675				
	Building Type (open vs. cellular)	0.424	0.067	0.339	6.364	0				
Coefficients, SPSS linear regression analysis of satisfaction between open vs. cellular plan offices										

Figure 328: SPSS linear regression analysis of satisfaction between open vs. cellular plan offices

Appendix K: Comfort in Open vs. Cellular Plan Offices

Figure 329 is the SPSS linear regression analysis of comfort level between the open and cellular plan layouts, based on 313 respondents. It shows a significant relationship between the surveyed comfort level and type of plan (i.e. P value = $0.000 < 0.05$). The R Square indicates that 5.4% of variance in comfort level can be explained by the type of plan, which is either open or cellular layout. It shows that comfort level in the two Norwegian cellular plan offices is 0.236 degree higher than in the Scottish open plan offices.

	Mean	Std. Deviation	Number of votes						
Comfort Building Type (open vs. cellular)	1.48	1.163	313						
	2.623	1.14286	313						
Descriptive Statistics, SPSS linear regression analysis of comfort between open vs. cellular plan offices									
Model	Sum of Squares	df	Mean Square	F	Sig.				
Regression	22.697	1	22.697	17.674	.000b				
Residual	399.374	311	1.284						
Total	422.07	312							
ANOVA, SPSS linear regression analysis of comfort between open vs. cellular plan offices									
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.232 ^a	0.054	0.051	1.133	0.054	17.674	1	311	0
Model Summary, SPSS linear regression analysis of comfort between open vs. cellular plan offices									
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.			
		B	Std. Error	Beta					
1	(Constant)	0.857	0.161		5.337	0			
	Building Type (open vs. cellular)	0.236	0.056	0.232	4.204	0			
Coefficients, SPSS linear regression analysis of comfort between open vs. cellular plan offices									

Figure 329: SPSS linear regression analysis of comfort between open vs. cellular plan offices

plan offices

Appendix L: Sick Building Syndrome Frequency Analysis

		Open or Cellular Plan Layouts		Total
		Open plan	Cellular plan	
Dry or Watery Eyes	Constantly	3	3	6
	Often	20	9	29
	Occasionally	30	25	55
	Never	77	108	185
Total		130	145	275
SPSS Frequency analysis of dry or watery eyes symptom				
		Open or Cellular Plan Layouts		Total
		Open plan	Cellular plan	
Blocked or Runny Nose	Often	4	6	10
	Occasionally	24	10	34
	Never	102	124	226
Total		130	140	270
SPSS Frequency analysis of blocked or runny nose symptom				
		Open or Cellular Plan Layouts		Total
		Open plan	Cellular plan	
Dry or Irritated Throat	Often	5	0	5
	Occasionally	26	12	38
	Never	99	130	229
Total		130	142	272
SPSS Frequency analysis of dry or irritated throat symptom				
		Open or Cellular Plan Layouts		Total
		Open plan	Cellular plan	
Chest Tightness	Occasionally	5	0	5
	Never	122	142	264
	Total		127	142
SPSS Frequency analysis of chest tightness symptom				
		Open or Cellular Plan Layouts		Total
		Open plan	Cellular plan	
Headaches	Constantly	9	0	9
	Often	1	0	1
	Occasionally	57	15	72
	Never	63	130	193
Total		130	145	275
SPSS Frequency analysis of headache symptom				
		Open or Cellular Plan Layouts		Total
		Open plan	Cellular plan	
Tiredness	Constantly	8	0	8
	Often	21	10	31
	Occasionally	63	41	104
	Never	37	88	125
Total		129	139	268
SPSS Frequency analysis of tiredness symptom				

Figure 330: SPSS Frequency analysis of sick building symptom

The following tables demonstrate the SPSS frequency analysis of each symptom for all the case study buildings in this study.

Ventilation System and Typology of Plan			Frequency	Percent	Valid Percent	Cumulative Percent
Building A: Air Conditioned, Openable Window and Heating in Cellular Plan	Valid	Often	9	9.5	11.4	11.4
		Occasionally	14	14.7	17.7	29.1
		Never	56	58.9	70.9	100.0
		Total	79	83.2	100.0	
	Missing	Not recorded	16	16.8		
Total			95	100.0		
Building B: Air Conditioned & Openable Window in Cellular Plan	Valid	Constantly	3	3.9	4.5	4.5
		Occasionally	11	14.3	16.7	21.2
		Never	52	67.5	78.8	100.0
		Total	66	85.7	100.0	
	Missing	Not recorded	11	14.3		
Total			77	100.0		
Building C: Natural Ventilation in Open Plan	Valid	Constantly	1	1.4	1.5	1.5
		Often	14	19.2	21.5	23.1
		Occasionally	14	19.2	21.5	44.6
		Never	36	49.3	55.4	100.0
	Total	65	89.0	100.0		
Missing	Not recorded	8	11.0			
Total			73	100.0		
Building D: Displacement Ventilation in Open Plan	Valid	Constantly	2	2.9	3.1	3.1
		Often	6	8.8	9.2	12.3
		Occasionally	16	23.5	24.6	36.9
		Never	41	60.3	63.1	100.0
	Total	65	95.6	100.0		
Missing	Not recorded	3	4.4			
Total			68	100.0		

Figure 331: SPSS Frequency analysis of dry or watery eyes symptom in detail

Ventilation System and Typology of Plan			Frequency	Percent	Valid Percent	Cumulative Percent
Building A: Air Conditioned, Openable Window and Heating in Cellular Plan	Valid	Often	3	3.2	4.1	4.1
		Occasionally	7	7.4	9.5	13.5
		Never	64	67.4	86.5	100.0
		Total	74	77.9	100.0	
	Missing	Not recorded	21	22.1		
Total			95	100.0		
Building B: Air Conditioned & Openable Window in Cellular Plan	Valid	Often	3	3.9	4.5	4.5
		Occasionally	3	3.9	4.5	9.1
		Never	60	77.9	90.9	100.0
		Total	66	85.7	100.0	
	Missing	Not recorded	11	14.3		
Total			77	100.0		
Building C: Natural Ventilation in Open Plan	Valid	Often	1	1.4	1.5	1.5
		Occasionally	16	21.9	24.6	26.2
		Never	48	65.8	73.8	100.0
		Total	65	89.0	100.0	
	Missing	Not recorded	8	11.0		
Total			73	100.0		
Building D: Displacement Ventilation in Open Plan	Valid	Often	3	4.4	4.6	4.6
		Occasionally	8	11.8	12.3	16.9
		Never	54	79.4	83.1	100.0
		Total	65	95.6	100.0	
	Missing	Not recorded	3	4.4		
Total			68	100.0		

Figure 332: SPSS Frequency analysis of blocked or runny nose symptom in detail

Ventilation System and Typology of Plan			Frequency	Percent	Valid Percent	Cumulative Percent
Building A: Air Conditioned, Openable Window and Heating in Cellular Plan	Valid	Occasionally	6	6.3	7.9	7.9
		Never	70	73.7	92.1	100.0
		Total	76	80.0	100.0	
	Missing	Not recorded	19	20.0		
	Total		95	100.0		
Building B: Air Conditioned & Openable Window in Cellular Plan	Valid	Occasionally	6	7.8	9.1	9.1
		Never	60	77.9	90.9	100.0
		Total	66	85.7	100.0	
	Missing	Not recorded	11	14.3		
	Total		77	100.0		
Building C: Natural Ventilation in Open Plan	Valid	Often	4	5.5	6.2	6.2
		Occasionally	15	20.5	23.1	29.2
		Never	46	63.0	70.8	100.0
		Total	65	89.0	100.0	
	Missing	Not recorded	8	11.0		
Total		73	100.0			
Building D: Displacement Ventilation in Open Plan	Valid	Often	1	1.5	1.5	1.5
		Occasionally	11	16.2	16.9	18.5
		Never	53	77.9	81.5	100.0
		Total	65	95.6	100.0	
	Missing	Not recorded	3	4.4		
Total		68	100.0			

Figure 333: SPSS Frequency analysis of dry or irritated throat symptom in detail

Ventilation System and Typology of Plan			Frequency	Percent	Valid Percent	Cumulative Percent
Building A: Air Conditioned, Openable Window and Heating in Cellular Plan	Valid	Never	76	80.0	100.0	100.0
	Missing	Not recorded	19	20.0		
	Total		95	100.0		
Building B: Air Conditioned & Openable Window in Cellular Plan	Valid	Never	66	85.7	100.0	100.0
	Missing	Not recorded	11	14.3		
	Total		77	100.0		
Building C: Natural Ventilation in Open Plan	Valid	Never	62	84.9	100.0	100.0
	Missing	Not recorded	11	15.1		
	Total		73	100.0		
Building D: Displacement Ventilation in Open Plan	Valid	Occasionally	5	7.4	7.7	7.7
		Never	60	88.2	92.3	100.0
		Total	65	95.6	100.0	
	Missing	Not recorded	3	4.4		
	Total		68	100.0		

Figure 334: SPSS Frequency analysis of chest tightness symptom in detail

Ventilation System and Typology of Plan			Frequency	Percent	Valid Percent	Cumulative Percent
Building A: Air Conditioned, Openable Window and Heating in Cellular Plan	Valid	Occasionally	7	7.4	8.9	8.9
		Never	72	75.8	91.1	100.0
		Total	79	83.2	100.0	
		Missing	Not recorded	16	16.8	
	Total		95	100.0		
Building B: Air Conditioned & Openable Window in Cellular Plan	Valid	Occasionally	8	10.4	12.1	12.1
		Never	58	75.3	87.9	100.0
		Total	66	85.7	100.0	
		Missing	Not recorded	11	14.3	
	Total		77	100.0		
Building C: Natural Ventilation in Open Plan	Valid	Constantly	5	6.8	7.7	7.7
		Often	1	1.4	1.5	9.2
		Occasionally	29	39.7	44.6	53.8
		Never	30	41.1	46.2	100.0
		Total	65	89.0	100.0	
	Missing	Not recorded	8	11.0		
Total		73	100.0			
Building D: Displacement Ventilation in Open Plan	Valid	Constantly	4	5.9	6.2	6.2
		Occasionally	28	41.2	43.1	49.2
		Never	33	48.5	50.8	100.0
		Total	65	95.6	100.0	
	Missing	Not recorded	3	4.4		
Total		68	100.0			

Figure 335: SPSS Frequency analysis of headache symptom in detail

Ventilation System and Typology of Plan			Frequency	Percent	Valid Percent	Cumulative Percent
Building A: Air Conditioned, Openable Window and Heating in Cellular Plan	Valid	Often	3	3.2	3.9	3.9
		Occasionally	19	20.0	25.0	28.9
		Never	54	56.8	71.1	100.0
		Total	76	80.0	100.0	
	Missing	Not recorded	19	20.0		
Total		95	100.0			
Building B: Air Conditioned & Openable Window in Cellular Plan	Valid	Often	7	9.1	11.1	11.1
		Occasionally	22	28.6	34.9	46.0
		Never	34	44.2	54.0	100.0
		Total	63	81.8	100.0	
	Missing	Not recorded	14	18.2		
Total		77	100.0			
Building C: Natural Ventilation in Open Plan	Valid	Constantly	7	9.6	10.9	10.9
		Often	9	12.3	14.1	25.0
		Occasionally	34	46.6	53.1	78.1
		Never	14	19.2	21.9	100.0
		Total	64	87.7	100.0	
	Missing	Not recorded	9	12.3		
Total		73	100.0			
Building D: Displacement Ventilation in Open Plan	Valid	Constantly	1	1.5	1.5	1.5
		Often	12	17.6	18.5	20.0
		Occasionally	29	42.6	44.6	64.6
		Never	23	33.8	35.4	100.0
	Total	65	95.6	100.0		
Missing	Not recorded	3	4.4			
Total		68	100.0			

Figure 336: SPSS Frequency analysis of tiredness symptom in detail

Appendix M: Productivity in Open vs. Cellular Plan Offices

Figure 337 is the SPSS linear regression analysis of productivity and type of plan, including open and cellular plan offices, based on 313 responses. It shows a significant relationship between productivity and type of plan (i.e. P value = 0.045 < 0.05). The R Square figure suggests that 1.3% of variance in productivity level can be explained by the type of the plan, which is a small number. The productivity level in the two cellular plan offices is 0.063 degree higher than the two open plan offices, which is not so significant.

	Mean	Std. Deviation	N						
Productivity Compared to the Normal State Building Type	0	0.633	313						
	2.623	1.14286	313						
Descriptive Statistics, SPSS linear regression analysis of productivity level between open vs. cellular plan offices									
Model	Sum of Squares	df	Mean Square	F	Sig.				
Regression	1.611	1	1.611	4.061	.045b				
Residual	123.386	311	0.397						
Total	124.997	312							
ANOVA, SPSS linear regression analysis of productivity level between open vs. cellular plan offices									
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.114 ^a	0.013	0.01	0.63	0.013	4.061	1	311	0.045
Model Summary, SPSS linear regression analysis of productivity level between open vs. cellular plan offices									
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.			
		B	Std. Error	Beta					
1	(Constant)	-0.168	0.089		-1.884	0.061			
	Ventilation System and Typology of Plan	0.063	0.031	0.114	2.015	0.045			
Coefficients, SPSS linear regression analysis of productivity level between open vs. cellular plan offices									

Figure 337: SPSS linear regression analysis of productivity level between open vs. cellular plan offices

Appendix N: Conference Papers

Windsor Conference 2014

Individual Thermal Control in the Workplace and Changes in Thermal Preferences in a Day: Norwegian Cellular vs. British Open Plan Layouts

Abstract

This research suggests that the thermal preference of occupants is subject to change during the day, and hence a particular thermal setting may not satisfy all occupants at all times. However, individual thermal control in the workplace increases their comfort and satisfaction. This research has two parts. The first part examines whether occupants find different thermal preferences appealing during a day rather than a particular thermal setting. The second part investigates the impact of individual thermal control on the comfort and satisfaction of users in the workplace. This is examined through environmental measurement and user comfort surveys in two office layouts with high and low levels of individual environmental control. Two air conditioned cellular plan offices in Norway are selected with high levels of individual environmental control, in which every user is provided with control over a window in addition to the ability to adjust heating and cooling. In contrast, two naturally and mechanically ventilated open plan offices in Scotland are selected with limited thermal control over the windows that is provided for limited occupants around the perimeter of the building. Complementary quantitative and qualitative methodologies are applied with particular emphasis on the grounded theory. Environmental measurements and questionnaires are further reinforced with semi-structured interviews to investigate the environmental control. The application of individual control is analysed by quantitative analysis, while changes in the thermal preference are analysed through a new qualitative visual recording technique. The latter is applied to qualitatively analyse the subject in its context. Information regarding all users and their environment is applied as colour codes to floor plate layouts. Overall, this research suggests that rather than setting a steady state thermal condition according to standard 'comfort zone' in an endeavour to satisfy all, it is proposed that buildings provide a degree of flexibility to allow occupants to adjust their thermal environment according to their requirements.

Environmental Control and Sick Building Syndrome: A Low Carbon Open Plan vs. a Cellular Plan Workplace

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John Brennan

Dimitris Theodossopoulos

ABSTRACT

This study investigates the effect of environmental control on Sick Building Syndrome (SBS). This is examined by environmental measurement, user health and satisfaction at two workplaces with respectively low and high levels of individual control over the thermal environment. The Anglo-Saxon practice of the open plan workplace is compared to the traditional Scandinavian practice, with a greater preponderance of cellular office accommodation. The research will lead to the formulation of specific strategies to enhance opportunities in providing thermal comfort in the workplace. Two case studies are described with respectively low and high provision of individual environmental control. A low energy open plan office in Scotland is selected with natural ventilation, where limited users have access to windows. In contrast, an air conditioned cellular plan office in Norway with excessive use of energy is selected providing every user with control over a window and the ability to adjust heating and cooling. Complementary quantitative and qualitative methodologies are applied. Particular emphasis is given to Grounded Theory methods. Building users' health conditions and perception of their thermal environment are recorded through a questionnaire and empirical building performance through the measurement of the thermal environment. These traditional techniques are further reinforced with semi-structured interviews to investigate the environmental control. A new visual recording method is applied to qualitatively analyse the subject in its context. Information regarding all users and their environment is applied as colour codes to floor plate layouts. The study examines the significance of environmental control and its effect on Sick Building Syndrome in a comparison between a low carbon open plan and a cellular plan workplace with higher energy consumption. Through this a balanced appraisal can be made of comfort profiles and user's health between the two benchmarked buildings.

INTRODUCTION

A question that is often raised is whether air conditioning is responsible for Sick Building Syndrome? Although researchers have compared air conditioned buildings to naturally ventilated offices in respect of building related symptoms (Jaakkola, 1995), any such findings concerning the relationship between ventilation typologies and Sick Building Syndrome have been contradictory (Mendell, 1990). Many report a higher risk of building related symptoms in air conditioned buildings (Rollins, 1997, Jaakkola, 1991 and Finnegan, 1984). However, others argue that energy efficient buildings may suffer more from Sick Building Syndrome due to the high level of insulation to maintain temperature allied to a lack of ventilation (Rayner, 1997). The World Health Organization identifies buildings that 'are energy efficient, kept relatively warm and have homogeneous thermal environment' as having a higher risk of Sick Building Syndrome (Rayner, 1997 and Chan, 2011). Increasing energy costs, climate change legislation and construction costs means that buildings are expected to be more sustainable (Nicol, 2012), and passive systems, such as natural ventilation are becoming more numerous. Sally S Shahzad is a PhD candidate in Architecture at the University of Edinburgh, UK. John Brennan is the head of the Edinburgh School of Architecture and Landscape Architecture, University of Edinburgh, UK. Dimitris Theodossopoulos is a lecturer at the School of Architecture, University of Edinburgh, UK.

Additionally, several studies show lower symptoms in naturally ventilated buildings (Jouni, 1995). However, there is a hazard in having an automatic expectation assuming that naturally ventilated buildings have a reduced incidence of Sick Building Syndrome. Jaakkola's research in Scandinavia reveals that air conditioned buildings do not increase symptoms 'when functioning properly' (Jaakkola, 1991). This paper explores the influence of environmental control on Sick Building Syndrome. It proposes that the introduction of adaptive opportunity in the design of workplaces reduces the symptoms relating to Sick Building Syndrome.

SICK BUILDING SYNDROME

After 1960 air conditioning and fluorescent lighting became prevalent in newly designed workplaces as it provided an opportunity to reap the financial benefits of deep open plan offices (Laing, 2006). However, these new technologies were thought to introduce building related diseases into the workplace (Bluyssen, 2009). By 1980, difficulties with health related issues in office buildings were apparent, and in 1986 Sick Building Syndrome (SBS) was recognized as a quantifiable phenomenon by the World Health Organisation (Akimenko, 1986). SBS is commonly used to describe poor indoor air quality in offices (Niemela, 2006). It may cause mild or extreme symptoms as the body reacts to an unhealthy environment (Camevale, 1995). Mild symptoms include tiredness, loss of concentration and depression, in addition to infections and allergic reactions, such as irritated skin, throat and eyes (Bluyssen, 2009 and Rostron, 1997). In extreme cases SBS or Building Related Illness is a term that can be applied to legionnaire's disease, cardiovascular problems and cancer. (Camevale, 1995). Several factors increase building related symptoms, such as high temperature (Berglund, 1984), poor ventilation rate (Seppanen, 1999 and Fisk, 2009), low relative humidity (Gelperin, 1973), poor lighting (Wilson, 1987 and Robertson, 1986), air born dust (Reisenberg, 1986), material (Wargocki, 2002) and chemical pollutants (Hicks, 1984). Improved indoor air quality (Niemela, 2006) and fresh air supply (Wargocki, 2002) reduce the SBS symptoms.

INDIVIDUAL USER CONTROL OVER THE THERMAL ENVIRONMENT

Marmot mentions that control and health are related (Marmot, 2010). Rollins and Swift describe lack of environmental control as a cause of increasing building related symptoms. They explain the importance of 'to be in control and not to be at the mercy of external forces' (Rollins, 1997). Rayner reports that the 'people with most symptoms have least perceived control over their environment' (Rayner, 1997).

Adaptive Opportunity. The adaptive comfort theory contrasts with simple empiric measurements of comfort as a function of temperature and humidity. Adaptive comfort considers the activity of occupants, who adjust themselves to retain comfort in changing environments (Nicol and Humphreys, 1973). In contrast, the steady state theory ignores this active and adaptive quality and searches for an optimum temperature that satisfies all (Fanger, 1970). Field studies of thermal comfort have been applied to research adaptive comfort, while experimental chambers or climate chambers have been used to investigate the steady state theory (Nicol, 2005). Field studies of thermal comfort deal with the context of real life, in contrast, experimental chambers provide an unfamiliar environment for participants with a limited set of controlled variables. Although the findings of the latter are valuable and useful to understand the heat balance between the body and the environment, they do not apply to those situations actually experienced in offices (Nicol, 2012). Based on the adaptive comfort theory, 'adaptive opportunity' was introduced by Baker to increase the environmental control for occupants to allow them to adjust their surrounding thermal environment to meet their requirements (Baker, 1995). Researchers report that environmental control increases user productivity (Leaman, 2005 and Kroner, 2006) and satisfaction (Bordass, 1993 and Leaman, 1996).

Environmental Control. Many researchers report the influence of environmental control on user comfort and satisfaction (Bordass, 1994, Leaman, 1998, Leaman, 2005, and Bordass, 2007). However, the prevalence of large open floor plates and the speculative nature of office development prevent the direct environmental control by the user and replace it with centralised facilities management (Roaf, 2004). Furthermore, there is an expressed preference for automatic systems to

eliminate users' input in the system in order to streamline the management of building services (Bordass, 1993). Many studies have already been conducted concerning the pattern of use of environmental controls, such as operating windows (Humphreys, 2007 and Bräger, 2004). This paper compares environments with high and low levels of individual control over the thermal environment. It compares cellular and open plan offices with respective high and low levels of environmental control.

Anglo-Saxon Open Plan vs. Scandinavian Cellular Plan Offices. There are differences in working culture, legislation and building traditions, and accordingly between Anglo-Saxon and Scandinavian workplaces, and the design and individual environmental control of buildings are very different (Van Meel, 2006). In Scandinavian countries, individual workers have the right to access natural light and ventilation (Van Meel, 2006). Therefore workstations are usually placed around the perimeter of the building to maximize the access to natural light and ventilation. The layout of these offices is often a traditional cellular plan configuration in which every individual has a personal room. There is therefore a high provision of thermal control for individual users in each room. In contrast, Anglo-Saxon countries have favoured open plan offices, where communication and efficient use of space is highly valued (Marmo, 2000, Laing, 2006). Because of the resultant deep plan layouts many workers are situated in the centre of the floor plate far from any windows and openings around the perimeter. Such users are provided with very limited individual environmental control.

METHODOLOGIES

Quantitative methodologies have been traditionally used to research thermal comfort studies, recently however, researchers have been encouraged to apply qualitative methods to research the field (Hitchings, 2009). In this research, a combination of qualitative and quantitative methodologies is applied with the focus on Grounded Theory. This method is a process of redesigning, collecting data and analysing information to formulate the research plan and to develop hypotheses into a theory (Glaser, 1967). Several pilot studies have been applied to formulate a research plan. Traditional thermal comfort data collection techniques are employed as measurements of the thermal environment alongside user questionnaires. A semi-structured interview is included as a qualitative tool to investigate environmental control in depth. Part of the questionnaire includes questions regarding the frequency of sick building symptoms regarding eyes, nose, throat, chest tightness, headaches, and tiredness based on other studies (Bluyssen, 2009 and Raw, 1995). The CO₂ level, temperature and humidity are recorded at each workstation as well as the availability of environmental control. The quality of the thermal environment is compared against the most worldwide and commonly used standard, ASHRAE Standard 55-2010, using the second version of the ASHRAE Thermal Comfort Tool.

CASE STUDIES

Two good practice examples of workplaces with low and high levels of individual environmental control are compared. A naturally ventilated open plan office in Inverness, Scotland, is researched with low levels of individual environmental control and energy use. In contrast, an air conditioned cellular plan office in Oslo, Norway, is investigated with high levels of individual environmental control but with higher levels of energy use. In the open plan office, only a few people sitting around the perimeter of the building have access to openable windows and blinds to control their thermal environment. The majority of the people are allocated to workstations in the middle of the open plan with no means of control. However, in the cellular plan office every individual has access to an openable window, internal and external blinds and a control device to adjust the temperature, see figure 1.



Figure 1 Comparing the environmental control between (a) open plan and (b) cellular plan offices

Building Performance

Energy Use. The energy uses of the two buildings are compared with the CIBSE TM 22 energy benchmark. However, this benchmark is a British model in which every aspect of electricity consumption is calculated separately, including lighting and office equipment, whereas the cellular plan office in Norway does not record this information separately and could only provide the researcher with overall electricity consumption as well as hot water. In order to compare the energy use of the two buildings, the diagram has been simplified and overall annual energy consumption has been considered. As shown in Figure 2, in 2012 the energy use of the open plan office, 155.45 KWh/m², is much lower compared to the cellular plan office, 552.80 KWh/m², this is mainly due to the use of air conditioning in the cellular plan office. With an office rating of 84%, the open plan office has one of the highest ratings for offices in the UK according to the Building Research Establishment Environmental Assessment Method (BREEAM).

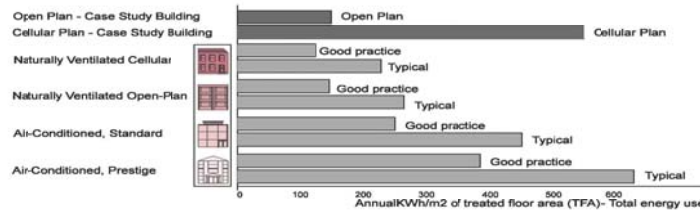


Figure 2 Comparing the open plan and cellular plan offices against the CIBSE energy benchmark 2003

Thermal Environment. The thermal environments of the two buildings during the period of a day are compared with the ASHRAE Standard 55-2010 comfort zone. The analysis shows that the thermal environments of the two buildings are relatively similar and within the range of acceptable thermal comfort zone, see Figure 3 (a).

CO₂ Levels. Figure 3 (b) shows that the CO₂ levels in the two buildings are low and relatively similar.

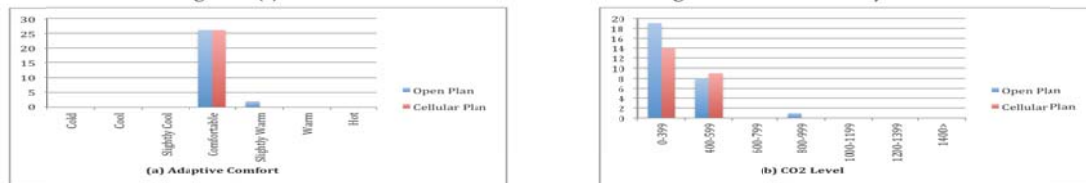


Figure 3 Comparing the two buildings (a) adaptive comfort, ASHRAE Standard 55-2010 and (b) CO₂ level

Environmental Control. The availability of control systems over temperature, ventilation and light for the occupants of the two buildings is compared in figure 4. The cellular plan office provides a much higher level of individual control over the thermal environment, as a window, door, control device over temperature, light switches, external and internal blinds are provided for every user, therefore the majority of people have a high level of environmental control. In contrast, in the open plan setting only people around the perimeter have medium level of control as they can adjust the window or an internal blind. The majority of occupants sit in the middle of open plan with no environmental control.

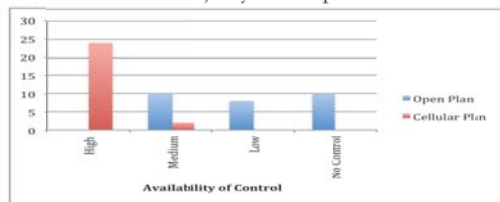


Figure 4 Comparing the availability of environmental control between the two workplaces

Analysis

Analysis Visual Recording Tool. Nicol et al. explain that even though the architectural design of the building envelope highly influences the internal thermal environment, architects have passed the responsibility for providing an acceptable thermal environment to engineers. Furthermore, they suggest that architects should be more involved in improving the thermal environment for the occupants as well as the design based on sustainable criteria (Nicol, 2012). However, architects utilise a different language and tools compared to engineers. For instance, while the equations that are broadly used in thermal comfort studies may not appear user friendly to architects, the visual tools to apply information on plans and sections of a building that are commonly used within the field of architecture add a different quality and perspective to the field. In this paper, based on the survey information, colour codes have been employed to demonstrate different information on the plan and section. For example, blue, green and red show a feeling of cold, neutral and warm, respectively. For example, when the colour of the 'plus' is deep green the occupant never or rarely suffers from any of the following symptoms - dry/watery eyes, blocked/runny nose, dry/irritated throat, chest tightness, headaches, or tiredness. In this case the overall suffering from the SBS is considered very low. Nevertheless, if the colour is deep orange, more than three symptoms are experienced often or constantly, in which the overall suffering from SBS is considered very high. A total of 60 occupants participated in the research, figures 5 (a) and (b) show a sample of the visual information on the open and cellular plan practices.

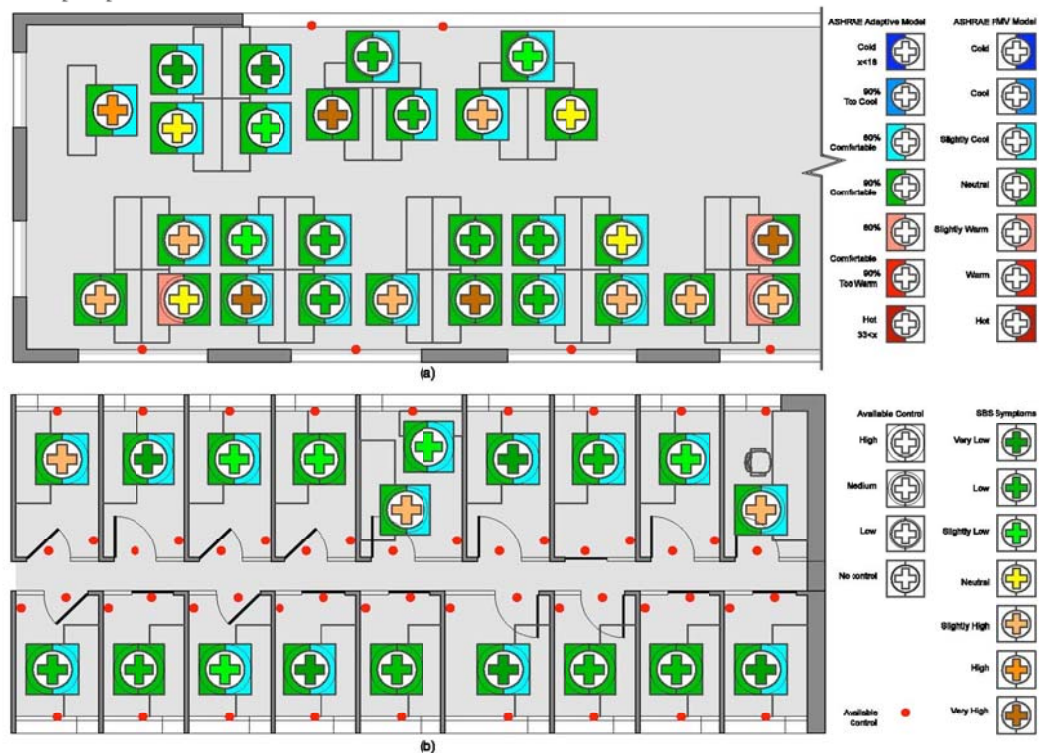


Figure 5 Plans of thermal environment and Sick Building Syndrome in the (a) open plan and (b) cellular plan office

This visual recording technique provides an overview of the situation including individuals' location, environmental control, thermal environment, and symptoms in a single place. For example, in the open plan there are less green 'pluses' that shows the people with low SBS symptoms. In addition, this method is useful to keep track of the information

regarding every individual as well as the connection between the data. For instance, in figure 5 (b), cellular plan, it is possible to spot the connection between symptoms and location, as the two occupants who suffer from symptoms, light orange crosses in shared rooms, have limited level of environmental control as they share the room and sit away from the window. The following analyses are based on this visual analysis.

Sick Building Syndrome. Common symptoms of SBS are compared in the two buildings, including dry/watery eyes, blocked/runny nose, dry/irritated throat, chest tightness, headaches and tiredness. Some of these symptoms are compared in figures 6 (a), 6 (b) and 7 (a), and the overall comparison between the frequency of these symptoms are compared in figure 7 (b). The results indicate that symptoms are higher in the open plan compared to the cellular plan office.

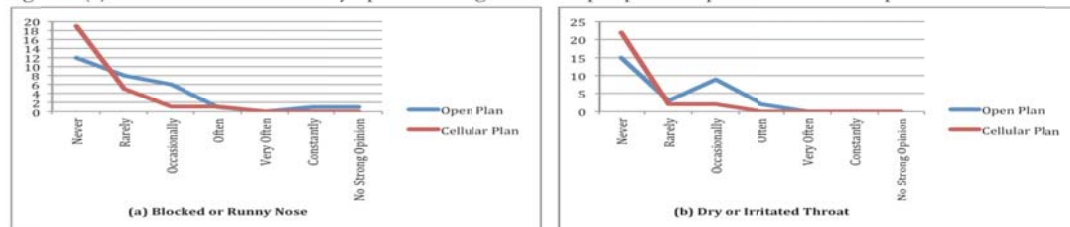


Figure 6 Comparing occupants' frequency of (a) headaches and (b) tiredness between the two buildings

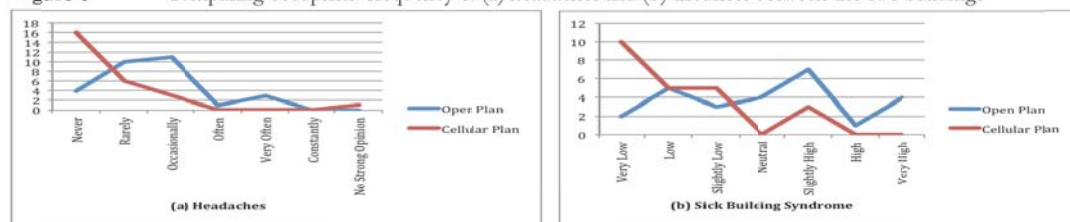


Figure 7 Comparing (a) blocked/runny nose and (b) overall Sick Building Syndrome between the two buildings

CONCLUSION

According to the analysis, the open plan office has a higher risk of SBS compared to the cellular plan workplace, figures 5, 6 and 7. In addition, the thermal environment and the CO₂ level in the two buildings are relatively similar and within the acceptable range, figures 3 (a) and (b). Therefore, the thermal environment and CO₂ level are not responsible for the different levels of symptoms in the two buildings. However, the availability of control systems over the thermal environment is significantly different between the two buildings, figure 4. The cellular plan office provides a higher level of environmental control for the occupants. In fact, it has gone so far as to combine two contradictory systems including air conditioning and openable windows simply to satisfy the occupants. This combination sacrifices the energy use of the building, which is much higher than that of the open plan office. Availability and proper design of individual control over the thermal environment is the possible reason that reduces the symptoms of SBS. Although the sample size is fairly small in this research, the in depth interviews are useful for estimating the impact of individual environmental control over the building related symptoms. Many participants reported in the interview that they did not feel healthy when they could not adjust the settings of the thermal environment to their needs. For instance, two of the occupants in the cellular plan office who reported suffering from tiredness and headaches identified the recently malfunctioning air conditioning in their room as being responsible for their symptoms as they could not change the settings of the temperature. Several participants in the open plan office reported that because of the thermal environment they often experience symptoms, such as dry eyes or skin, and hence, they work from home. If they were able to adjust the thermal environment to eliminate or reduce their symptoms, they would prefer to work in the office to communicate with colleagues. These findings confirm Rollin and Rayner's reports that individual environmental control reduces the risk of SBS (Rollin, 1996 and Rayner, 1996). Another

unavoidable factor that was discovered in the open plan was that of 'the others'. Occupants of the open plan office were particularly aware of their immediate colleagues. Even the users with a window seat did not adjust the window as much as they wanted, based on the requests or complaints of 'the others'. Most occupants of the open plan office preferred an automatic system so that no individual is able to tamper with the system, as some users may desire temperatures outside other people's tolerance. However, if 'the others' factor did not exist and they were alone in the office, they would be very happy to have control over the thermal environment. Even occupants who would like an automatic thermal system they would still prefer a degree of control over the system, in case they were uncomfortable. The occupants of the cellular plan office highly valued their individual environmental control and identified it as one of the main reasons they did not like to move to an open plan setting. The occupants of both settings, open and cellular plan, were very much aware of the individual differences in tolerating and accepting the thermal environment as well as the impact of the environmental control on their symptoms.

Field studies of thermal comfort are criticised based on the complexities of the context and number of different variables influencing thermal comfort (Bluyssen, 2009). In addition, Nicol et al. discuss that the results of one field may not be applicable to another field as the context changes, and therefore, generalising the findings may not be easy (Nicol, 2012). In addition, due to the constraints on time and resources in a PhD research and because collecting the data in a qualitative way, such as interviews requires more time, the sample size is fairly small. Therefore, generalising the results and achievements is difficult. However, Nicol et al. explain that the way forward is through more research in a variety of contexts to gain a better understanding of this complicated field to both clarify the findings and enable their generalisation (Nicol, 2012). This paper focuses on the impact of individual environmental control on users' health. It proposes that the implications of adaptive opportunity in the design of workplaces reduce the risk of SBS. Workplaces should be designed based on sustainable criteria (Nicol, 2012). Furthermore, many researchers have reported that naturally ventilated buildings are healthier than air conditioned buildings (Finnegan, 1984). However, there is a danger in assuming that naturally ventilated buildings are more sustainable and healthy compared to air conditioned buildings. The design of a building, and its flexibility to provide users with environmental control, influences occupants' health and is important. For instance, a poorly designed naturally ventilated building that has corners or dead space with no fresh air has a high risk of building related symptoms. In contrast, a well equipped and designed air conditioned building that provides individual control may have a much lower risk of SBS. Rayner claims that if an air conditioning system is designed properly, it has lower rates of building related symptoms (Rayner, 1997). According to the observations, the air conditioned cellular plan office in this research is better than the low carbon naturally ventilated open plan practice in terms of symptoms of SBS. In the cellular plan office 86.96% of the occupants reported low symptoms, while only 38.46% of people reported such in the open plan.

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Quantitative vs. Qualitative Methodologies to Investigate Environmental Control in the Workplace:

Neutral Thermal Sensation and Thermal Environmental Intention



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This study compares the application of qualitative and quantitative methods to investigate user comfort and environmental control in the workplace. This is examined by environmental measurement and user satisfaction in two workplaces with respectively low and high levels of individual environmental control. An open plan office in Scotland is selected with automatic displacement ventilation, where users have access to limited windows. In contrast, a cellular plan office in Norway is chosen that provides every user with control over a window, in addition to the ability to adjust heating and cooling. Complimentary quantitative and qualitative methodologies are applied with particular emphasis on Grounded Theory methods. Questionnaire, environmental measurements and semi-structured interviews are used. A new visual recording method is applied to analyse the subject in its context qualitatively. Information regarding all users and their environment is applied as colour codes to floor plate layouts. The results are compared with the quantitative analysis. The study examines the significance of applying a qualitative method to question the 'Neutral Thermal Sensation' and expand on the importance of the 'Thermal Environmental Intention'. This paper suggests that the quantitative appraisal could be associated with a risk of misjudgement.

Keywords: methodologies, thermal comfort, individual control

Quantitative vs. Qualitative Methodologies to Investigate Environmental Control in the Workplace: Neutral Thermal Sensation and Thermal Environmental Intention

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ABSTRACT: *This study compares the application of qualitative and quantitative methods to investigate user comfort and environmental control in the workplace. This is examined by environmental measurement and user satisfaction in two workplaces with respectively low and high levels of individual environmental control. An open plan office in Scotland is selected with automatic displacement ventilation, where users have access to limited windows. In contrast, a cellular plan office in Norway is chosen that provides every user with control over a window, in addition to the ability to adjust heating and cooling. Complimentary quantitative and qualitative methodologies are applied with particular emphasis on Grounded Theory methods. Questionnaire, environmental measurements and semi-structured interviews are used. A new visual recording method is applied to analyse the subject in its context qualitatively. Information regarding all users and their environment is applied as colour codes to floor plate layouts. The results are compared with the quantitative analysis. The study examines the significance of applying a qualitative method to question the 'Neutral Thermal Sensation' and expand on the importance of the 'Thermal Environmental Intention'. This paper suggests that the quantitative appraisal could be associated with a risk of misjudgement.*

Keywords: *methodologies, analysis, thermal comfort, individual control, workplaces*

INTRODUCTION

This paper compares the application of a quantitative and a qualitative methodology to research the thermal environments of two buildings with high and low levels of environmental control. The aim is to discover differences and misjudgements of these two approaches. Through this comparison, the 'Neutral Thermal Sensation', which is the basis of thermal comfort studies, is questioned. In addition, the qualitative analysis highlights the importance of the 'Thermal Environmental Intention, which is the user's intention to change and apply control over the thermal environment.

NEUTRAL THERMAL SENSATION

ASHRAE presents a seven-point scale for thermal sensation surveys as hot, warm, slightly warm, neutral, slightly cool, cool and cold [1]. The ASHRAE standard and defining the comfort zone are based on the neutral thermal sensation [2]. For instance, the ASHRAE handbook explains that 'acceptability is determined by the percentage of occupants who have responded as neutral or satisfied with their thermal environment' [2]. Other studies of thermal comfort including the experimental chambers and adaptive comfort are also based on the neutral thermal sensation. For example, Fanger's experiments to find the optimum temperature are on this basis. Bluyssen explains that Fanger 'strongly believes that comfort can be reached when the heat balance of the human body is neutral' [3]. He

discovered that 'for practical purposes the neutral temperature is invariant [4].

Based on a study in 2007, Humphreys found that many people were comfortable when they did not feel neutral regarding the surrounding thermal conditions. In the UK, where the temperature is generally cold, people were comfortable when experiencing sensations, such as neutral, slightly warm, warm and occasionally hot [5]. Hitchings explains that 'instead of talking about what temperatures feel neutral in particular places when we have already accepted this to be dynamic, the ambition may now be to reveal which techniques people are willing to employ to get through particular periods more sustainably' [7]. Although this was recognised in 2007, adaptive comfort studies are still based on the neutral thermal sensation [5 & 8]. For example, Nicol's 'scatter of neutral temperature', which is presented in figure 1, shows how neutral temperature changes according to outdoor temperatures in free running buildings [6].

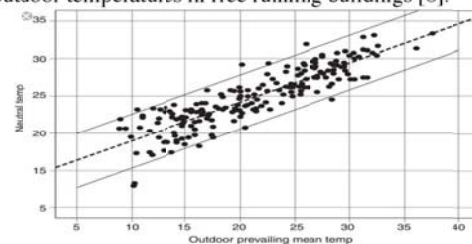


Figure 1: Neutral temperature and the prevailing mean outdoor temperatures in free-running buildings [6]

ENVIRONMENTAL CONTROL

Different studies explain the impact of environmental control on user comfort [9, 10, 11 and 12]. Nevertheless, the prevalence of deep open plan layouts and the speculative nature of workplace development prevent the direct influence of users on the indoor thermal environment and replace it with centralised facilities management [13]. In addition, there is a strong preference for centralised automatic systems to eliminate users' influence on the system to streamline the facilities management [14]. Different studies have been conducted regarding the pattern of use of environmental controls, such as windows [5, 15]. This paper compares environments with high and low levels of individual control over the thermal environment. It compares cellular and open plan offices with respective high and low levels of environmental control.

Anglo-Saxon Open Plan vs. Scandinavian Cellular Plan Offices. The working culture, legislation and building traditions of Anglo-Saxon and Scandinavian countries are very different. This is followed by a difference in the design of workplaces as well as individual environmental control [16]. In Scandinavia, every worker has the right to access natural light and ventilation [16]. In order to maximise these two aspects, offices are located around the perimeter of the floor plates, in the form of traditional personal offices. In this case, every individual is provided with a high level of environmental control. In contrast, the open plan layout has become common in Anglo-Saxon countries. The high level of communication and very efficient use of space are the benefits of an open plan office [17, 18]. In the deep open plan offices, many occupants are allocated far from windows and openings, and they are provided with very limited environmental control.

METHODOLOGY

Traditionally, in thermal comfort studies, quantitative methodologies have been used, however the application of the qualitative methods has recently been encouraged [7]. In this study, a combination of quantitative and qualitative methods is employed with particular emphasis on the qualitative part, which is the Grounded Theory. The latter is a cycle process of designing, collecting and analysing the information to develop hypotheses into a theory [19]. In this research, different pilot studies were conducted to formulate a research plan to be employed at the site. Measurements of the thermal environment and questionnaires are used simultaneously at every workstation as the traditional techniques. The questionnaire is based on the ASHRAE seven-point scale. In addition, semi-structured interviews are applied as a qualitative tool to investigate environmental control and comfort in depth. The quality

of the thermal environment at every workstation is compared to the commonly used worldwide standard, ASHRAE Standard 55-2010, by using the second version of the ASHRAE Thermal Comfort Tool.

CASE STUDY BUILDINGS

This research includes two good practice examples of workplaces with low and high levels of individual environmental control. An open plan office with centrally controlled displacement ventilation in Aberdeen, Scotland, is researched with low levels of individual environmental control. In contrast, an air conditioned cellular plan office in Oslo, Norway, is investigated with high levels of individual environmental control. The plans are presented in figure 9 and the sections in figure 2. In the open plan office, only people seated around the perimeter of the building have access to limited openable windows and blinds to control their thermal environment. The majority of the people are allocated to workstations at the centre of the open plan with no means of control. However, in the cellular plan office every individual has access to an openable window, internal and external blinds and a control device to adjust the temperature, see figure 2. In the open plan practice 81 votes and in the cellular plan office 97 votes are considered in this study. Approximately equal numbers of men and women with a variety of ages have participated in the research.

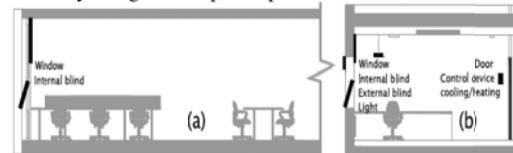


Figure 2: Sections: Environmental control in (a) British open plan and (b) Scandinavian cellular plan office

BUILDING PERFORMANCE

Energy Consumption. The energy use of the two buildings is compared with the CIBSE TM 22 energy benchmark [20]. As shown in figure 3 the cellular plan office has a much higher energy use, 552.80 KWh/m², compared to the open plan office, 159.39 KWh/m².



Figure 3: Comparing the overall energy use of the two buildings against the CIBSE energy benchmark (simplified)

CO₂ Level. As shown in figure 4a, the cellular plan office has slightly lower CO₂ levels, but both of the buildings are within the acceptable range.

Environmental Control. The availability of control over temperature and ventilation in the two buildings is compared in figure 4b. In the open plan, 77% of the participants have no access to any means of environmental control as they sit close to the centre, in contrast to 91% of the participants in the cellular plan who have full personal control over a window, door, corridor blind, internal and external blinds, as well as a control device to adjust cooling and heating.

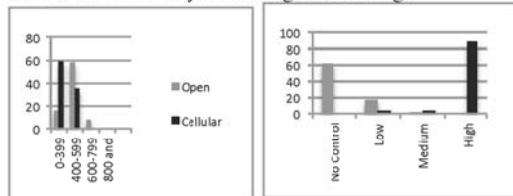


Figure 4: Comparing the two buildings in terms of (a) CO₂ levels; and (b) availability of environmental control

Predicting Thermal Comfort. The thermal environments of the two buildings during the period of a day are compared with the ASHRAE Standard 55-2010 comfort zone, both adaptive and PMV models, see figures 5a and 5b. The basis of both models is the 'Neutral Thermal Sensation'. The adaptive model predicts that 94% of the people in the open plan layout and 100% in the cellular plan office are thermally comfortable. The PMV model predicts that 48% of the people in the cellular plan office have a neutral thermal sensation, while only 9% of the people in the open plan workplace have the same neutral feeling.

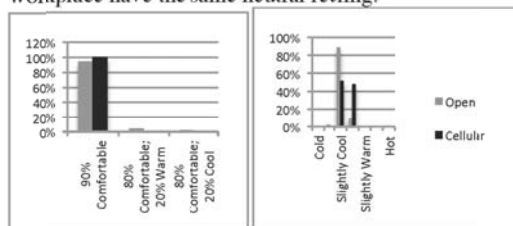


Figure 5: Thermal environments (a) adaptive (b) PMV models

The building performance analysis of the two buildings shows that both buildings provide relatively a good quality of an indoor thermal environment, although the performance of the cellular office is slightly better. Both buildings perform well according to the energy benchmark, in this case the open plan is more efficient. The cellular office provides significantly a higher level of individual environmental control compared to the open plan office.

QUANTITATIVE VS. QUALITATIVE ANALYSIS

Although steady state and adaptive comfort theories oppose each other, both of them use quantitative methods and analysis. The former takes place in

experimental chambers with a few controlled variables, while the latter is measured in the real life context of workplaces [21].

Quantitative Analysis. In the open plan office, 40% of the participants reported having a neutral thermal sensation, 49% reported having no desire for a change in temperature, 40% reported being satisfied, and 64% reported being thermally comfortable, see figure 6. The number of respondents who reported neutral, no change and satisfied is very similar. In addition, the level of comfort reported by participants in the open plan office is much higher than the PMV prediction, while much lower than the adaptive model. Furthermore, the number of respondents who reported a neutral thermal sensation is much lower than the adaptive model and much higher than the PMV model. In the cellular plan office, 46% of the occupants reported having a neutral thermal sensation, 46% reported having no desire for a change in temperature, 71% reported being satisfied, and 81% reported feeling thermally comfortable, see figure 6. The number of respondents who reported neutral and no change is very close. The level of comfort reported by participants in the cellular plan workplace is much higher than the PMV prediction, while lower than the adaptive model. In addition, the neutral sensation reported in the cellular office is much lower than the adaptive prediction, but very close to the PMV model. With the exception of the latter, the actual survey results are significantly different from either the adaptive or PMV predictions in both buildings.

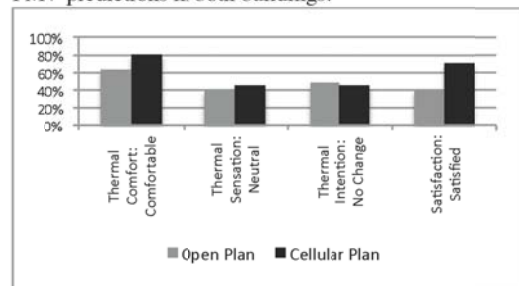


Figure 6: Comparing the two buildings regarding the desired thermal comfort, sensation, intention, and satisfaction

In addition, the survey statistics in both buildings suggest a close relationship between the 'Neutral Thermal Sensation' and 'No Change' thermal intention, as the results are very close. However, they also suggest that more people reported being thermally comfortable than those with a neutral thermal sensation or no change intention in both buildings.

Qualitative Analysis. Although the architecture of a building directly influences the indoor thermal environment, architects have passed the responsibility to provide thermal comfort to engineers [6]. The results of

thermal comfort studies, such as Fanger's heat balance equation, although very useful, are often expressed in a language that may not be convenient for architects.

Visual Analysis Tool. Visual tools are commonly used in the field of architecture to apply information on plans and sections. They add a different value and perspective by putting together different information regarding a specific aspect in a visual way. In this paper, a visual recording technique shown in figure 9 has been used, in which the information has been expressed by applying different colours to the floor plates. Figure 7 shows the analysis of an individual workstation, which is a top view of a seated person. The colours inside the squares show the PMV and adaptive predictions based on the ASHRAE tool and environmental measurements. The colours inside the ellipses symbolising the person's body, indicate the person's reported survey at the time of the measurements at the particular workstation. The green colour shows an acceptable situation, while blue, red, and orange are respectively cold, warm, and an unacceptable situation.

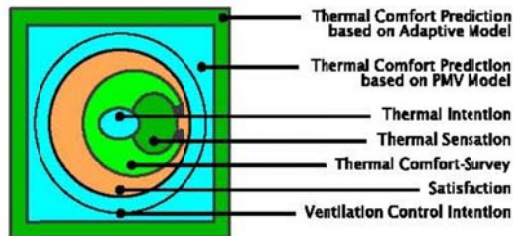


Figure 7: Qualitative demonstration of the information regarding a workstation, top view

Neutral Thermal Sensation. The qualitative analysis shows that 48% of the participants in the cellular plan and 45% in the open plan prefer to have other thermal sensations than neutral. Many respondents want no change in the temperature when they feel slightly warmer or cooler, while others prefer a change in the temperature when they have a neutral thermal sensation, see figure 8. Occasionally respondents may have an extreme temperature desire, such as a slightly cooler intention when they already feel cool.

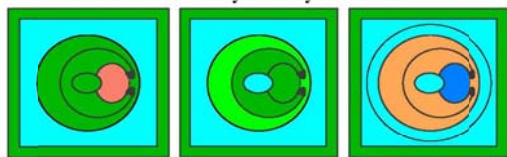


Figure 8: Sample of participants who do not prefer a neutral thermal sensation, top view

Neutral Thermal Sensation and Comfort. Qualitative analysis shows that 50% of the respondents in the cellular plan office and 53% of the participants in

the open plan are comfortable when they do not have a neutral thermal sensation. In addition, the interview results confirm that the majority of participants desired temperatures other than neutral for working; 40% of the participants preferred to work feeling slightly cool and occasionally cool, in order to feel fresh and not sleepy, while 30% of the participants desired slightly warm and occasionally warm working conditions since they were not physically active at work. Only 30% of the participants preferred to work feeling neutral.

Environmental Thermal Sensation and Satisfaction. Quantitative analysis shows lower levels of satisfaction compared to thermal comfort in both buildings, see figure 6. Qualitative analysis shows that in the cellular plan, 100% of the participants who reported satisfied are also comfortable, while only 62% of the participants who reported being comfortable are also satisfied. In the open plan office, 86% of the respondents who reported being satisfied are also comfortable, while only 35% of the people who reported being comfortable are also satisfied. This suggests that satisfaction is more of a delicate matter compared to comfort and that user satisfaction has a strong relationship with their thermal comfort so that satisfied people are more likely to be thermally comfortable.

No particular pattern or relationship was found between the use of environmental control and user satisfaction or comfort. However, the qualitative analysis shows a strong relationship between satisfaction and thermal environmental intention, including user intention to change the temperature and ventilation. In the cellular plan office, 93% of the respondents with a less than satisfied also reported having a thermal intention other than 'No Change'. In addition, 90% of the people with a 'No Change' thermal environmental intention reported being satisfied. In the open plan setting the number of respondents who reported being satisfied as well as no change is 62%, which is lower than the cellular plan. However, the number of respondents with a ventilation intention, who would like to apply a change to the air quality or air movement is 90%.

In addition, 96% of respondents with a 'No Change' thermal environmental intention reported satisfied. The satisfaction of the participants in the cellular plan with easy access to a window is more related to their desire to change the temperature, while people's satisfaction in the open plan with no access to any window or environmental control is more related to their desire for ventilation, such as the air movement and air quality. Conclusively, the qualitative analysis suggests a significant influence of overall thermal environmental intention on user satisfaction.



Figure 9 (a): Plan: Sample of the qualitative analysis of the Scandinavian cellular plan office, morning of 22 May 2012

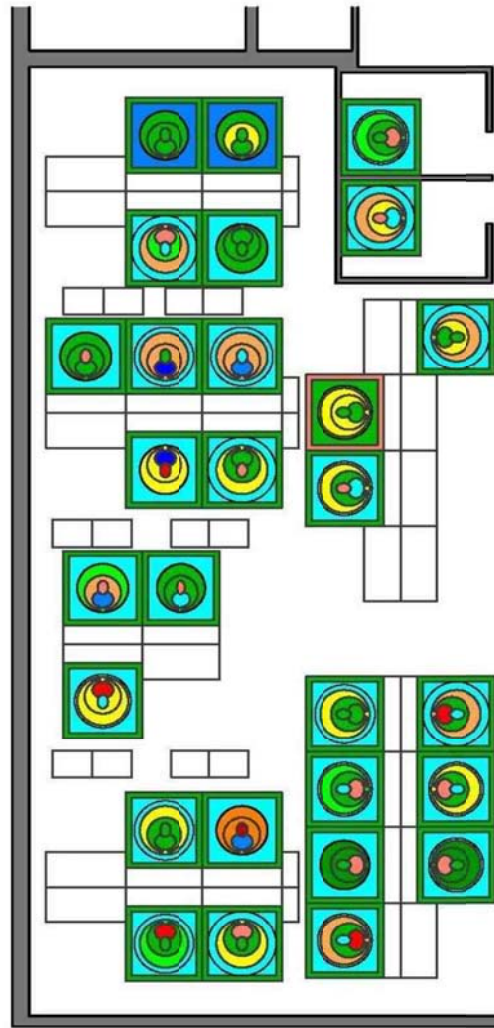
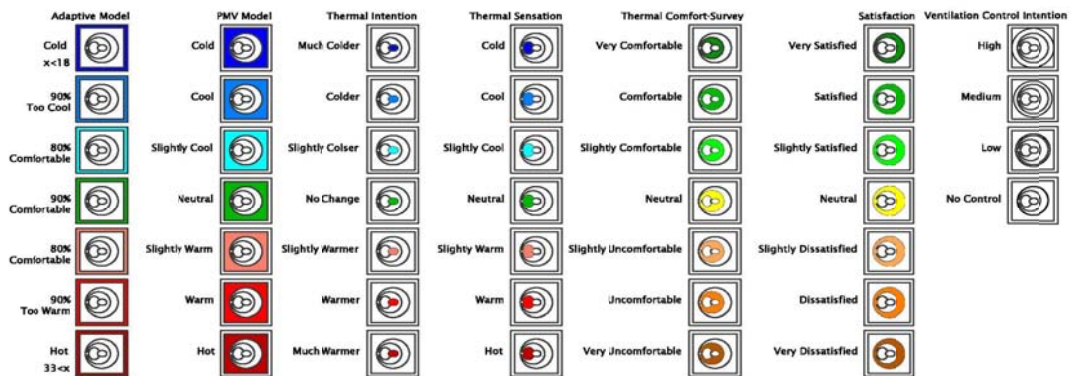


Figure 9 (b): Plan: Sample of the qualitative analysis of the British open plan office, morning of 28 August 2012



CONCLUSION

This paper compares a quantitative and a qualitative approach to research thermal comfort. These two approaches have different applications. It suggests that the quantitative approach is more suited for general understanding of a situation such as the overall satisfaction. However, the interpretation of the connection between information through a quantitative approach could drive to a misjudgement. Here, 'the significance of often straightforward mathematical relationships becomes almost talismanic' [22]. Therefore, user competence is required as to where to apply the quantitative or qualitative method. The qualitative analysis of the collected information reveals connections between the data regarding a particular person that changes the meanings and influences the findings of the research. The qualitative analysis in this paper suggests that the 'Neutral Thermal Sensation' does not guarantee thermal comfort as the quantitative analysis of the same data suggests as well as being presumed in the previous studies of thermal comfort. This confirms Humphreys' findings regarding the 'Neutral Thermal Sensation' that many people prefer thermal sensations other than neutral to feel comfortable [5]. In addition, qualitative analysis suggests that satisfaction is significantly influenced by the 'Environmental Thermal Intention', such as temperature and ventilation. Satisfied respondents have limited intention to change the temperature, ventilation rate or air quality. Finally, occupants of the cellular plan office with a high level of individual environmental control report much higher levels of thermal comfort and satisfaction compared to the occupants of the open plan workplace with limited access to environmental control, such as openable windows.

Field studies of thermal comfort have been criticised for the complexities of the context and diversity of variables influencing the comfort conditions [3]. In addition, Nicol et al. suggest that the findings of a field study may not be applicable to other buildings since the context changes, thus generalising the findings of a field study is difficult [6]. In addition, in this study, due to the constraints on time and resources in a doctoral study period, as well as collecting the data in a qualitative way, such as interviews, the sample size is fairly small. However, this research suggests that the qualitative analysis reduces the risk of misjudging the information, so the results are more likely to be accurate and applicable. In addition, Nicol et al. explain that the way forward is through more research in a variety of contexts to gain a better understanding of this complicated field to both clarify and generalise the findings [6].

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