Approaches to Skycourt Design and Performance in High-Rise Office Buildings in a Temperate Climate

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DEDICATION

This thesis is dedicated to people without whom, none of my success would have happened:

To my Parents,
For their countless love and prays
For giving me motivation to reach my dream and teaching me that I am capable of doing anything

To my husband, Amer
For supporting me all the way with his love and patience
Together we achieved our first milestone

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ABSTRACT

Skycourts recently have been considered as beneficial spaces in commercial buildings, particularly offices. Research is steadily growing on the energy performance of these spaces but there is a lack of conclusive results in the available literature.

Ventilation is a main contributor to energy consumption in offices. This study aims to examine the potentials of skycourts to perform as transitional buffer zones with suitable ventilation strategies in office buildings in a temperate climate, such as London. The goal is to investigate reduction in energy demands of heating and cooling for the building; and in addition to ensure an accepted level of thermal comfort for occupants in these skycourts.

The study was conducted in three key phases. Firstly, a literature review highlighted issues related to the skycourt and ventilation requirements in high-rise office buildings. Secondly, common prototypes of skycourts in the research context were extracted through analysing their spatial configurations as transitional buffer zones. Thirdly, simulations were conducted using a coupled approach between Building Energy Simulation and Computational Fluid Dynamics to define efficient configurations of skycourts that have potentials of energy saving, and offer an accepted level of thermal comfort.

The annual energy demand for heating and cooling for the building, in addition to air temperature, and airspeed in the occupied area of the skycourt were adopted as main criteria for comparing the results. According to the results, the skycourt as a free-heated and free-cooled buffer zone, which is ventilated by the maximum airflow volume rate exhausted from the adjacent offices, achieved a total reduction of over 55% in building heating and cooling energy demands annually. In addition, it accomplished a comfort occupied zone. Finally, the study developed guidelines to help designers define the most effective configurations of ventilated skycourts in office buildings for temperate climates, which reduced building energy consumption, according to the design needs.

PUBLICATIONS

The following papers have been published according to the results of this study:

1. Alnusairat, S. and Jones, P. (2017). The influence of skycourt as part of combined ventilation strategy in high-rise office buildings. In: *Proceedings of ECSEE (European Conference on Sustainability, Energy & Environment) 2017, Brighton, UK, 7-9 July 2017*. pp. 49–64.

2. Alnusairat, S., Jones, P. and Hou, S.S. (2017). Skycourt as a ventilated buffer zone in office buildings: assessing energy performance and thermal comfort. In: *Proceedings of PLEA 2017 Conference, Edinburgh, UK, 2-5 July 2017*. pp. 4901–4908.

3. Alnusairat, S., Hou, S.S. and Jones, P. (2017). Investigating spatial configurations of skycourts as buffer zones in high-rise office buildings: Coupling building energy simulation (BES) and computational fluid dynamic (CFD). In: Spaeth, A. B. and Jabi, W. (eds.) *Proceedings of the 5th eCAADe Regional International Symposium, Cardiff University, UK, 26-28 April*. Brussels, pp. 83–92.

4. Alnusairat, S. and Elsharkawy, H. (2015). Passive design approach for high-rise buildings: From courtyards to skycourts. In: *Proceedings of the 4th ZEMCH 2015 International Conference, Lecce, Italy, 23-25 September*. pp. 739–748.

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CHAPTER ONE: INTRODUCTION

1 INTRODUCTION

1.1 RESEARCH BACKGROUND

Globally, it has been projected that over 60% of the world's population will be relocated to cities by 2030 (United Nations, Department of Economics and Social Affairs, Population Division 2016). High-rise buildings, which are increasingly being seen in many cities, provide a solution for this growing demand for urbanisation and the rapid movement towards cities (Soomeren *et al.* 2016; Hadi *et al.* 2014; McNeill 2005).

A high-rise building is a tall structure with a small footprint area, and it can offer residential, office, commercial and mixed-use functions (Hudgins 2009). Such a massive construction, in which its specific height depends on the context itself (Allford and Monaghan 2008), requires special structural, mechanical, electrical, fire protection, vertical transportation and movement systems (Yeang 2002).

High-rise buildings according to the London Plan, which regulates the built environment in this city, are defined as: structures that are taller than their surroundings and cause a significant change to the skyline or structures that are larger than the threshold sizes set for the referral of planning applications. High-rise buildings adjacent to the River Thames are 25 m in height, those in the City of London are 150 m in height, and elsewhere in London they are 30 m in height (Greater London Authority 2015), (Figure 1-1). The focus of this study is the city of London, as most recent development are constructed in this area.

Figure 1-1. Skyline panorama for London

Source: Wikimedia Commons

However, these developments could have significant impacts on the built environment and the building construction industry (Losantos and Cañizares 2007). In the United Kingdom (UK), for instance, buildings accounted for more than 33% of the total energy consumption in 2015.[1] Therefore, the primary challenge is how to create a high-rise building that is connected to the city, climate, and people; and how to use sustainable designs that consume minimum operational costs and offer comfort for occupants (Lotfabadi 2014; Feng and Xingkuan 2011; Sev and Aslan 2014).

Recently, architects have attempted to integrate solutions and introduce elements that could improve the quality of the indoor environment and provide beneficial effects for occupants (Parker and Wood 2013). One of these features is the skycourt, which is a transitional space that could offer a diversity of social, environmental and economic benefits, and improve the overall performance of buildings.

The skycourt concept is initiated from adapting the traditional (vernacular) elements of low-rise buildings, such as courtyards and atriums, which have significant potential in dealing with the climate, the culture and the context (Pomeroy 2014; Aldawoud 2008, 2013; Edwards *et al.* 2005), (Figure 1-2). Skycourts in mid-rise and high-rise buildings could provide a contemporary alternative to courtyards through allowing natural light to penetrate deeper into interior spaces (Johnson 2015), and promoting ventilation while avoiding unwanted solar gain. These could lead to a significant reduction in energy consumption, and an increasing improvement in health, wellbeing and productivity (Yeang 1999).

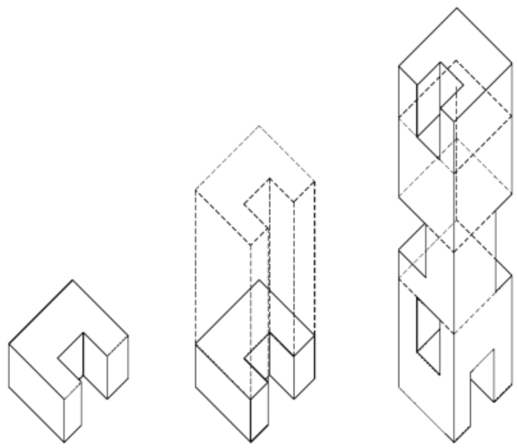

Figure 1-2. Transformation from courtyard at low-rise to skycourt at mid-rise and high-rise buildings

[1] https://visual.ons.gov.uk/uk-perspectives-2016-energy-and-emissions-in-the-uk

Other possible advantages provided by skycourts include the support of occupants' social networking by offering space for seating and relaxation for users while enjoying the outside views (Pomeroy 2007), (Figure 1-3). Such potentials make the skycourt an important responsive element that facilitates the holistic sustainable environment and improves the performance of the building.

Figure 1-3. Skycourts in high-rise office buildings; (above left) Heron tower, London (Photo credit: kpf.com); (above right) 20 Fenchurch tower, London (Photo credit: fousquare.com); (below) Commerzbank, Frankfurt (Photo credit: fosterandpartners.com)

Source: www.pinterest.co.uk

Research considering the environmental performance of skycourts is steadily growing. However, there are inconclusive results about the actual energy consumption of these spaces in the available literature. Attention recently has focused on the effect of skycourts on the ventilation performance as HVAC (Heating, Ventilating, and Air-Conditioning) systems present a significant portion, nearly 40% of the total energy consumption, for high-rise buildings (Al-Kodmany 2015).

The influence of skycourts is considered in relation to two main issues in ventilation. The first one concerns the potential of skycourts to improve the efficiency of airflow in buildings. Skycourts could be included in buildings to act as features to promote air supply, air exhaust and air circulation when combined with other design elements such as an atrium (Taib *et al.* 2010), segmentation (Liu *et al.* 2012), smart facades and wing forms[2] (Wood and Salib 2013). Although these strategies might enhance ventilation in buildings, the implication of them in high-rise buildings is restricted, particularly for offices, due to the difficulty of control and problems in significantly achieving comfort requirements, thermally and acoustically, in temperate climates (Larsen *et al.* 2008; Strelitz 2011). Such strategies may reduce the effectiveness of ventilation due to the requirements of offices that include greater floor plan depth, higher population density, and higher heat gain through equipment, compared to other types of buildings (Etheridge and Ford 2008; Hacker *et al.* 2005). Other strategies include mixed ventilation. These require implementing a smart building management system (BMS) that consists of sensitive sensors inside and outside the building to measure climate parameters. This system is connected with operable windows, vents, shading devices, and air handling units to activate the natural or mechanical mechanism (Goncalves and Umakoshi 2010). However, energy effectiveness in this case is a result of total design strategies and operation systems, not the skycourt alone. Therefore, studies are needed to investigate the real effect of the skycourt space only.

The second issue to be considered relates to the impact of skycourts when mechanically ventilated. Skycourts perform as transitional zones situated in-between outdoor and indoor environments in buildings (Pomeroy 2014). It has been recognised that closed indoor buffers consume higher cooling energy than other spaces of similar sizes in buildings to achieve the same level of thermal comfort (Pitts *et al.* 2008; Göçer *et al.* 2006). This is associated with higher energy costs. In addition, current HVAC system might not be enough to provide thermal comfort in areas of a large volume, particularly, when they act as transitional spaces. Most of these areas suffer from excessive temperatures compared to other small spaces (Kaynakli and Kilic 2005).

[2] Wing forms include curvilinear forms of walls and roofs in buildings. These features can create strong pressure zones by increasing wind velocity and pressure coefficient to adapt both single-sided and cross ventilation (Givoni 1998)

Yet, there are limited studies addressing the influence of skycourts on the total performance of buildings (Katolicky *et al.* 2002). This study explores the possible benefits of skycourts as transitional buffer spaces to improve ventilation.

Previous studies showed that potentials for energy reduction in buildings could be enhanced by minimising spaces that are consuming heating and cooling energy or by minimising requirements for comfortable conditions (Alonso *et al.* 2011). Utilising such strategies in enclosed transitional spaces serving as buffer zones could achieve energy savings (Chun *et al.* 2004). In addition, accepted levels of thermal comfort could be achieved in these spaces (Serghides *et al.* 2017). For example, controlling air conditioning cooling devices, while maintaining adequate indoor comfort levels, by increasing the temperature set-point of 26°C of the air conditioning system with moderate air velocity during non-peak hours in working days, achieved about a 1.2% reduction of the building energy consumption without compromising safety requirements and human comfort (Kwong *et al.* 2013). Increasing the temperature set-point of the air conditioning up to 27.2°C could achieve more energy savings, ranged between 6% and 10% (Yang and Su 1997), while increasing the air temperature to 28°C accomplished 34.4% of energy savings in the air conditioning power (Chiang *et al.* 2012). In conclusion, the previous research indicates that such transitional spaces could provide significant reductions in building energy consumption by lowering the demand of heating and cooling loads. This raises the following question:

What is the impact on energy savings provided by skycourts when acting as a transitional zone in high-rise buildings with the absence of heating and cooling in these spaces?

Therefore, this study seeks to investigate potential energy savings of implementing such strategies in skycourts taking into consideration achieving accepted levels of thermal comfort in these spaces.

1.2 LONDON: A REPRESENTATIVE CITY IN A TEMPERATE REGION

The UK is a temperate country situated in the northwest of Europe between 49° to 61° N latitude and extends from 9° W to 2° E longitude. London, the capital, is situated in the southern part of the country on the River Thames. It experiences a temperate oceanic climate with rainfall over the year according to the Köppen-Geiger climate classification (Peel *et al.* 2007). Generally, this zone has average temperatures below 22°C in all months and at least averaging above 10°C in four months. Heating is required from early autumn to late spring, while cooling is needed in warm days in the summer.

1.2.1 High-rise Office Buildings and Skycourts in London

London is recognised as a leading city and financial centre due to its location, time zone, legal system, and relatively stable political environment (Barton and Watts 2013). Recently, there is increasing attention and governmental incentives for the construction of high-rise buildings in London, as these structures promote strategies of power and development (Moazami and Slade 2013; Barton and Watts 2013). Currently, London is the third city in Europe by number of completed buildings of over 150 m high. Figure 1-4 shows the individual building height and the number of high-rise buildings in London between 1968 and 2014.

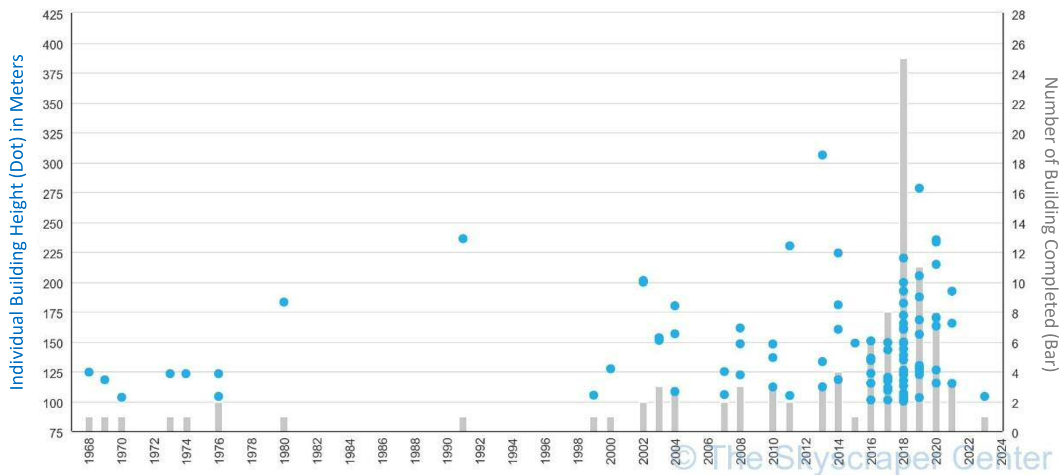

Figure 1-4. High-rise buildings completions with timeline in London

Source: The Global Tall Building Database of the CTBUH 2017

One of the growing trends in the building sector in London is the provision of offices. The London Plan indicates that central London needs 2.3 million m^2 (net) office floor space over the period 2011 to 2031 (Greater London Authority 2015). Therefore, the development of high-rise office buildings is enhanced and supported to meet this increase in demand. Currently, offices account for over 50% of the total usage of high-rise buildings over 150 m in height (Figure 1-5) and over 40% of the total usage of high-rise buildings of all heights (Figure 1-6), according to the Global Tall Building Database of the CTBUH (2017). Approximately 67% of completed office buildings have an average height range between 100 m and 199 m (The Global Tall Building Database of the CTBUH 2017), (Figure 1-7).

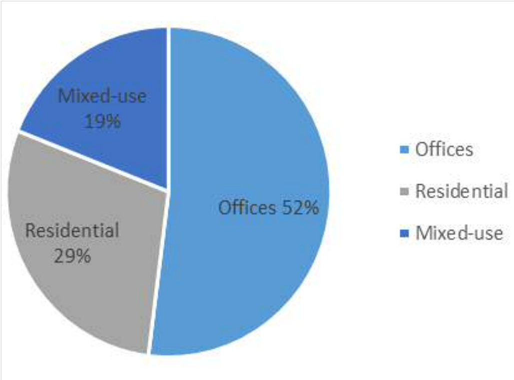

Figure 1-5. Percentages of high-rise buildings supply in London based on 150+ m heights

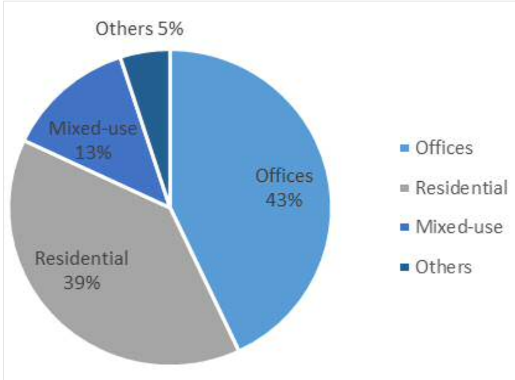

Figure 1-6. Percentages of high-rise buildings supply in London based on all heights

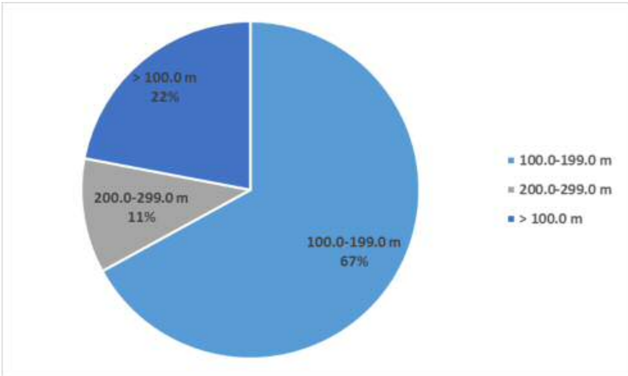

Figure 1-7. Percentages of average height range of completed high-rise office buildings in London between 1960 and 2014

Source: The Global Tall Building Database of the CTBUH 2017

Most of the high-rise office buildings are air-conditioned (British Council for Offices (BCO) Guide 2014; Pout *et al*. 2012). Significantly, such structures are seen as commercial developments (Hitchin and Pout 2001). The targets are to achieve higher comfort level for occupants, more productive environments and increase the rental value of floor spaces (Spasis 2007).

Another important reason for installing such systems in buildings is concern about the impact of global warming. Temperatures in London are predicted to increase by the end of the century by about 5°C depending on the emissions scenario in the UK (Committee on Climate Change 2016). This causes warmer summers with an increase in the number of very hot days and a decrease in the number of cold days. By 2080, the internal temperature of some offices will reach over 28°C for a quarter of the occupied hours over the year (Hacker *et al*. 2005). This indicates that mechanical cooling for London's offices will be required in developments as natural ventilation can be a risky design option in hours of overheating (Sharples and Lee 2009).

The above scenarios show that there will be a trend for increasing mechanical ventilation in London. However, these systems account for about 55% of the total energy consumption in offices (Pérez-Lombard *et al.* 2008). A study (Yuana *et al.* 2016) analysed the overall level of energy consumption based on survey data of energy consumption in office buildings that hold sustainable certificates such as LEED and BREEAM, concluded that HVAC system should be given significant attention when determining energy subsidies. These account more than 45% of the energy use in certified offices. Efficient ventilation in office buildings is therefore significant to improve their energy performance, with the aim of achieving energy conservation and reducing the environmental impact.

Skycourts are increasingly incorporated in high-rise office buildings in London to enhance business efficiency and visual connectivity. The London Plan Policy addresses such spaces as a requirement for buildings to be successful places to live, work, and attract investments (Greater London Authority 2014). These spaces facilitate collaboration, networking and offer volumetric variety and a community focus (Strelitz 2011). One important issue observed in skycourts in London offices is that spaces are enclosed glazed volumes, where opening windows are not preferred. Such areas in a temperate climate cause high energy consumption due to the excessive solar heat gain in summer and heat loss from large glazed surfaces (Göçer *et al.* 2006). This situation questions the importance of optimum energy consumption in such transitional spaces, as these spaces do not generate income in office buildings (Pitts and Saleh 2007). Therefore, this study focuses on the potential of skycourts to improve the energy efficiency of ventilation systems in such buildings. This can support achieving the required reduction of 60% in energy consumption by 2050, according to Intergovernmental Panel on Climate Change (Goncalves and Bode 2011).

1.3 RESEARCH AIM, QUESTIONS AND OBJECTIVES

The research aims to investigate the potential of skycourts to perform as transitional buffer spaces that complement the ventilation strategy in office buildings in a temperate climate, such as London. This could potentially reduce the energy demands of heating and cooling for buildings; furthermore it could ensure an accepted level of thermal comfort for occupants in these skycourts.

In order to accomplish this aim, the research explores the following key questions:

- Can skycourt enhance and drive efficient heating and cooling demands in high-rise office buildings?
- Can skycourt achieve an accepted level of thermal comfort for its occupants?
- What is the optimum configuration of this skycourt in temperate climates such as in the London context?

The research objectives are set to embrace the following:

- Extract the common prototypes of skycourts in the research context through analysing their spatial configurations as transitional buffer spaces in existing high-rise office buildings.
- Investigate the influence of skycourts when accompanying ventilation to reduce heating and cooling demands for offices and to afford an accepted level of thermal comfort in skycourts. Several ventilation strategies to mediate thermal conditions in skycourts are investigated.
- Examine the impact of various design parameters, which include the orientation, height, area, length and depth of skycourts, and in addition, air inlet and outlet opening locations inside skycourts. These help to determine the most critical ventilation conditions.
- Outline recommendations for designing skycourts in high-rise office buildings in temperate climates – London city – that have potentials of energy saving, and an accepted level of thermal comfort.

1.4 RESEARCH SCOPE AND FOCUS

To achieve the research aim and objectives, the study will focus on the following:

- Skycourts in high-rise office buildings are selected based on their function as transitional buffer zones.

- The study focuses on the potential of the skycourt to perform as a buffer zone that suits the ventilation strategy. Therefore, two ventilation modes are developed in this study. These are mode one, the reference model, which represents a heated, ventilated, air-conditioned skycourt; and mode two, alternative models, which incorporate unheated and uncooled skycourt that combines ventilation strategies with adjacent offices' zones. In addition, six parameters, which include the skycourt's orientation, area, length and depth and air inlet and air outlet openings locations within the skycourt will be examined to determine the most critical ventilation conditions.

- The efficiency of the proposed approach will be assessed in terms of two criteria. First, the annual heating and cooling demands (kWh/m^2.yr) for the building. Second, air temperature (°C) and airspeed (m/s) at the occupied zone of the skycourt in summer, winter and transitional seasons.

- Weather data: Gatwick statistics for London weather data will be employed in the study, these applied 51° 9' N latitude and 0° 10' longitude. The weather forecast data is imported from EnergyPlus weather format, which is derived from several sources including the Chartered Institution of Building Services Engineers (CIBSE), the (UK) Met Office, and the International Weather for Energy Calculations (IWEC) from up to 18 years of archived hourly weather data.

1.5 RESEARCH METHODS AND FLOW

The research is organised in three main phases: literature review, case study analysis, and simulation. Figure 1-8 summaries the research phases.

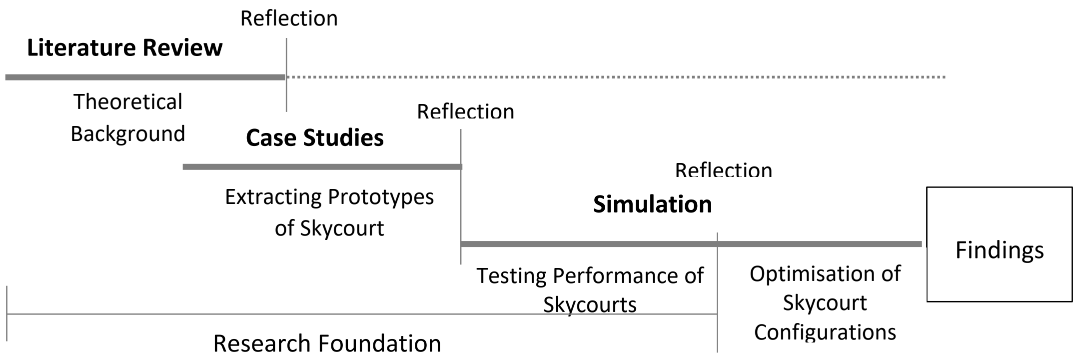

Figure 1-8. The research phases and how they are interconnected (literature review, case study, and simulation)

1.5.1 Phase One: Theoretical Background (Literature Review)

The literature review provides a theoretical background for the research on which questions can be formulated and can influence the design and the direction of the research. This phase investigates the key issues of the research. The outcome of the approach demonstrates an overview of the local context of the study, issues related to the skycourt, such as function, need, significance, geometry, and design requirements. Furthermore, ventilation requirements in high-rise office buildings and research methods to carry out the study are addressed. In addition, it provides the needed data for the selected case studies in the next phase.

1.5.2 Phase Two: Extracting Prototypes of Skycourts (Case Studies)

In this phase, skycourts in existing high-rise buildings are explored. The investigation identifies the common prototypes of skycourts in high-rise office buildings in the research context. The focus of the research is on skycourts that act as transitional buffer zones in office buildings. This investigation analyses skycourts' spatial configurations. In addition, it discusses other issues of skycourts in the selected cases, such as design attributes.

1.5.3 Phase Three: Testing the Assumption (Simulation)

This stage tests the assumption of the research. It intends to construct the study models; investigate effects of skycourts on the ventilation system, and examine the effect of the selected parameters of skycourts on improving and promoting a ventilation performance to achieve optimum configuration in terms of thermal comfort and energy efficiency. The hypothetical model is formulated to represent a high-rise office building in London based on the design guidelines suggested by the British Council for Offices (BCO). As the study focuses on the skycourt and adjacent offices' zones, the hypothetical model is constructed to include the offices that are integrated with the skycourt in the building. Numerical simulation is carried out to predict energy and thermal performance in the study by coupling HTB2, the Building Energy Simulation (BES) and WinAir, the Computational Fluid Dynamic (CFD) tool. Then, the collected data will be analysed and compared. This approach provides information on the impact of the skycourt as a buffer zone in office buildings, and affords design guidelines for skycourts in a temperate climate that ensure thermal comfort in these spaces, and maximise reductions in heating and cooling demands for the building.

The framework of the research is presented in Figure 1-9. This includes the research phases connected with objectives, methods and stages for each phase, starting from exploring the theoretical background of the research, the empirical work, and ending with findings, conclusions, and recommendations.

1.6 STRUCTURE OF THE FOLLOWING CHAPTERS

The thesis is organised in seven chapters including this introduction. These represent the main parts of the research: the introduction; the literature review; the research design and methodology; analysis of the results, discussion; and finally the conclusion.

Chapter two reviews the main issues that influence the topic of the study. It looks at skycourts in high-rise buildings, and the different ventilation principles that interact with both thermal comfort and energy efficiency in buildings. In addition, it reviews related methods that are used to investigate energy and the thermal impact of ventilation.

Chapter three is concerned with developing the assumption of the study. It presents the main prototypes of skycourts as buffer zones in the context.

Chapter four identifies the research design and the method that is used to achieve the research objectives. Moreover, it illustrates the steps of the simulation.

Chapter five presents the results of the study according to the established process. Chapter six provides comparisons in which the obtained results are discussed. Chapter seven presents the main conclusions of this study.

Appendices provide additional information. Appendix A includes weather data about London used in this study. Appendix B presents comparison tables regarding prototypes of skycourts in the research context. Appendix C includes samples of the simulation files that are used in this study. Appendix D illustrates main results obtained from data analysis.

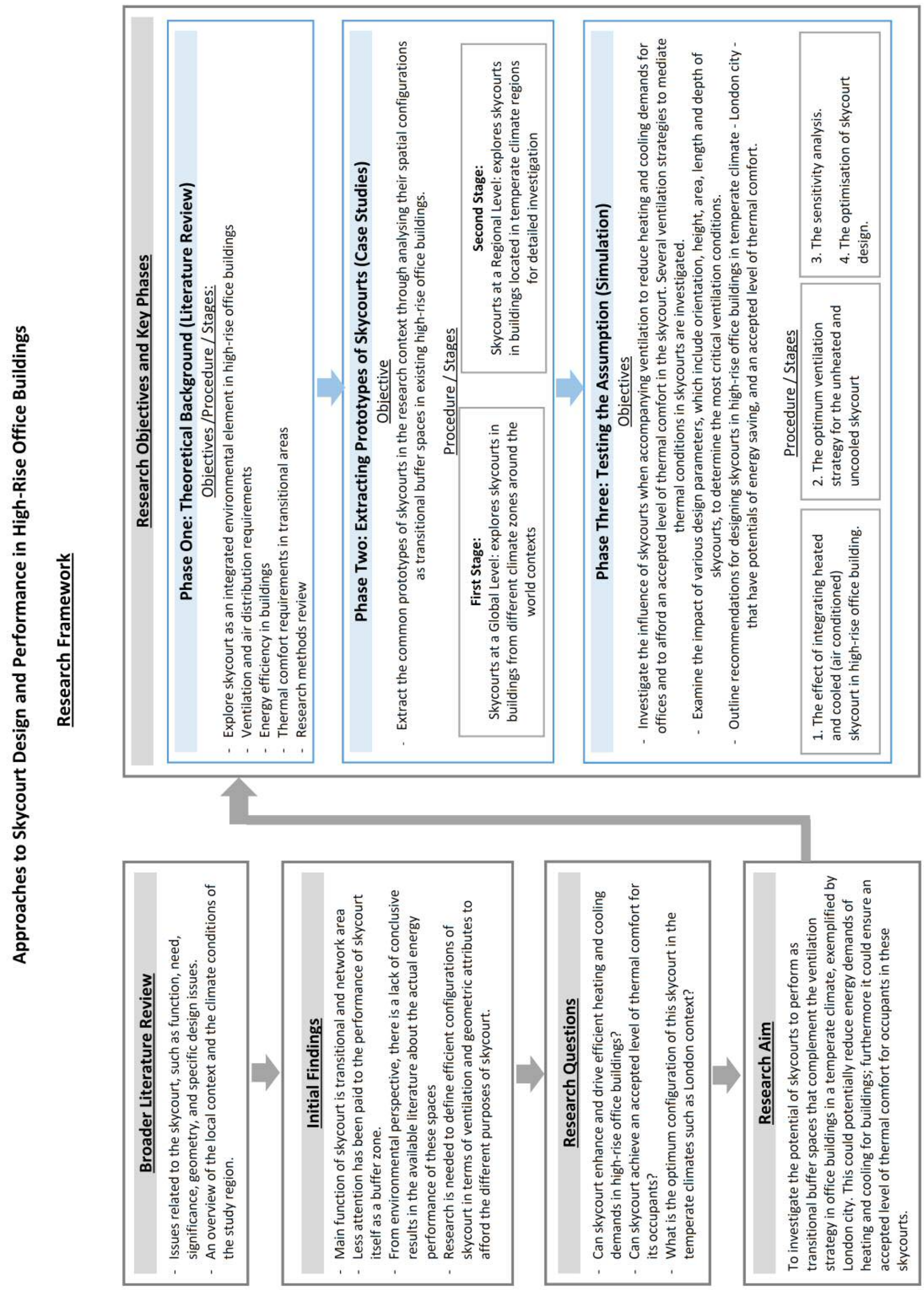

Figure 1-9. Research framework

CHAPTER TWO: LITERATURE REVIEW

2 LITERATURE REVIEW

2.1 INTRODUCTION

This chapter aims to review skycourts in buildings, and in addition to develop the theoretical background necessary to answer the study questions and achieve its objectives. The chapter consists of four main parts.

Part one explores the development of skycourt spaces and their fundamental functions in buildings. Discussion focuses on previous studies that investigated the performance of skycourts and their potentials to improve ventilation emphasising the function of transitional buffer spaces in buildings.

Part two reviews the main principles, types, requirements and considerations for ventilation in buildings. Such issues are important to develop an overall understanding of the ventilation process in order to improve ventilation strategies and develop the proposed approach for this study.

In part three, principles for achieving indoor comfort and energy efficiency due to ventilation are described.

Part four reviews the main methods that are useful to carry out such research to define the suitable method for the present study.

Summaries of key contributions and gaps that shape the study questions are defined for each part. Also, concluding remarks from the overall literature are provided at the end.

Figure 2-1 illustrates the literature review flowchart that was applied in this study. The contents of the literature were developed based on an accumulative process starting from the preliminary statement of the research, and ending with a definition of key contributions and gaps that shape the research questions.

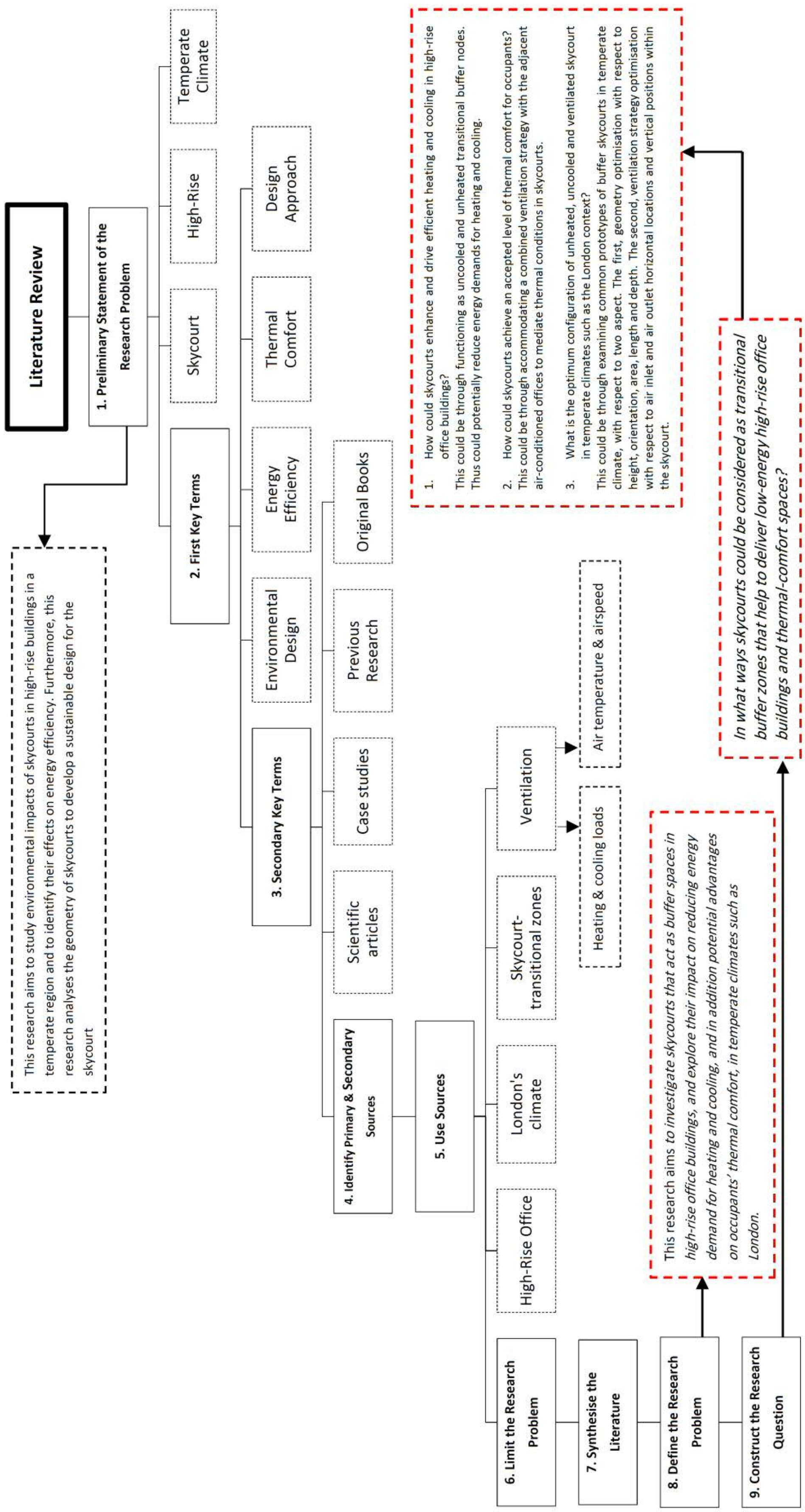

Figure 2-1. Literature review plan for the key terms of the research

2.2 SKYCOURTS: AN OVERVIEW

Skycourts are increasingly being included in high-rise buildings. These spaces perform as spaces for social gatherings and transitional nodes. In addition, they have the potential to provide environmental and economic benefits. This part of the literature review aims to develop an understanding of skycourt spaces as environmentally sustainable design elements in high-rise buildings. An overview is provided of the evolution of skycourt spaces focusing on its role in ventilation. Then, the fundamental environmental functions of skycourts and their social and economic benefits are deliberated. A discussion regarding the design guidelines of skycourts is presented. Finally, gaps in the current literature regarding skycourts' design and performance are identified.

2.2.1 Development of the Concept of Skycourts in High-Rise Buildings

The environmental role of skycourts has been recognised since the first generation of high-rise buildings. The skycourt was developed from the principles of atria and courtyards to promote ventilation and catch adequate daylight (Figure 2-2). It was included in high-rise buildings between 1890 and the 1930s as void layouts within the U, H, E and O-shaped plans of office buildings to enhance ventilation and lighting (Sev and Aslan 2014). However, significant problems appeared in those buildings concerning noise and the inefficient amount of humidity and ventilation. This implied the need for an efficient ventilation system to supply adequate fresh air and eliminate problems affecting the comfort of indoor environments. As a result, mechanical systems became necessary (Wood and Salib 2013).

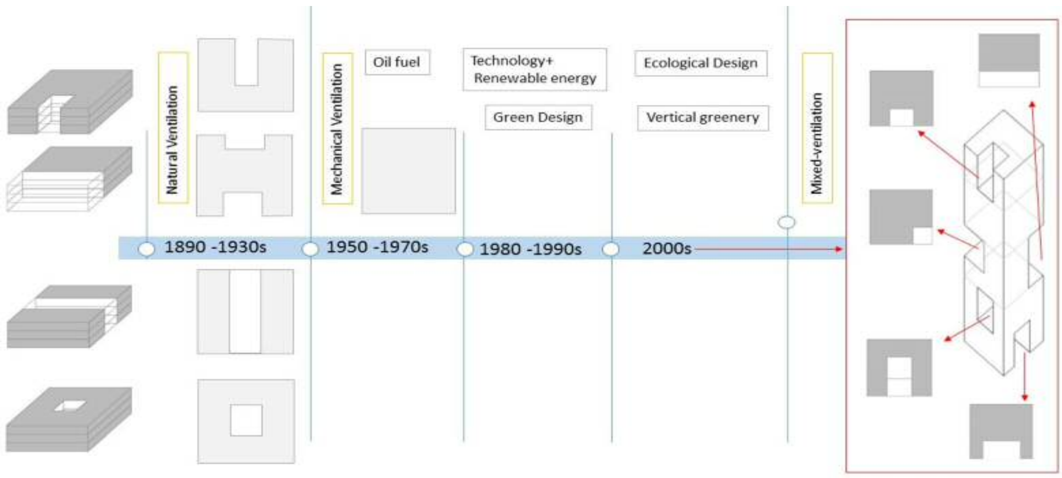

Figure 2-2. The evolution of skycourts in high-rise buildings

High-rise buildings that relied on mechanical systems became increasingly common between 1950 and the 1970s with the invention of air conditioning (Al-Kodmany 2015). Low cost energy, and the efficiency of mechanical systems in controlling indoor air temperature and humidity, especially for deep spans, were key reasons for their widespread use in high-rise constructions, particularly in office buildings of fully glazed facades (Sev and Aslan 2014). This minimised the adoption of skycourts in these buildings. However, the oil crises of 1973 was a major reason to start thinking about new mechanisms to reduce the energy consumption for heating, ventilation, cooling and lighting. Attention was focused on renewable supply schemes for energy, such as the solar panels that were used in office buildings between 1980 and the 1990s (Oldfield *et al.* 2009). Furthermore, efficient HVAC systems and chilled (heated) surfaces were introduced as effective strategies for reducing internal heat loads and achieving energy savings in these buildings in the 21st century (Jones *et al.* 2015). In addition, the use of smart facades such as double skin façades, was considered as an effective strategy to improve the building energy performance. This feature acts as a high-insulation envelope and a thermal-buffer zone to mediate temperature between the interior and the exterior (Chartered Institution of Building Services Engineers (CIBSE) Guide B 2005). Moreover, it has the potential to reduce heating and cooling loads between 30% and 90% in temperate climates (Pomponi *et al.* 2016). On the other hand, the implication of passive principles such as solar ventilation strategies, wing walls and wind towers was restricted in high-rise office buildings. This is due to the difficulty of controlling temperature and humidity, and the overheating problems in summer, which could affect the comfort level in these buildings and cause negative impacts on the productivity of workers (Hitchin and Pout 2001).

Lack of open spaces, greenery and diversity in buildings could affect the interior environment and social communication between users (Thomas 2012; Pomeroy 2007). Therefore, ecological design strategies[1] were adopted in the design of high-rise buildings. Skycourts, as one of these ecological features, were re-introduced to facilitate occupants' interaction, provide daylight, enhance ventilation and avoid undesirable solar gain (Yeang 1999). Skycourts were integrated as recessed multi-storey transitional zones located

[1] Ecological design aims to integrate the building with the environment, considering the role of the context, physically and culturally. This includes features such as nature's utilities; biodiversity balancing and environmental connectivity; renewable energy systems; technological and carbon natural system; and human enclosures (Yeang 1999).

between the inside and the outside walls of high-rise buildings (Pomeroy 2014; Yeang 1999). These have the potential for conserving energy and improving the satisfaction of the occupants (Zhou *et al*. 2014). Also, they were used as open spaces to divide buildings into vertical segments (Pomeroy 2012; Mohanty 2010), (Figure 2-3).

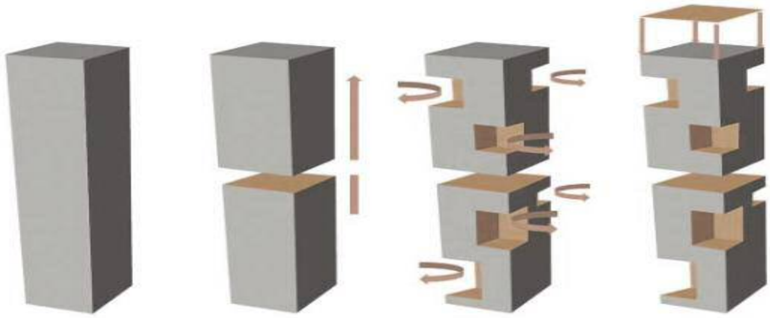

Figure 2-3. Skycourts in high-rise buildings

Source: Pomeroy (2012)

2.2.2 Fundamental Functions of Skycourts in High-Rise Buildings

This section discusses the various functions of skycourts in high-rise buildings from environmental, social and economic perspectives.

2.2.2.1 Overview of Skycourts from an Environmental Perspective

Skycourts provide different benefits from an environmental perspective, taking into consideration their impact on the urban setting, starting from the city scale narrowing down to the building scale. Thermal comfort, indoor air quality, biodiversity, and potential to be efficient spaces in buildings are the main matters.

The skycourt is an environmental filter or buffer: Skycourts could be defined as environmental filters (Table 2-1). They could play the role of thermal buffers to mediate the temperature between exterior and interior, allowing air to penetrate to the interior (Pomeroy 2014), and reducing the impact of solar radiation (Jahnkassim and Ip 2006). These features could provide positive impacts on the interior thermal conditions and occupants, as it offers a comfortable indoor environment in terms of air temperature, relative humidity and air velocity (Ismail *et al.* 2011). In addition, skycourts could allow daylight to penetrate into the interior environment (Pomeroy 2014), and act as acoustic buffers between spaces (Wong *et al.* 2010), which, therefore, improves occupants' satisfaction. Transitional spaces such as skycourt gardens at balconies and roofs could enhance thermal comfort performance and air temperature variations in high-rise buildings (Taib *et al.* 2014). Moreover, greenery could enhance air quality by filtering out pollutant organisms (Lovell and Johnston 2009; Khan *et al*. 2005). Sky-gardens at the top of buildings could reduce room temperatures beneath the structure by 10% (Wong *et al*. 2010), and have potential in reducing roof heat losses during cold days in winter in hot climates (Jaffal *et al*. 2012).

Table 2-1. Benefits of skycourts in different studies from environmental perspective – skycourts as buffer zone

The Skycourt as an Environmental Buffer Filter			
(Pomeroy 2014)	(Jahnkassim and Ip 2006)	(Ismail *et al.* 2011)	(Taib *et al.* 2014)
Skycourts can allow light and air to penetrate into the interior	Skycourts may play a role as a ‘thermal buffer’ that reduces the impact of solar radiation and glare	Bioclimatic elements such as skycourts offer a more comfortable indoor environment, and increase satisfaction	Skycourts as transitional spaces (skycourt garden, balcony garden and rooftop) can enhance thermal comfort
(Lambeth Council 2010)	(Castleton *et al.* 2010)	(Jaffal *et al.* 2012)	
Sky-roof offers benefits to building and its surrounding environment	Sky-roof with greenery can reduce the summer indoor air temperature by 2°C, and the annual energy demand by 6%	Sky-roofs with gardens are thermally beneficial for hot, temperate, and cold European climates. In the summer, the roof passive cooling effect was three times more efficient with the green roof. In the winter, the green roof reduced roof heat losses during cold days; however, it increased these losses during sunny days.	
(Khan *et al.* 2005)	(Lianga *et al.* 2014)	(Giridharan *et al.* 2008)	
Plants improve air quality, increase pleasantness, and help to improve performance	Vertical greenery can lower the temperature of its surroundings	Increasing the tree cover from 25% to 40% in the pocket parks in coastal area could reduce daytime urban heat island intensity (UHI) by further 0.5-1°C. Future research in high-rise environments should incorporate sky-roof and sky terrace gardens.	

The skycourt as a ‘biodiversity enhancer’: Biodiversity represents the degree of variation in life systems within a specific ecosystem, as well as being a measure of the health of an ecosystem (Hui and Chan 2011). Scholars argued that planted skycourts, sky-terraces and sky-roofs could form examples of design elements in buildings, which could enrich the biodiversity and enhance urban ecosystems starting from the city scale down to the building scale (Pomeroy 2014), (Table 2-2). It was found that improvement of biodiversity could have positive impacts on the quality of life of occupants and facilitate preservation of biodiversity in natural ecosystems (Savard *et al.* 2000). Hui and Chan (2011) claimed that the built environment created by green roofs is one of the methods for biodiversity conservation, as green roofs have the potential to function as islands of biodiversity within urban and suburban environments. Williams *et al*. (2014) found that spatial plans, heights, linkages and total areas of green roofs within a city are key elements contributing to biodiversity benefits. These should be considered in any policies advocating green roofs as habitats (Williams *et al.* 2014). Burghardt *et al*. (2009) stated that enhancing the biomass and the diversity of native plants would increase the diversity of insects, creating a resource base for important animals such as birds (Burghardt *et al.* 2009). However, the real impact of skycourts on biodiversity based on real-state high-rise buildings needs more investigation.

Table 2-2. Benefits of skycourts in different studies from environmental perspective – skycourts as biodiversity enhancer

Skycourt Greenery as a Biodiversity Enhancer			
(Williams *et al.* 2014)	(Burghardt *et al.* 2009)	(Hui and Chan 2011)	(Savard *et al.* 2000)
Sky-roofs' gardens might help achieve urban biodiversity conservation goals	Enhancing the biomass and diversity of native plants would increase the diversity and abundance of insect herbivores and thus create a greater resource base for important insectivores such as birds	Sky-roofs' gardens have the potential to function as islands of biodiversity within urban and suburban environments. Building development in the urban areas will destroy the habitats and result in biodiversity loss	Improvement of biodiversity in urban systems can have a positive impact on the quality of life and education of dwellers and thus facilitate the preservation of biodiversity in natural ecosystems

The skycourt as a passive design enhancer: Passive design refers to a series of strategies integrated in the architectural design to develop a building that responds to climatic requirements such as sun and wind among other contextual needs (Cantón *et al.* 2014). Such designs could have potential to reduce energy consumption and to improve the quality of life. Skycourts could provide contemporary alternatives to the vernacular courtyard in high-rise buildings due to their potential to allow natural air to enter deeper into the interior of buildings. In addition, skycourts could be considered as passive cooling techniques due to their greenery effect that are thermally beneficial in different climatic regions, hot or cold, (Table 2-3).

Table 2-3. Benefits of skycourts in different studies from environmental perspective – skycourts as passive element

The Skycourt as a Passive Design Element			
(Zhou *et al.* 2014)	(Jaffal *et al.* 2012)	(Ismail *et al.* 2011)	(Castleton *et al.* 2010)
Passive ventilation in buildings has a great potential for conserving energy and improving the health of occupants	In summer, the passive cooling effect of a sky-roof with greenery was three times more efficient than a plain roof. In winter, the green sky-roof reduced roof heat losses during cold days	A building which incorporates skycourts can offer a more comfortable indoor environment in terms of air temperature, relative humidity and air velocity in passive manners	Sky-gardens are passive cooling technique that stop incoming solar radiation from reaching the building structure below. This has potential in energy efficiency and offers benefits in winter heating reduction as well as summer cooling

Cooling utilisation in summer and heating use in winter were reduced with sky-gardens at the top of buildings, which in turn cause reductions in annual energy demands by 6% (Castleton *et al*. 2010). The passive cooling effect of sky-roofs with greenery was found to be three times more efficient than ordinary concrete roofs during the summer in hot climates (Jaffal *et al*. 2012). Moreover, these green roofs could reduce heat gain by about 60% compared to smoother surfaces due to reflection (Yeang 1999).

Furthermore, skycourt can provide environmentally indoor public space that has potential to be lit and introduce daylight into the adjacent spaces in buildings, significantly, when it acts such as transitional buffer areas. Previous studies have recognised the daylight potential of similar vertical spaces of skycourts such as atria (Chi *et al.* 2017; Li *et al.* 2014; Chows *et al.* 2013; Samant 2010; Sharples and Lash 2007). Generally, daylight levels within atrium spaces are sufficiently high. In addition, such spaces can reduce lighting energy demand of buildings. However, concerns regarding comfort levels of illumination and glare, in addition to overheating in adjoining spaces could be raised. Therefore, daylight-linked lighting controls can deliver excellent energy savings in such circulation spaces. For example, in a study investigated this issue in an atrium' corridors, it was found that over 90% could be saved of the energy spent using lighting controls (Chows *et al.* 2013). As well as, control strategies in offices can provide lighting energy savings rate of 60% (Xu *et al.* 2017).

In conclusion, from an environmental perspective, skycourts are a microclimate human-friendly space, which could improve human comfort levels through low-energy design guidelines.

2.2.2.2 Overview of Skycourts from a Social Perspective

There are three key benefits of skycourts from a social perspective; these look at the direct impact of skycourts on occupants' interaction, social needs and wellbeing (Table 2-4).

The skycourt as a space for social networks: Skycourts could provide a medium for different levels of social interactions between people: public, semi-public and private interactions. For example, skycourts at the lower levels of buildings could enhance public interactions; skycourts at the middle levels and rooftops of buildings could develop semi-public interactions; and, interior spaces such as sky-terraces provide private social networks (Pomeroy 2014).

The skycourt as an enhancer of socio-physiological experience: Social design could be defined as a responsible design practice that focuses on the social dimension, by introducing the social needs and impacts of this approach, and then applying these on projects (Schwarz and Krabbendam 2013). Grounded on that, a skycourt could be defined as a socially responsible design element that emphasises the social good in the design to create social values.

The skycourt as an enhancer of psycho-physiological wellbeing: The skycourt could be defined as an element that enhances the psycho-physiological wellbeing of the occupants, and as a result improves the quality of living. This includes social, environmental and economic attributes. Skycourts could foster a sense of community and promote the community life (Kuo *et al.* 1998; Bay 2004). For example, it allows social interaction, which in turn has effects on the feeling of belonging and security. Skycourts could enhance exposure to natural features such as air, daylight, views, and greenery. These improve the quality of architectural spaces, which in turn offer beneficial psychological effects for occupants. Studies found that there is a relation between occupants' health and the indoor daylight, vegetation, and the nature of views from and within the building. For example, daylight could foster beneficial effects in the health of people that live in buildings (Altomonte 2009). Furthermore, exposure to natural views contributes substantially to occupants' satisfaction and desire to keep in contact with the surrounding context, and augments wellbeing, attitude, mood, concentration and lower cholesterol levels (Honold *et al.* 2015; Altomonte 2009; Kaplan 2001) and reduces obesity, diabetes, and other chronic health problems (Lovell and Johnston 2009). In addition, spaces with indoor plants cause beneficial psychological changes such as stress-reduction (Dijkstra *et al*. 2008), mitigate pain (Bringslimark *et al*. 2009), and therefore, improve human performance (Raanaas *et al.* 2011; Khan *et al.* 2005). Also, spaces with green plants were preferred over the ones with no plants in offices (Shibata and Suzuki 2004).

Table 2-4. Benefits of skycourts in different studies from social perspective

The Skycourt as Enhancer of Socio-physiology and Psycho-physiology of the Occupants			
(Pomeroy 2014)	(Schwarz and Krabbendam 2013)	(Yeang 1999)	(Honold *et al.* 2015)
Skycourts enhance various levels of social interaction	Spaces such as skycourts emphasise the social good in design to create social values	Skycourts are transitional zones located between the insides and the outsides of high-rise buildings to promote connection with the city	Exposure to different kinds of natural elements were related to lower cortisol levels
(Altomonte 2009)	(Bringslimark *et al.* 2009)	(Dijkstra *et al.* 2008)	(Kaplan 2001)
Daylight can foster advantages to the quality of architectural spaces, bringing benefits to the occupants' health	Indoor plants cause beneficial psychological changes such as stress-reduction and increased pain tolerance	Perceived stress was lower and room attractiveness was higher with plants	Settings in the view from the window contribute substantially to residents' satisfaction with their neighbourhood and with diverse aspects of their sense of wellbeing

In conclusion, the skycourt is defined as a responsible typology that enhances social sustainability and the occupants' experience in buildings.

2.2.2.3 Overview of Skycourts from an Economic Perspective

Skycourts provide several economic benefits in buildings (Table 2-5). Examples of these are the following:

The skycourt as a productivity enhancer: There is a direct relation between productivity and the indoor environment. It was found that productivity could be improved by 4% to

10% by enhancing the office environmental conditions such as indoor air quality and pollution (Clements-Croome and Baizhan 2000). Skycourts could enhance productivity as they provide an alternative informal working environment (Pomeroy 2007). Healthier buildings could reduce sick leave and increase productivity. For example, natural light, good ventilation, absence of organic compounds and appropriate temperature could result in happier and healthier workers (Miller *et al.* 2009). Skycourts could help in creating such environments.

The Skycourt as a means of reducing energy consumption: Skycourts could enhance utilisation of passive elements such as natural light and ventilation. In addition, a skycourt and its greenery could reduce heat gain and the ambient temperature (Jahnkassim and Ip 2006). Skycourts when acting as transitional spaces could attain wider limits of thermal comfort (Alonso *et al.* 2011). These could enhance potentials to reduce energy consumption.

The skycourt as an income generator: Skycourts could provide different functions to generate income. For example, they could be used to increase the rentable space, function as an observation deck, and provide food and beverage destinations. In addition, the skycourt could enhance the property value of the high-rise building (Pomeroy 2014).

Table 2-5. Benefits of skycourts in different studies from economic perspective

Skycourt As An Economic Enhancer Space- productivity enhancer			
(Clements-Croome and Baizhan 2000)	(Pomeroy 2007)	(Lambeth Council 2010)	(Miller *et al.* 2009)
Productivity could be improved by 4% to 10% by improving the office environmental conditions	Skycourts provide networking space between workers	A sky-roof with garden has the potential for building energy savings to reduce annual heating and cooling loads	Spaces that improve happiness and health of workers attain reduction in sick time and an increase in productivity. Spaces that provide exposure to daylight and natural elements can create such environments
(Jahnkassim and Ip 2006)	(Ismail *et al.* 2011)	(Alonso *et al.* 2011)	(Pomeroy 2014)
The highest savings in terms of energy performance are mainly attributed to features that have the highest solar control.	Bioclimatic design elements such as skycourts show an improvement in energy saving	Energy reduction in transitional spaces could be enhanced by minimising requirements of their comfort conditions	Skycourts provide an iconic value to the building

In conclusion, from an economic perspective skycourts provide an energy reduction element in high-rise buildings that carries an iconic value to the building and increases the productivity of the occupants.

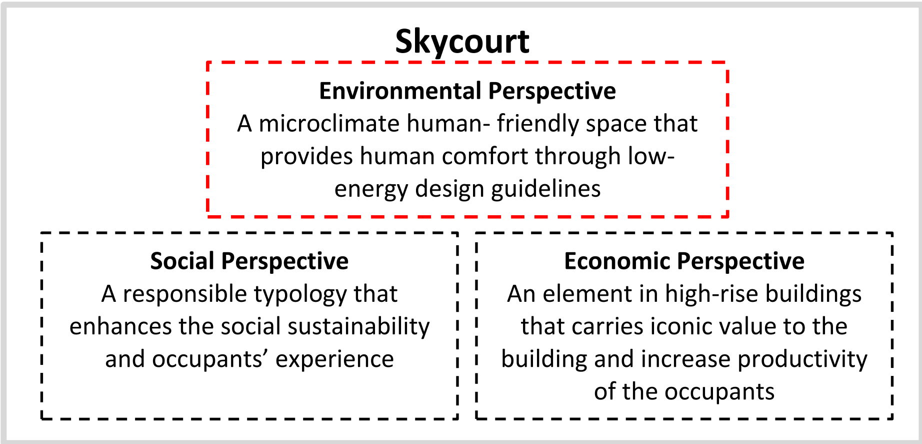

Figure 2-4. Definition of skycourts from social, environmental, and economic perspectives

Although skycourts can be beneficial in the environmental, social and economic aspects, they have their disadvantages. One main problem is fire safety. The vertical void feature of skycourt that contain several floors requires cautious consideration in the design process (Hung and Chow 2011). For example, smoke emitted from fire would spread more rapidly through such void compared to non-skycourt building (British Standard BS 9999:2017 2017). This would lead to human and property losses. Therefore, fire safety aspects for skycourts including design and management should be considered when designing skycourts in buildings. Other problems include solar collection through skycourt glazed facades and discomfort glares. This requests potential high energy demand to keep comfort level in these spaces (Göçer *et al.* 2006). In addition, skycourts reduce the total efficient area of the building as it displayed throughout many levels of the building.

2.2.3 Configurations of Skycourts in High-rise Buildings

Skycourts could be located at the lower part of the building as a sky-entrance, between the middle floors as a skycourt, or at the top of the building as a sky-roof. Such void spaces could be of two-floor height or more, linked with the surrounding indoor and outdoor areas by open or enclosed walls (Figure 2-5).

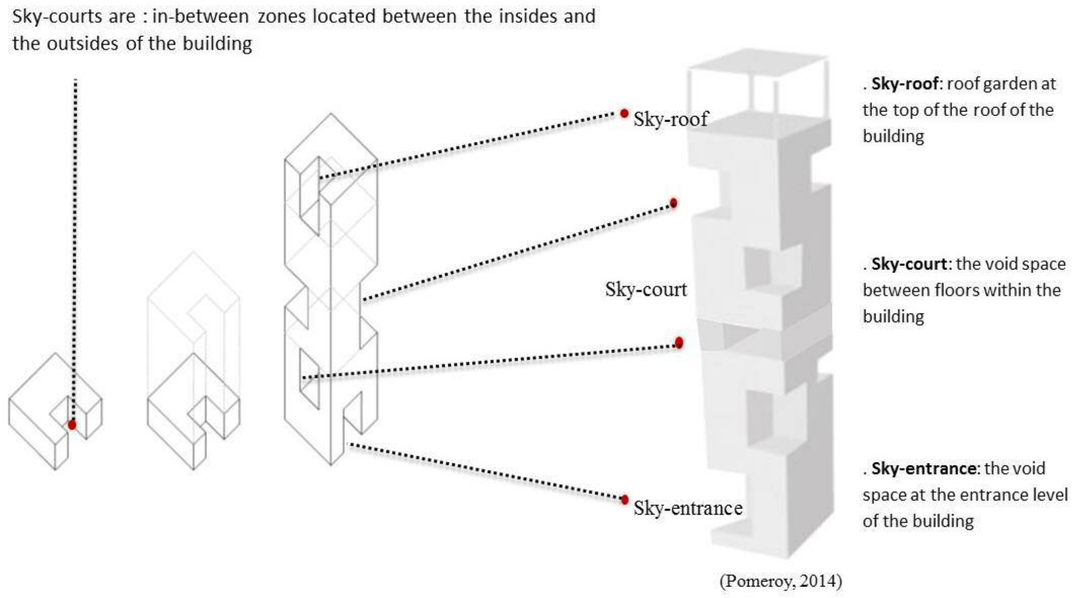

Figure 2-5. Types of skycourt according to location within the high-rise building

The spatial configuration of skycourts could be classified into six prototypes: (i) hollowed-out space, (ii) corner space, (iii) sided space, (iv) interstitial space, (v) chimney, and (vi) infill space (Pomeroy 2014), (Figure 2-6).

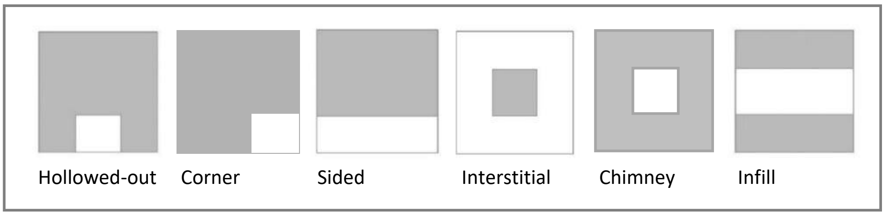

Figure 2-6. Spatial configuration of skycourts in high-rise office buildings (the white shaded zone represents the skycourt)

Attention recently has focused on the influence of the skycourt impact to improve the environmental performance and energy efficiency of buildings. However, there are limited guidelines regarding the design of skycourts (Table 2-6). The Commission for Architecture and the Built Environment (CABE) guide for tall buildings in the UK emphasises the importance of creating zones that could support social engagement, diversity, vitality and sense of place (CABE and English Heritage 2007). Skycourts could act as such spaces within the high-rise building to help it interact with and contribute positively to its surroundings. However, this guide did not provide specific design guidelines for those spaces. On the other hand, the Urban Redevelopment Authority (URA) in Singapore set the following conditions for the design of skycourts. Firstly, these areas should adapt a 45-degree line for the underside of the structure, and at least 40%

of the area should be planted. Secondly, the skycourt should be uncovered and exposed to the sky; or if covered, to be open sided and naturally ventilated. At least 40% of the perimeter wall of a skycourt must be open or at least 60% of these walls should be kept open with low walls. Thirdly, additional residual areas falling outside the 45-degree line can also be exempted with a cap of 20% of the same floor plate (URA 2008). Ken Yeang suggested that the design of skycourts should involve an ecological solution, which is relevant to the physical and climatic conditions of the site such as topography, density, proximity, aesthetics, cultural parameters, biodiversity, and social organisation. In addition, it should provide low-energy solutions (Yeang 1999).

It is clear that there is a priority for studies addressing the impact of skycourt performance on buildings. In addition, investigations regarding the design requirements for skycourts are needed.

Table 2-6. General regulations relating to the design of skycourts in high-rise buildings

Climate	Design Regulations	Reference
Temperate	- Emphasises the importance of including public spaces in high-rise buildings.	CABE, Guide on Tall Buildings, UK (CABE, 2007)
Temperate	- Emphasises the importance of including integrated design elements such as atria, wind scoop, double skin façade to encourage airflow - Provides guidelines of geometry for efficient ventilation strategies such as depth-to-height ratio, atrium opening to be at the top and bottom between 5% and 10%	CIBSE Guide A (2015), UK
Temperate	-Increase construction of sky-roof gardens by 13.5 million square metres per year	Germany
Tropical	-Skycourt design should occupy 45-degree line -Skycourts must be accessible to all occupants -Access to skycourts must be from common areas -Skycourts are used for communal activities or for landscaping -At least 40% of the perimeter wall of skycourt must be open -Areas falling outside the 45-degree line can be released to 20% of the same floor plate	Urban Redevelopment Authority, Singapore (URA, 2008)

2.2.4 Summary

A skycourt is considered a multifunctional space that performs environmental, social, and economic functions. The previous review indicated that several arguments have recently emphasised the potential of skycourts for creating a friendly buffer space and saving energy in buildings. However, there is limited evidence to prove the potential of skycourts in scientific studies. Moreover, there is less attention on the performance of the skycourt as a transitional zone and the energy impact of these spaces in temperate climates, such as London. Therefore, research is needed to investigate such functions of skycourts and define their possible contribution to improve efficiency.

Accordingly, this study intends to determine the extent to which skycourts, as transitional zones, affect ventilation in high-rise office buildings, and how they affect the energy efficiency for heating and cooling loads. Therefore, it is important to understand the ventilation principles, processes, conditions, and control parameters in high-rise buildings. These will be discussed in the next part of the chapter.

2.3 VENTILATION IN BUILDINGS

Indoor environmental quality is important for human satisfaction. Recent studies show that people spend nearly 90% of their time in indoor spaces (Jenkins *et al.* 1992). However, 40% of enclosed spaces do not provide human comfort and meet health requirements (Dorgan Associates 1993). Furthermore, nearly 50% of poor indoor quality is due to inadequate ventilation (Robertson 1990). Lack of fresh air is considered a main reason for sick building syndrome (SBS) , building-related illness (BRI) and the rise in sick absence rate in offices (Olesen *et al.* 2008).

Ventilation is the process used to maintain a satisfactory environment within a building or enclosed space, by controlling the temperature, humidity and providing good quality air (Moghaddam *et al.* 2011). Ventilation has an important role to facilitate the following functions. First, it filters the indoor air of the space and enhances its quality by removing pollutants. Second, it supports natural cooling. Third, it provides adequate ventilation for operation processes. Fourth, it enhances the heat exchange mechanism. Fifth, it prevents condensation within the building fabric (CIBSE Guide B2 2016). However, the main purpose of ventilation is to provide outside fresh air for cooling, ventilation, and thermal comfort (CIBSE Guide B2 2016). Ventilation can induce thermal comfort, significantly cooling internal spaces due to air movement that increases convective heat transfer and evaporative heat loss from the human body (Prajongsan and Sharples 2012).

There are two main strategies for ventilation: natural or passive ventilation, which relies on passive processes and mechanical ventilation, which relies on active systems.

Passive or natural ventilation is defined as the process of supplying and eliminating air from occupied spaces through natural means (Al-Kodmany 2015). This airflow or air movement occurs through specific routes such as openable windows, ventilators, ducts, shafts, etc., in buildings. This movement is driven by wind and/or density differences. Natural ventilation in buildings can enhance both the thermal comfort and energy efficiency. It can improve the indoor environment by providing better quality spaces via fresh air movement, and reducing CO_2 emissions by reducing the use of fossil fuels. In addition, it can increase the thermal comfort for occupants by creating a cooling sensation due to heat loss by convection. Passive ventilation can reduce energy consumption in building operation (Al-Kodmany 2015; Goncalves and Umakoshi 2010; British Council for Offices (BCO) Guide 2014). On the other hand, there are some constrains regarding passive ventilation for high-rise buildings, particularly in office buildings. These include the following: (i) difficulty of control such as, variable rates of air change, little or no control of airflow pattern, which in turn can result in unnecessary heat loss (CIBSE Guide F 2012); (ii) concerns regarding the quality of the entering air; (iii) the noise resulting from wind movement; (iv) difficulty with respect to individuals' comfort requirements for low cooling capacity and poor flexibility and adaptability (Goncalves and Umakoshi 2010; BCO Guide 2014). Natural ventilation alone may not be efficient in high-rise office buildings. Therefore, it is hard to rely only on it for providing comfort in enclosed spaces such as offices and skycourts in extreme climate conditions and local context of London.

Mechanical ventilation is about supplying a controlled rate of fresh air or eliminating the indoor air by using mechanical devices such as fans (Liddament 1996). The use of this mechanism is preferable in office buildings due to its capabilities to control airflows inside the space independently from the external weather conditions. The fan produces a continuous flow by the aerodynamic action of the blades on the air; it can enforce fresh air to enter through purpose-provided openings and cracks in the building fabric, as well as force the indoor air to leak out from the building through ducts. Then the air that is removed is replaced by fresh air (Awbi 1998a). However, the supply air should be filtered and pre-heated or pre-cooled. Despite the fact that this approach is connected with high energy consumption for cooling or heating the air supply, this strategy is the most frequent in use in London's high-rise office buildings for different types of spaces including skycourts (Pout *et al.* 2012; Strelitz 2011).

Based on the previous analysis, mechanical ventilation is the system most often used in the different zones of office buildings, particularly the high-rise. However, this approach is connected with high energy consumption for cooling or heating the air supply.

The first step for implementing a ventilation system in buildings is understanding the design process of this system. There is no specific well-defined design processes for all types of spaces, and hardly any for these in high-rise buildings, due to the complexity and the wide variety of building types and functions (CIBSE Guide B2 2016). However, a number of issues should be discussed when designing a ventilation strategy. These include: (i) the airflow patterns; (ii) the ventilation performance assessment; and (iii) variables and parameters that influence the airflow performance. These are discussed in the next sections. This process is important in order to understand the ventilation principles in depth and apply this knowledge to develop an effective ventilation strategy for skycourts.

2.3.1 Ventilation Airflow Patterns

The air quality in ventilated spaces is influenced by the airflow pattern and the quality of the supplying air. However, the airflow pattern in the mechanical system is determined by the method of air distribution (Awbi 1998a).

Air distribution is the transfer of air through ducts or plenums to indoor spaces. Such a system has a major influence on the performance of ventilation and the various indoor environment parameters, such as thermal comfort, indoor air quality and heating and cooling energy efficiency (Cao *et al.* 2014).

There are two main air distribution systems applied in office buildings. The mixing system, and displacement ventilation. However, there are other types developed based on integrating characteristics of these two systems, i.e. the hybrid system such as impinging jet ventilation, and confluent jet ventilation. Other systems include stratum ventilation, protected occupied zone ventilation, local exhaust ventilation, and piston ventilation (Cao *et al.* 2014). The following discussion defines principles, airflow mechanisms, heating and cooling features, and ventilation effectiveness of the most common systems used in general office spaces. These are the mixing, displacement, and hybrid air distribution systems (Figure 2-7).

(i) The mixing system

This system is based on mixing the supply air with the air in office spaces to reduce contaminant concentration. The air supply and exhaust openings are located at high levels close to the ceiling and walls. However, the use of wall jets is the most common airflow system.

A high speed of air momentum (jet), i.e. typically above 2 m/s is required to supply and expel air. While the air speed is low at floor level, i.e. < 0.25 m/s, this is significant to provide uniform mixing of air. Airflow rates are determined by the air changed and the heat emitted from internal gains, e.g. people and equipment. This system is used to provide fresh air, heating and cooling. However, this system is not efficient regarding air quality and energy use. Ventilation effectiveness might be around 70% (< 1) (Karimipanah and Awbi 2000). Extracted air temperature is the same as the air temperature in the interior space because of uniform mixing. The air supply temperature could be 10°C approximately. This reduces the energy efficiency (Awbi 1998a).

(ii) The displacement system

This system is based on replacing the air in office spaces with the supply air. Supply and exhaust air openings are positioned in opposite directions to create upward air movement (thermal plumes), e.g. airflow from the ceiling down, from the floor up, from wall to wall or from wall to floor then up to the ceiling. However, air is supplied at lower levels from floor or wall, and extracted at upper levels. Therefore, a buoyancy effect drives the stratified flow.

A low speed air momentum (jet) is applied, i.e. typically below 0.5 m/s. A stack effect determines the airflow, and this causes pollutants to rise. This system is suitable only for cooling. Therefore, a separate system for heating should be supplied such as chilled beams, and chilled ceilings. In addition, this system provides limited flow penetration, yet a high ventilation effectiveness, i.e. usually 120% (>1.0). Furthermore, it is considered a high energy efficient system, as lower fan power is required and supply air temperature should be above 17°C. Air is allowed to stratify until the air temperature reaches the desired temperature at the occupancy level and the expelled air temperature is higher (Karimipanah and Awbi 2000).

(iii) The hybrid system

This air distribution system is based on combining the positive characteristics of mixing and displacement systems, and overcomes the disadvantages of the displacement system. Firstly, these systems require a medium speed of momentum flow, i.e. lower than mixing and higher than wall displacement ventilation. A high momentum of air is required at the initial stage to spread clean air in the lower zone of the occupied area. Secondly, these systems are able to provide better air quality and require less energy than the mixing ventilation. Thirdly, hybrid systems are able to provide deep airflow penetration more than the displacement system, i.e. about 40 W/m^2 of floor area from the air supply openings. These systems can be used for heating and cooling. Finally, such systems show high potentials for ventilation effectiveness and energy efficiency.

Examples of this system are impinging jet ventilation and confluent jet ventilation. Air supply and extraction occur at the ceiling level for the impinging ventilation, while air supply takes place at lower level of walls and extraction at the ceiling level for the confluent jet ventilation (Awbi 2015).

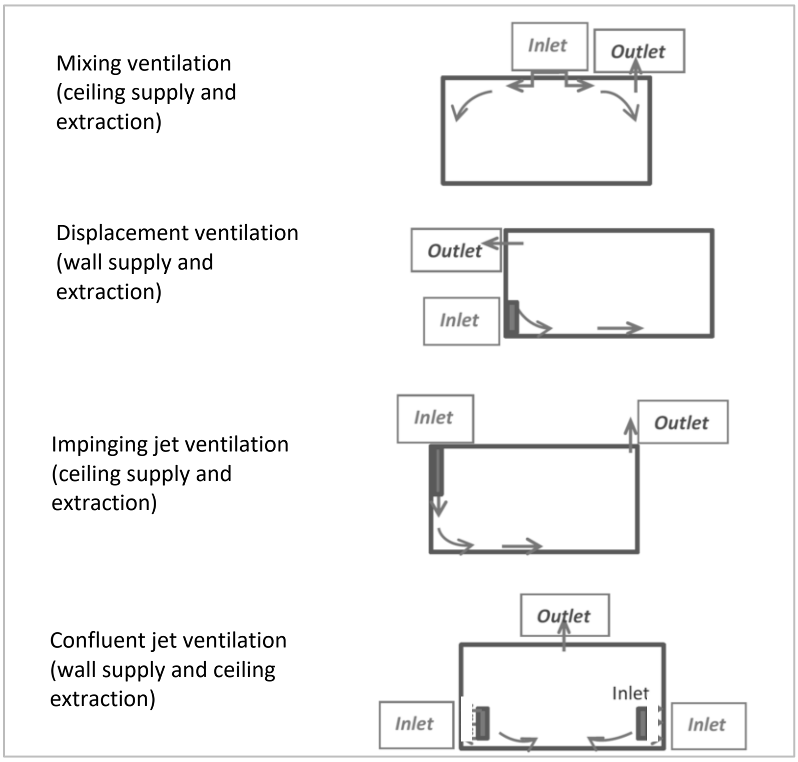

Figure 2-7. Air distribution systems in buildings

Source: Awbi (2015)

2.3.2 Assessment of Ventilation Performance

This section discusses features that are adopted to evaluate the performance of ventilation systems. Energy use is a major aspect that is considered when implementing ventilation systems in buildings. This is affected by different issues, e.g. usage of space, heat gains, inlet air quality, and dimensions of the space (Cao *et al.* 2014). Recently, ventilation is considered a process of providing fresh air to the building occupants, rather than the buildings themselves (Awbi 1998a). Therefore, achieving human comfort is another major aim for ventilated spaces. Other indexes include effectiveness to remove containment and heat from these spaces (Sandberg 1981). These aspects are described here:

(i) Energy performance is evaluated by efficiency in terms of the energy consumption required for the ventilation process or/and the carbon emissions produced from the energy operations of ventilation in spaces (Goncalves and Bode 2011). Energy consumption is frequently used to evaluate energy efficiency due to ventilation (Calautit and Hughes 2014; Al-Sallal 2004). This is directly linked to their energy demand. Therefore, the most efficient strategy is able to minimise energy demand (Kwong *et al.* 2014). The energy efficiency index expresses the energy saving potential of the ventilation system. These include ventilation, heating and cooling energy demands.

(ii) Human comfort is experienced when the immediate environment shows a balance in thermal, hygienic, acoustic, visual, and electromagnetic factors, together with a harmonious influence of colour, surface and material, and avoidance of containment (Eisele and Kloft 2003). Human comfort (satisfaction) consists of many aspects that represent issues surrounding the human environment. These include thermal comfort, indoor air quality (IAQ) (Olesen *et al.* 2008), acoustical, visual, and aesthetic qualities (McMullan 2017). Table 2-7 summaries human comfort standards for workplaces in office buildings according to guidelines of the British Council for Offices (BCO).

Table 2-7. Human comfort standards at workplace of offices

Air temperature	For summer	22˚C (±2˚C)
	For winter	20˚C (±2˚C)
Air quality	Outdoor air	10 to 12 L/s per person
Humidity	Relative Humidity	35% to 40%
Acoustics	Open plan offices	NR 38 (Leq)
	Cellular offices	NR 35 (Leq)
Visual comfort: optimum for office workplace (Daylight factor: lux inside/lux outside x 100%)	Minimum daylight factor	> 0.5 %
	Average daylight factor	>2% to 5%
	Lighting	
	Ceiling reflectance	75% to 80%
	Wall reflectance	60% (min)
	Working plane reflectance	>30%

Source: British Council for Offices (BCO) Guides (2009 and 2014)

Several scholars argued that complaints about comfort due to ventilation are related to thermal comfort and air quality (Olesen *et al.* 2008; Dorgan Associates 1993; Robertson 1990). The preferred temperature during the day in an office environment is 23°C, which is linked to a 15% reduction in absenteeism. Extreme temperatures have negative impacts on productivity, and cause low humidity rates and discomfort in office workers due to dry eyes and throats, while improving office air quality could enhance productivity by 20% (BCO 2005).

However, it is important to mention that requirements for comfortable conditions in transitional spaces have wider limits than in normally occupied zones (Alonso *et al.* 2011).

(iii) Ventilation effectiveness is used to express the ability of a ventilation system to remove contaminants and heat in spaces (Sandberg 1981). The ventilation effectiveness is determined by the percentage of contamination removal and efficiency of heat removal. These are expressed as the following:

- Effectiveness of contamination removal in the occupied zone or in the breathing zone. This is determined by pollutant concentration in exhaust air, pollutant concentration in supply air, and the mean contaminant concentration in the occupied zone. This index is large when the two previous factors are equal (Sandberg *et al.* 1986; Conceição *et al.* 2013).

- Effectiveness of heat removal. This refers to the temperature distribution by the ventilation airflow in the space. It is expressed in terms of how efficiently the heat will be removed from the space (Awbi and Gan 1993). Ventilation effectiveness increases when the temperature difference between the supply air and space decreases (Cao *et al.* 2014).

2.3.3 Parameters for Designing Ventilated Spaces

The success of a ventilation system in buildings relies upon the design and the performance of its elements (Moghaddam *et al.* 2011). These include climate, function, geometry, orientation, layout of internal spaces, façade design and control and settings (Goncalves and Umakoshi 2010). Other factors contributing towards success include incorporating efficient HVAC equipment, heat recovery techniques and shading devices (Azarbayjani 2010). It is recommended that these parameters be optimised based on environmental principles and architectural rules to influence the overall building performance (Voss *et al*. 2007), as these elements determine energy requirements in a building, which in turn can enhance energy savings (Goncalves and Umakoshi 2010).

The current study focuses on improving ventilation efficiency in office buildings due to the inclusion of a skycourt. In addition, it investigates comfort in the skycourt. Therefore, parameters that affect the ventilation performance in skycourts as ventilated spaces should be considered. These can influence the thermal conditions in skycourts, which in turn impact on the energy demand of the buildings.

Several studies found that orientation, height, length, depth, size and form are the most effective elements in building energy performance, when considering ventilation. In addition, air openings' characteristics influence the ventilation performance (Table 2-8). However, there are few studies that investigated the effects of skycourt attributes on both the building energy performance and skycourt interior environment.

Table 2-8. Studies exploring design parameters of ventilated spaces

Year	Research Findings	Reference
2018	Orientation Glazing area and distribution	(Kosir *et al.* 2018)
2018	Orientation Glazing area and specification	(Delgarm *et al.* 2018)
2017	Orientation Envelope properties Attributes of adjacent spaces Shape and type Glazing area	(Wang *et al.* 2017)
2015	External surface area Adjoining spaces	(Tabesh and Sertyesilisik 2015)
2014	Season Skycourt type	(Taib *et al.* 2014)
2015	Air inlet openings characteristics (number, position, size and location)	(Moosavi *et al.* 2015)
2014	Height Width and length	(Cantón *et al.* 2014)
2012	Height Type of glazing Wall thickness	(Al-Masri and Abu-Hijleh 2012)
2011	Space dimensions Height	(Ai *et al.* 2011)
2010	Location of skycourts	(Taib *et al.* 2010)
2010	Building form Orientation Internal spaces configuration Arrangement of internal space Façade	(Goncalves and Umakoshi 2010)
2009	Height Size	(Zhang *et al.* 2009)
2006	Orientation of skycourt	(Jahnkassim and Ip 2006)
2005	Number of opening sides of skycourt	(Mak *et al.* 2005)

For example, in a study that investigated the thermal comfort of different types of skycourts (sky-roof, skycourt and sky-balcony) during wet and dry seasons in a tropical climate, it was found that there is a significant difference between these skycourts in terms of mean air temperature and radiant temperature. The middle skycourt between floors is the most comfortable thermal zone, followed by the sky-roof and the sky-balcony. The skycourt has the highest mean value of air velocity of 0.67 m/s, while the sky-roof has the second highest value of 0.58 m/s (Taib *et al.* 2010). In addition, there was an impact of weather conditions on the performance of the three spaces. The average temperature during the wet season in these spaces is lower than the average temperature during the dry season (Taib *et al.* 2014).

The orientation plays an important role in the performance of skycourts. For example, skycourts located on western facades in tropical Singapore could act as thermal-buffer areas that reduce the impact of solar radiation and glare, which in turn affect the energy consumption. In addition, this location can reduce noise and high wind speed penetration. It was found that changing the orientation and the location of skycourts in a simulated model of Mesiniaga tower decreases the energy use in the building (Jahnkassim and Ip 2006).

The number of sides that open up in skycourts influences the thermal comfort of occupants. It was argued that a skycourt with four sides that open up provides more optimum conditions than a skycourt with two sides that open up in summer, and vice versa in winter, in the Hong Kong climate. The higher air speed provides a good thermal comfort in summer, but poor thermal comfort in winter (Mak *et al.* 2005). Inlet air openings have an impact on the thermal performance of spaces; it affects the airflow and the air distribution. Outlet openings are important to enhance ventilation (Moosavi *et al*. 2015).

Other studies found that the central narrow form and the rectangular higher length to width ratio are more effective for ventilation than the square shape (Aldawoud 2013; Moosavi *et al.* 2014).

2.3.4 Summary

A mechanical ventilation system is preferable in high-rise buildings, particularly offices. However, this approach is connected with high energy consumption for cooling or heating the supply air.

Ventilation mechanisms, requirements, air distribution systems, assessment process, and parameters that are commonly adopted for developing ventilation strategies in buildings have been discussed. This provides a theoretical background to define the basic principle of the proposed ventilation strategy in the present study.

The displacement air distribution system is widespread in office buildings due to ventilation effectiveness compared to the mixing system. Spatial and geometric configuration of ventilated spaces influence ventilation effectiveness in these areas. These features comprise orientation, height, area, length, and depth of the space, in addition to air openings inside these spaces. Climate has a great effect on this issue; therefore, ventilation strategies should be investigated in different seasons.

Defining the most effective and efficient ventilation system is considered a difficult task. Energy efficiency and comfort due to thermal conditions and air quality in ventilated spaces are the main indicators for ventilation performance. Therefore, these factors will be explained in detail, in the following section.

2.4 ENERGY EFFICIENCY AND HUMAN COMFORT

Energy efficiency connected to thermal comfort are major targets that are considered in offices to promote occupants' productivity, comfort and wellbeing (Antoniadou *et al.* 2018). Significantly, when implementing ventilation systems in buildings (Awbi 1998a).

In this part of the chapter, energy efficiency is explained and related benchmarks due to ventilation performance are defined. Then optimum conditions for human comfort emphasising thermal comfort and air quality in ventilated spaces are presented. Parameters that influence these terms, and methods to predict the level of comfort are discussed. This knowledge is important to determine the energy efficiency of the ventilation approach adopted in this study, and in addition, to be able to assess the comfort level in the skycourt.

2.4.1 Energy Efficiency

Energy consumption is the common variable used for evaluating energy efficiency (Calautit and Hughes 2014; Al-Sallal 2004). Therefore, it is recommended that the energy consumption of a building should be reduced to decrease its energy demand (Alonso *et al*. 2011). The energy consumption due to ventilation processes is expressed here by energy demands required to heat or cool the supply air. Demand per square metre (kWh/m^2) per month or per year can be used to describe consumption (Goncalves and Bode 2011).

Every new building should provide an Energy Performance Certificate (EPC) based on predictions of energy consumption and actual measured performance data as part of the Energy Performance Building Directive (EPBD) in the European countries. The UK prepared a benchmark for ventilation based on energy use. For high-rise office buildings, the benchmark shows that good practice for mechanical ventilation in buildings is able to reduce energy demand annually from 127 kWh/m^2 to 144 kWh/m^2. This accounts for a 40% to 45% saving of energy used per year (CIBSE Guide F 2012), (Table 2-9).

Table 2-9. Energy consumption benchmark for ventilation in high-rise (tall) office buildings in the UK

	Standard Practice	**Good Practice**
Energy use/ mechanical ventilation	300 to 330 kWh/m^2 per year	173 to 186 kWh/m^2 per year

Source: CIBSE Guide F (2012)

CIBSE Guide F (2012) presents benchmarks for energy consumption for office buildings in terms of fossil fuel air conditioning and electric air conditioning under good and typical practice. The comparison shows that air conditioning using fossil fuels consumes less energy than electrical air conditioning. It was found that switching from electric air conditioning to fossil fuel conditions under standard air conditioning achieves an average 30 kWh/m^2 to 48 kWh/m^2 per year, and an average 120 kWh/m^2 to 148 kWh/m^2 per year under prestige air conditioning, (Table 2-10).

Air-conditioned, standard offices are often intensively used and have typical size ranges from 2,000 m^2 to 8,000 m^2, while, air-conditioned, prestige defines offices as technical or administrative centres, with typical size ranges from 4,000 m^2 to 20,000 m^2, including large catering kitchens and/or regional server rooms (Building Research Energy Conservation Support Unit (BRECSU) 2003).

Table 2-10. Energy consumption benchmark for fossil and electric ventilation for offices in the UK

	Energy Consumption Benchmarks for Existing Buildings (kWh/m^{-2} per year)			
Offices	Good Practice		Typical Practice	
	Fossil fuels	Electricity	Fossil fuels	Electricity
Air-conditioned, standard	97	128	178	226
Air-conditioned, prestige	114	234	210	358

Source: CIBSE Guide F (2012)

The breakdown of energy requirements in office buildings as illustrated in Table 2-11 shows that under good practice, over 45% annual savings can be achieved in heating demands, and energy demands for cooling have the potential to be reduced by 55% per year compared to typical practice. This indicates the influence of ventilation processes on energy consumption in office buildings.

Table 2-11. Detailed energy benchmarks for offices in the UK

System	Delivered Energy for Stated Office Types (kWh/m² per year)			
	Standard Air-conditioned		Prestige Air-conditioned	
	Good Practice	Typical	Good Practice	Typical
Gas/oil heating and hot water	97	178	107	201
Catering gas	0	0	7	9
Cooling	14	31	21	41
Fans, pumps and controls	30	60	36	67
Humidification	8	18	12	23
Lighting	27	54	29	60
Office equipment	23	31	23	32
Catering electricity	5	6	13	15
Other electricity	7	8	13	15
Computer room	14	18	87	105
Total gas or oil	**97**	**178**	**114**	**210**
Total electricity	**128**	**226**	**234**	**358**

Source: CIBSE Guide F (2012)

2.4.2 Thermal Comfort

Thermal comfort describes the thermal conditions around the human body. This condition expresses satisfaction of person mind with the thermal environment. For example, ASHRAE defines seven-point measure thermal sensation scale. These include cold, cool, slightly cool, neutral, slightly warm, warm, and hot (ANSI/ASHRAE 2017). The most satisfactory thermal comfort is the condition of neutral thermal sensation by which people feel neither too warm nor too cool for the body as a whole. However, other sensation scales than neutral can be considered as comfort (Shahzad et al. 2018). Thermal comfort in indoor environment depends on adequate ventilation, heating and cooling to keep a balanced condition for occupants (Enescu 2017).

The balanced condition in the indoor environment is influenced by physical and social factors. Therefore, designers need to consider these parameters and understand the mechanisms of heat exchange between the human body and the environment and thus create a thermal balance for the body. The heat balance of the human body is measured based on the following equation (Olesen *et al.* 2008):

$$S = M - W - C - R - E_{sk} - C_{res} - E_{res} - K (Wm^{-2})$$

Where:
S = heat storage in body;
M = metabolic heat production; W = external work;
C = heat loss by convection; R = heat loss by radiation;
E_{sk} = evaporative heat loss from skin; C_{res} = convective heat loss from respiration;
E_{res} = evaporative heat loss from respiration; K = heat loss by conduction.

Heat transfer between the body and the environment occurs by conduction, convection and radiation modes, by which the body may gain or loss heat. Thermal comfort is evaluated through mathematical balance between heat gain and heat loss (Enescu 2017; Djongyang *et al.* 2010). Heat exchange occurs due to respiration, metabolic processes, and it can happen at the skin or surface. For example, in cold climates, the body needs to conserve its heat, while in hot climates, the body needs to reduce external heat gain. However, imbalance in heat gains and losses, over a period can cause significant problems to the body. For example, if the body loses too much heat, the core temperature drops below 35°C, and this causes hypothermia. On the other hand, hyperpyrexia occurs when the body gains too much heat. Hyperthermia and hyperpyrexia occur if the core temperature exceeds 38°C and 40°C, respectively, and then shivering and sweating may occur. This has a significant impact on human behaviour and productivity.

2.4.2.1 Parameters Influencing Thermal Comfort

An environment providing thermal comfort can create satisfaction that makes a person comfortable depending on comfort factors (Djongyang et al. 2010). Thermal comfort is affected by two types of parameters, these are defined by Macpherson (1962) as: (i) physical (ambient) parameters, which are objective and could be measured and predicted; and (ii) social (personal) parameters, which are subjective related to occupants' activities and clothes and may differ from one person to another.

Physical parameters relating to thermal comfort include air temperature and airspeed. The air temperature is the average temperature of the air surrounding the person at a specific location and time. The ASHRAE 55 standard defining the location as a spatial average depends on the ankle, waist and head levels for seated or standing occupants. The time is defined as a temporal average that is based on three-minute intervals with at least 18 equally spaced points in time. Air temperature is also known as the dry-bulb temperature that is indicated by a dry thermometer, which is shielded from radiant exchanges. This is the main parameter used to define the thermal comfort of the environment. However, according to the seasonal nature of the human body, there are two comfort ranges: winter and summer. Airspeed is a measure of air movement in a space; it is defined as the rate of movement of air at a significant location and time, without regard to direction. According to ANSI/ASHRAE Standard 55, the temporal average is based on three-minute intervals with at least 18 equally spaced points in time, the same as the air temperature, while the spatial average is based on the assumption that the body is exposed to a uniform air speed, according to the standard effective thermo-physiological model. Air movement in a space can be generated by wind (e.g. open windows), by temperature differences (e.g. a hot surface and a cold surface in the same space), or by mechanisms (e.g. fans).

Other physical indicators are relative humidity and mean radiant temperature. Radiant temperature, or the mean radiant temperature (MRT), is the temperature that is related to the amount of radiant heat transferred from a surface. This radiation depends on the surface material's ability to absorb or emit heat, or its emissivity. In addition, it depends on the temperature and emissivity of the surrounding surfaces as well as the amount of the surface. Therefore, the mean radiant temperature experienced by a person in a space with the sunlight streaming in, varies based on how much of the body is in the sun. Relative humidity (RH) is defined as the percentage of moisture contained in the air at a specific temperature and pressure. The comfort level of indoor humidity is in the range of 30% to 60%. The relative humidity (RH) of a space affects the human body, particularly the skin. It also affects the mouth and eyes. For example, high relative humidity causes sweating of the skin as a mechanism to lose heat, whereas low relative humidity or a dry environment affects mucous membranes.

2.4.2.2 Predicting Thermal Comfort

The thermal comfort level could be estimated in spaces based on the following:

- Predictions based on single parameters; this method depends on testing physical parameters such as air temperature, air velocity, relative humidity or mean radiant temperature in spaces individually. Then results are compared with the standard comfort requirements to predict level of indoor thermal comfort (Djamila 2017).

- Predictions based on combined temperatures; this can indicate comfort by combining air temperature and mean radiant temperature as an output for the temperature of the space. This is defined as the uniform temperature that is measured by a globe thermometer, which is an ordinary thermometer with its bulb surrounded by a hollow sphere painted matt black on the outside. The black sphere is non-reflective, and absorbs all the radiation reaching it from the enclosure as well as air temperature. Thus occupant would exchange (gain or lose) the same amount of heat by convection and radiation combined as in the real environment (De Dear 1998). This is known as environmental temperature[2] according to CIBSE Guide A (2015), or operative temperature[3] in ASHRAE.

- Predictions depend on the relation between dry-bulb temperatures against relative humidity by using the bioclimatic comfort charts and psychometric charts to analyse the local climatic conditions at a given place (Givoni 1992).

- Predictions based on combining the physical environmental variables and the personal ones of clothing and activity in a single index, e.g. a) predicted percentage of dissatisfied (PPD); b) predicted mean vote (PMV) that depends on the average judgement of comfort level in the environment in question; c) adaptive comfort.

PMV cannot be used for transitional space thermal comfort predictions due to its instability and dynamic physical value (Chun *et al.* 2004).The adaptive comfort depends on the perception of comfort, taking into account many behavioural factors that affect perception of comfort, such as the contextual, climatic, cultural and social factors. However, climatic conditions are the major circumstances determining a comfortable temperature. For example, people in regions with a hot climate can sufficiently adapt with the increase in temperature during summer rather than people in cold climate areas.

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[2] Environmental temperature presents the equivalent temperature to which a body can gain or lose heat by convection and radiation combined. It is determined as defined by CIBSE as:
Tenv = 1/3 T_{air} + 2/3 T_{mrt}
Where:
T_{env} is the environmental temperature
T_{air} is the dry bulb temperature of the air in the spaces
T_{mrt} is the mean radiant temperature of the space.

[3] Operative temperature reflects the equivalent temperature to which a body can gain or lose heat by convection and radiation combined. However it defined by ASHRAE as:
T_{env} = 1/2 T_{air} + 1/2 T_{mrt}
Where:
T_{env} is the environmental temperature
T_{air} is the dry bulb temperature of the air in the spaces
T_{mrt} is the mean radiant temperature of the space.

It is important to define and understand the range of acceptance of temperature. Therefore, 2010 ASHRAE 55 was revised with a new adaptive comfort standard (ACS) developed by analysing over 21,000 sets of raw data (Figure 2-8). Although this indicator is commonly used to evaluate comfort levels in free mechanically ventilated spaces, it can provide more accurate comfort practices and adaptation of occupants than standards for mechanically ventilated buildings (Serghides *et al*. 2017). Furthermore, it allows for a greater range of acceptable warmer indoor temperatures for spaces (Brager and Dear 2001), which in turn can achieve low-energy alternatives for the conditioning of spaces (Albatayneh *et al.* 2016).

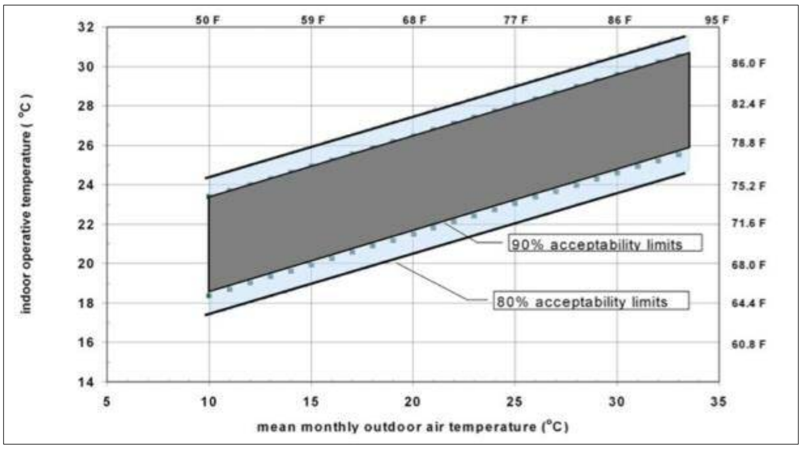


Figure 2-8. ASHRAE55 Adaptive comfort standards

Source: Wood and Salib (2013)

In energy calculation studies, indoor air temperature should be specified to evaluate the thermal comfort level (British Standard BS EN 15251:2007 2008). A comfortable temperature is one of the most important factors to be considered in office environments (Shahzad *et al.* 2018), as indicated by over 80% of interviewees who highlighted features that employees prioritise in office spaces (BCO Guide 2009). In addition, it is important to avoid excessively high airspeeds (Mak *et al*. 2005). These two parameters are measured in the occupied area and the breathing zone (Figure 2-9), which are the main areas of concern for the provision of comfortable conditions. This zone occupies the lower part of the ventilated space above the floor level up to 1.8 m height and 0.5 m to 1.0 m at a distance from surrounding walls (Nielsen and Awbi 2008). Consequently, in this study, the level of thermal comfort in the skycourt will be determined in terms of air temperature and airspeed in the occupied zone.

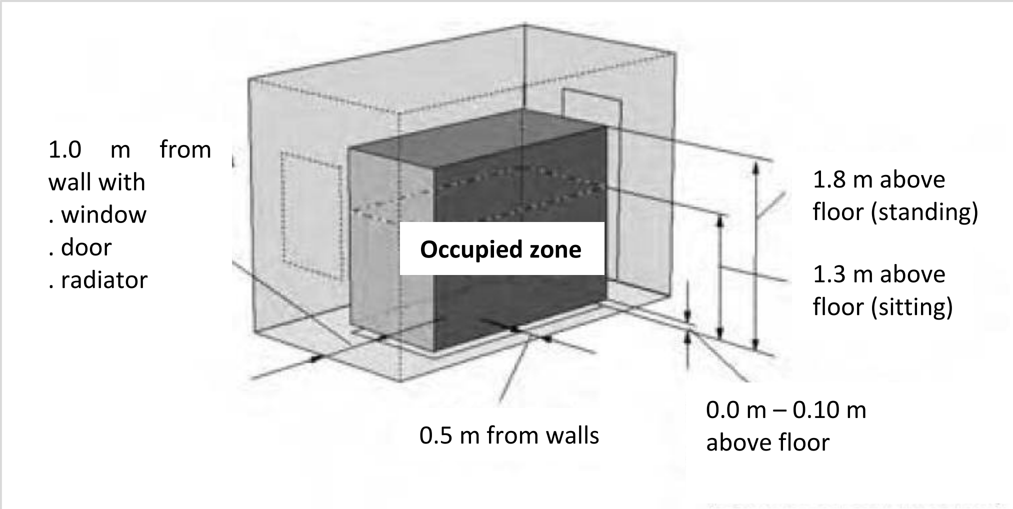


Figure 2-9. Occupied zone in ventilated space

Source: Nielsen and Awbi (2008)

The acceptable temperature limits are defined according to the function of the space including level of activity and number of occupants. For instance, these limits in offices are defined in building standards such as CIBSE Guide A (2015) and the BCO Guide (2014), with indoor temperature comfort limits between 18°C and 23°C in winter and less than 26°C in summer (Table 2-12). Airspeed can be perceived as discomfort when it is greater than 0.2 m/s or when air movement is combined with cold temperature (Chen 2010). The most comfortable air movement is within the range 0.1 m/s and 0.2 m/s. However, within mechanically ventilated spaces, the forced air movement means that airspeeds are generally greater than 0.1 m/s, and could be greater than 0.2 m/s in areas close to air supply devices which can give rise to significant comfort dissatisfaction (McMullan 2017).

Table 2-12. Recommended temperature comfort criteria for office building

	BCO Guide	CIBSE Guide A
Air temperature - Winter	20°C ± 2°C	21°C to 23°C
Air temperature - Summer	24°C ± 2°C	22°C to 24°C

Source: BCO Guides (2009 and 2014), CIBSE Guides A (2007 and 2015)

The British Standard BS EN 15251:2007 categorised office buildings according to air temperatures into three classifications: I, II, and III (Table 2-13). The best offices (category I) provide indoor environments that obtain 21°C in winter and not more than 25.5°C in summer. Category III offices attain 19°C in winter and up to 27°C in summer (BS EN 15251:2007 2008).

Table 2-13. Recommended design values of indoor air temperature for offices

Category	**Temperature (°C)**	
	Winter	Summer
I	21.0	25.5
II	20.0	26.0
III	19.0	27.0

Source: BS EN 15251:2007 (2008)

However, no recommendation on acceptable thermal comfort including air temperature ranges and air velocity has been specified for enclosed transitional spaces, e.g. skycourts (ANSI/ASHRAE Standard 55-2017 2017; BS EN 15251:2007 2008; BS EN ISO 7730:2005 2006; CIBSE Guide A 2015). Yet, studies showed that accepted levels of thermal comfort in transitional areas could be wider than in normally occupied spaces (Alonso *et al*. 2011) and can be adapted very widely compared to comfort inside buildings (Chun and Tamura 2005). This is due to the fact that occupants in these areas have a high levels of liberty to adjust their clothing insulation, activity level and staying time (Hou 2016). Table 2-14 shows accepted levels of thermal comfort in transitional spaces and compares it to standard comfort limits in several studies.

A study investigating this range in transitional spaces in the UK in south Wales found that people in these spaces have a higher acceptance of their thermal environment than that shown according to CIBSE criteria. The comfort limits are 14°C to 27°C in winter and 14.5°C to 27.8°C in summer (Hou 2016). It is clear that majority of occupants in transitional spaces accepted a deviation of ± 2°C to 3°C from the standard temperature.

Table 2-14. Studies comparing accepted level of temperature for thermal comfort and standard temperature in transitional spaces

Year	Accepted Level of Temperature	Standard (Design) Temperature	Reference
2017	26.3°C in summer 21.6°C in winter	23°C to 26°C	(Serghides *et al.* 2017)
2016	14.5°C to 27.8°C in summer 14°C to 27°C in winter	21°C to 25°C in summer 20°C to 22°C in winter	(Hou 2016)
2016	24.5°C to 26.5°C in summer	23°C to 25°C in summer	(Yu *et al.* 2016)
2015	16.9°C to 17.4°C in winter	20°C to 22°C in winter	(Yu *et al.* 2015)
2014	24.2°C to 28.3°C	16°C to 20°C	(Kwong *et al.* 2014)
2011	26.8°C was accepted by 79%	16°C to 20°C	(Kwong and Adam 2011)
2011	27°C to 30°C in summer	23°C to 26°C	(Ghaddar *et al.* 2011)
2007	24.7°C to 27.5°C	23°C to 26°C	
1990	23°C to 27°C in summer was accepted by 80%		Berglund and Gonzalez in (Hensen 1990)

2.4.3 Indoor Air Quality (IAQ)

Indoor air quality (IAQ) or air exchange effectiveness considers the following components: indoor air pollution, fresh air supply, and air change rate (Awbi 1998a). This index measures air exchange effectiveness in delivering the supply air to a particular point in a space. In other words, how quickly the air in the ventilated space air is changed by fresh air (Etheridge and Sandberg 1996).

The quality of the indoor environment has a great influence on performance and productivity, and has more impact on workers' performance than job satisfaction and job stress. Self-reported performance (WEP) in offices could be determined in accordance with the equation (Olesen *et al.* 2008):

$$WEP = 6.739 – 0.419E – 0.164JD – 0.048JS$$

Where
E = dissatisfaction with environment
JD = job satisfaction
JS = job stress

This formula shows the greatest influence of the indoor environment on performance (Olesen *et al.* 2008).

Previous studies show that ventilation has a significant effect on the indoor air quality. For example, a recent study shows that higher ventilation rates up to 25 L/s per person in offices can reduce the symptoms of sick building syndrome (SBS) (Sundell *et al*. 2011). Also, the spread of infectious diseases is associated with ventilation and air movement in buildings (Cao *et al*. 2014). The ventilation rate in (L/s per person), and the air change rate in (ac per hour) are used to define the level of indoor air quality. Ventilation standards recommend values for these two parameters based on the function of the space.

British Standard BS EN 13779 provides four classifications of indoor air quality for office spaces based on the fresh air ventilation rate (L/s per person), (Table 2-15). According to this classification the indoor air quality standard is as follows: (i) High, when the fresh ventilation rate is above 15 L/s per person; (ii) Medium, when the ventilation rate ranges between 10 and 15 L/s per person; (iii) Moderate, when the ventilation rate ranges between 6 and 10 L/s per person; (iv) Low, when the ventilation rate is below 6 L/s per person. The standard of indoor air quality determines the indoor CO_2 concentration (Clark 2013).

Table 2-15. Indoor air quality classifications in BS EN 13779

	Fresh Air Ventilation Rate (L/s per person)	**Approximate Indoor CO_2 Concentration (CIBSE Guide A) (ppm)**
High	> 15	700 to 750
Medium	10 – 15	850 to 900
Moderate	6 – 10	1150 to 1200
Low	< 6	1550 to 1600

Measuring indoor air quality is a complicated process because air comprises thousands of compounds. Main indoor air pollutants includes odour, carbon dioxide, tobacco smoke, formaldehyde, ozone, radon, particulates and water vapour. Therefore, when measuring air quality, the allowable limits of the main components of air is considered (Olesen *et al.* 2008). Climatic comfort is relatively associated with the situation of balance between oxygen supplied and carbon dioxide absorbed in the immediate environment surrounding a person (McMullan 2017). This requires carbon dioxide not to exceed the allowable limits. Therefore, ventilation standards specified ventilation rates based on the function of the indoor environment. For example, the average carbon dioxide level in general office spaces is estimated to be 1000 ppm when the space is fully occupied. Consequently, to keep CO_2 concentration below this average, the minimum fresh (outside) air requirement of 8 to 10 L/s per person ventilation rate is typically adopted in mechanically ventilated offices. This is equivalent to 1.2 CO_2 air change per hour (ach) (CIBSE Guide A 2015). However, fresh air requirements for naturally ventilated spaces are treated differently.

Standards take both people and buildings into account when calculating the required ventilation rates in buildings. The British Standard BS CEN pre-standard prEN 15251 classifies buildings into four categories according to predicted dissatisfied (PD) occupants based on ventilation rate (Table 2-16). The following categories are used: (i) Category I, which has an air supply rate of 10 L/s per person and corresponds to 15% of the occupants predicted dissatisfied (PD). (ii) Category II has 7 L/s per person and corresponds to 20% PD. (iii) Category III has 6 to 4 L/s per person that corresponds to 30% PD. 4) Category IV attains lower than 4 L/s per person and corresponds to more than 30% PD (BS EN 15251:2007 2008).

Table 2-16. Categories of predicted dissatisfied for occupants in non-residential buildings based on ventilation rate per person or per floor area

Category	Airflow per Person (L/S per Person)	Expected Percentage Dissatisfied (%)
I	10	15
II	7	20
III	6 –4	30
IV	< 4	> 30

The ventilation rate control stands on a mass balance calculation basis. This could be determined by the prescriptive procedure, [4] in which two ventilation rates are determined. These are the person-related ventilation rate as defined in Table 2-16 or the floor area per square metre ventilation rate (Table 2-17). These are commonly carried out

[4] The outdoor airflow in the breathing zone of the occupied area in a zone is calculated by the following equation:

$V_{bz} = R_p P_z$ or $V_{bz} = R_a A_z$

Where

V_{bz} = the breathing zone outdoor airflow

R_p = outdoor (fresh) airflow rate required per person (L/s per person)

P_z = zone population: the greatest number of people expected to occupy the zone

R_a = outdoor airflow (fresh) rate required per unit area (L/s per m^2)

A_z = zone floor area: the net occupied floor area of the zone (m^2)

in energy calculation studies. Other methods include an analytical procedure[5] based on comfort perceived odour and health requirements (Olesen *et al.* 2008).

Table 2-17. Categories of pollution from non-residential buildings based on ventilation per floor area

Category	Airflow per Building Emissions Pollutions (L/s per m²)		
	Very Low Polluting Building	Low Polluting Building	Non Low Polluting Building
I	0.5	1	2
II	0.35	0.7	1.4
III	0.2	0.4	0.8

Source: BS EN 15251:2007 (2008)

2.4.4 Summary

Energy efficiency and thermal comfort are major aspects that needed to be considered when implementing ventilation systems in spaces. These include indicators to reveal thermal performance affecting airflow performance in the ventilated spaces. These variables, in turn, affect the energy performance of the building (Figure 2-10).

It is recommended that the energy efficiency of a ventilation system should be defined by the heating and cooling demands of the building. Therefore, this study will consider those parameters. Evaluating these parameters is related to defined benchmarks. The air temperature and air speed at the occupied zone of the skycourt define the level of thermal comfort in this space. The level of comfort will be determined with regard to general office spaces because comfort limits have not been specified for enclosed transitional spaces such as skycourts in current standards. However, a deviation of ± 2°C to 3°C from the standard temperature can be accepted in transitional spaces.

[5] The ventilation rate is determined by the equation:

$$Q = \frac{G}{(C_i - C_0) \cdot E_v} \quad (ls^{-1})$$

Where
G = total emission rate (mgs^{-1})
C_i = concentration limit (mgl^{-1})
C_0 = concentration in outside air (mgl^{-1})
E_v = ventilation effectiveness.

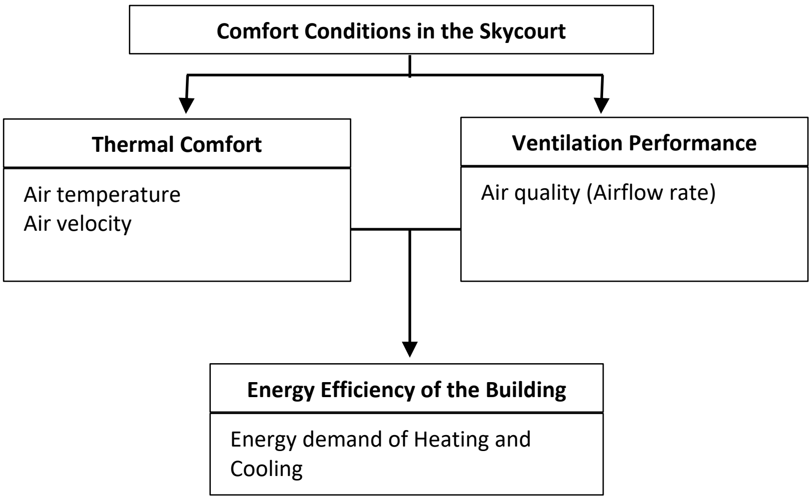


Figure 2-10. Summary of main variables for assessing ventilation in the study

A good ventilation strategy has potential to achieve 45% to 55% savings per year on heating and cooling in office buildings according to CIBSE Guide F (2012) for energy efficiency. The present study will focus on potentials to decrease energy demands for heating and cooling by proposing an energy saving ventilation strategy for skycourts, and benefiting from their comfort requirements as transitional buffer zones.

In the next section of this chapter there will be a discussion of potential methods to investigate energy efficiency in buildings due to ventilation and thermal conditions in ventilated spaces.

2.5 METHODS FOR INVESTIGATING ENERGY EFFICIENCY FOR BUILDINGS AND THERMAL COMFORT IN VENTILATED SPACES

Generally, investigating environmental problems that consider energy efficiency and thermal conditions calls for a combination of both qualitative and quantitative responses (Groat and Wang 2013; Creswell and Clark 2011; Gray 2009). This procedure involves several research methods such as surveys, experiments, case studies and simulation. As a result, each method will complement the other.

A critical review of research methods commonly used for collecting and analysing data in relevant environmental studies is provided in Table 2-18. These were analysed in terms of questions, criteria, variables, methods and design of the research.

For example, investigating the energy performance of specific features of the building could be carried out by case study and simulation approaches. Studying thermal comfort parameters could be conducted by simulation and experiments. However, sensitivity analysis studies that involve studying the effect of the geometric configuration and suggesting design solutions could be adapted by simulation.

A survey approach is useful to obtain information, which can be analysed to extract patterns and make comparisons. Moreover, it can be conducted to answer the questions of *What, Where, When* and *How*. However, it cannot meet the *Why* question (Bell 2010). Examples of this approach are found in studies 6 and 25 in Table 2-18, as they inform background data about the research topic to develop the research framework.

Case studies could be conducted to explore a phenomenon within its real-life context, especially when the relation between the phenomenon and the context is not clear. Many scholars used this approach for exploring the technical areas of environmental research (Groat and Wang 2013). This method is ideal to answer the questions of *Why* and *How* for a contemporary setting (Gray 2009). For example, a case study method could be adopted to collect data about building characteristics. These are followed by making a comparison and analysis to investigate information regarding several environmental issues such as thermal and energy performance, such as studies 6, 15 and 19 in Table 2-18. A case study as a strategy of research involves three main phases; each phase consists of a number of steps. These are as follows: (i) defining the design of the strategy, (ii) preparing and collecting data, and (iii) analysing the collected data and drawing conclusions. The first phase involves developing a theoretical stand such as question(s) based on previous research, selecting the case studies, and designing research tools. The analysis should be grounded on a definite 'unit of analysis' and should involve creating a data base to increase reliability and facilitate the process of concluding generalisations (Gray 2009), (Figure 2-11).

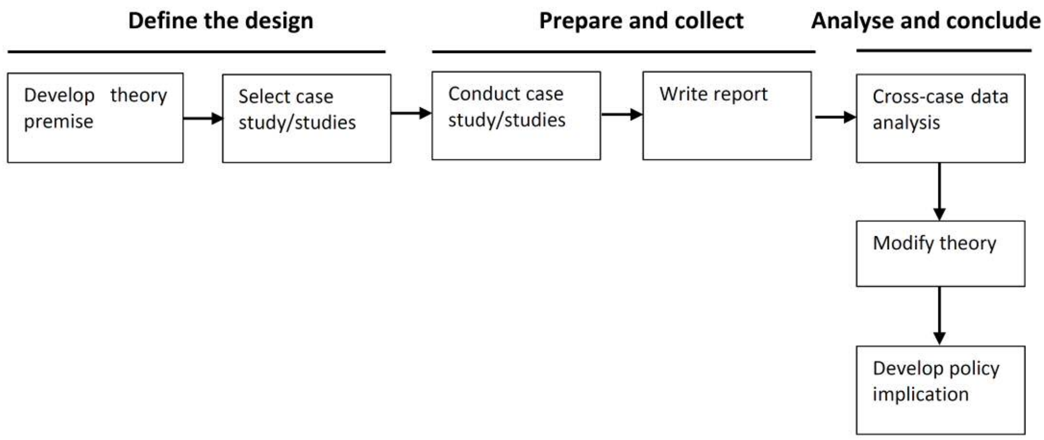


Figure 2-11. Model for case study process

Source: Gray (2009)

Table 2-18. Examples of relevant studies for areas of environmental research in buildings

	Study	Research Aim / Questions	Criteria	Variable(s)	Research Methodology and Framework	
					Method(s)	**Stages/Steps**
1	(Li and Li 2015)	Establish a method to predict the ventilation potential for residential buildings	- Energy saving - Air temperature - Airflow rate	- Building type - Climate condition - Opening area - Internal heat gain - Plan area density	- Simulation (S)	1. Standard for evaluation 2. Input data 3. Determining impact of variables
2	(Calautit and Hughes 2014)	Investigate the ventilation performance of a commercial multi-directional wind tower	- Air velocity - Air pressure	- Wind tower	- Simulation (S) - Laboratory measurement (LM)	1. Simulation: base mesh model 2. Lab: build 1:10 scaled model 3. Compare results of both methods
3	(Cantón *et al.* 2014)	Evaluate the effect of different open space design variables on the energy consumption to obtain comfort conditions in the interior space	- Energy consumption - Thermal comfort	- Courtyard geometry (perimeter, height, width and length)	- Field measurement (FM) - Simulation (S)	1. Site measurement 2. Simulation: the base case model 3. Use Form Factor (FF) and Effective Form Factor (EFF)
4	(El-deeb *et al.* 2014)	Study the effect of the courtyard on energy consumption based on height proportions and thickness of the built area surrounding it in multi-storey air-conditioned courtyard buildings	- Energy consumption	- Height proportions - Thickness of the surrounding built area	- Simulation (S)	1. Sensitivity analysis: different thickness and different building heights 2. Analyse results
5	(Hughes *et al.* 2014)	Discuss ventilation found in domestic buildings and use heat pipe technology to recover the energy from them	- Temperature - Energy consumption	- Ventilation performance	- Simulation (S)	1. Simulation based on numerical code

6	(Stormont 2014)	Determine if it is possible or not to use ventilation in modern day architecture design for the Middle East	- Air Temperature - Humidity	- Ventilation performance	- Case study (CS) - Survey	1. Selection of case studies -locations 2. Research trips
7	(Taleghani *et al.* 2014)	Analyse the impacts of transitional spaces on energy performance and indoor thermal comfort in the dwelling at present and projected in 2050	- Thermal comfort	- Construction (wall and roof types) - HVAC - Glazing	- Simulation (S)	1. The reference model (tested for five climates) 2. Effect of courtyard 3. Effect of atrium 4. Optimisation (to combine models of phases 2 and 3)
8	(Almhafdy *et al.* 2013)	Assesse the microclimate performance of a U-shape courtyard in a general hospital in Malaysia	- Air temperature - Humidity - Wind patterns	- Courtyard shape	- Field measurement (FM) - Simulation (S)	1. Site measurement 2. Simulation: the base case model 3. Parametric analysis
9	(Ezzeldin and Rees 2013)	Provide a systematic assessment of the performance of various mixed-mode cooling strategies for office buildings with different levels of internal heat gain function in four cities representative of arid climates	- Air temperature - Humidity	- Internal gains - Four cities	- Simulation (S)	1. Prototypical office building design 2. Alternative cooling strategies 3. Performance evaluation criteria
10	(Al-Masri and Abu-Hijleh 2012)	Determine the overall energy use energy savings potential and available daylight levels	- Energy saving - Daylight level	Variables for geometry - Number of floors - Type of glazing - Wall thickness - Insulation type and thickness	- Simulation (S)	1. Comparison between conventional and courtyard buildings 2. The effects of variables on the performance of a courtyard type building 3. An optimised courtyard model encompassing the best of each of the parameters studied in the second step is generated and tested

11	(Haw *et al.* 2012)	Examine the wind-induced ventilation tower performance under a hot and humid climate	- Air velocity	-Ventilation tower	- Simulation (S) - Laboratory measurement (LM)	1. Numerical simulation of computational fluid dynamics (CFD). 2. Reduced-scale experiments
12	(Karava *et al.* 2012)	Explore mixed-mode cooling strategies in buildings with hybrid ventilation in building with motorised facade openings integrated with an atrium	- Thermal performance	- Façade opening	- Field measurement (FM)	1. Assessment of hybrid ventilation and thermal conditions in the atrium 2. Assessment of night cooling strategies
13	(Prajongsan and Sharples 2012)	Evaluate the ability of ventilation shaft to increase air velocity and the comfort hours in a room in a high-rise building	- Air velocity - Operative temperature - Comfort hours	- Wind conditions - Opening sizes - Operation schedule	- Simulation (S)	1. Climate data 2. Build the model 3. Test the alternatives
14	(Hughes and Mak 2011)	Examines the relationship between external wind and buoyancy forces and the indoor ventilation rate achieved	- Temperature	- External wind	- Simulation (S) - Field measurement (FM)	1. Assessment using CFD modelling 2. Validate using full-scale experimental testing in the natural environment
15	(Moghaddam *et al.* 2011)	Explore the potential of using ventilation as a passive cooling scheme for public buildings	- Passive cooling	- Openings type, size and location	- Case study (CS)	1. Analyse the characteristics of present public buildings in terms of climate and technology 2. Compare results 3. Provide design guidelines
16	(Xing *et al.* 2011)	Investigate the ventilation effect in the building	- Surface pressure	- Ventilation effect	- Laboratory measurement (LM) - Simulation (S)	1. Simulation model 2. Experimental model

17	(Breesch and Janssens 2010)	Develop a methodology to predict the act of night ventilation taking into consideration the uncertainties in the input	- Thermal comfort defined by eight parameters	- Ventilation effect	- Simulation (S)	1. Thermal comfort model to evaluate the performance of natural night ventilation, 2. Simulation: base building model 3. Estimation of the uncertainties on the input parameters 4. Two weather data sets 5. Uncertainty and sensitivity analysis
18	(Li *et al.* 2010)	Evaluate the natural wind environment of a high-rise residential construction under two unit design schemes	- Wind performance	- Opening location - Opening size	- Case study (CS) - Simulation (S)	1. Numerical Method and Boundary Conditions 2. Evaluation Method for Numerical Results
19	(Pomeroy 2008)	Whether skycourt could be considered an open space within the high-rise building to generate balance with the built up area	- Skycourt as open space	- Adaptability - Continuity and enclosure - Ease of movement - Legibility - Diversity - Figure ground	- Case Study (CS) - Survey	1. Compare four skycourt case studies with two semi-public comparator case studies 2. Identify the social and urban morphological characteristics of successful public spaces
20	(Voss *et al.* 2007)	Generate information on energy use in office buildings	- Energy consumption	- Heating - Ventilation - Air conditioning - Lighting	- Field measurement (FM)	Five years of research monitoring: - Energy consumption - Thermal comfort and health
21	(Jahnkassim and Ip 2006)	Evaluate climatic and energy performance of key 'bioclimatic features' (core position, skycourt, and bioclimatic envelope) and the overall 'bioclimatic' forms	- Energy use of the selected features separately - Energy use of the overall forms	- Core position - Skycourt - Bioclimatic envelop	- Case study (CS) - Simulation (S)	1. Simulation: the base case model 2. Add climatic data 3. Compare simulation results with post-occupancy study to validate the simulation results
22	(Breesch *et al.* 2005)	Evaluate the overall performance of passive cooling for thermal comfort in the office building	- Surface temperature - Air temperature	- Cooling performance	- Case study (CS) - Field measurement (FM) - Simulation (S)	1. Site measurement 2. Simulation: The case model 3. Comparison

23	(Chun and Tamura 2005)	Discuss thermal comfort in urban transitional spaces	- Air temperature - Relative humidity - Air velocity	- Transitional spaces	- Field measurement (FM) - Laboratory measurement (LM)	1. Site measurement 2. Construct laboratory conditions 3. The same sequenced experiment (as in the laboratory) at a number of urban transitional spaces
24	(Capeluto 2005)	Present a computer-based design method to improve the thermal comfort conditions in the built environment by controlling wind access and ventilation	- Temperature - Humidity - Solar radiation - Wind - People's activity levels and their clothing.	- Access of ventilation	- Simulation (S)	1. Set climatic data - wind roses (graphics) 2. Define desirability or undesirability of existing winds
25	(Al-Sallal 2004)	Assess tower buildings in Dubai in terms of sustainable issues under the harsh desert climate of the UAE	- Energy performance	- Energy features	- Survey: questionnaire, interviews, photographs	1. Collect data about energy audit and building design 2. Analyse and compare the data
26	(Kotani *et al.* 2003)	Predict ventilation rate in voids (light wells) in high-rise buildings	-Temperature distribution - Ventilation rate	- Void wells	- Field measurement (FM)	1. Compare the scale model measurements and calculation of temperature and ventilation 2. Use Bernoulli's equation

The experimental approach deals with measurable phenomena. It can allow finding the cause and effect relationship (Bell 2010). Several methods could be adopted for conducting experiments about the environmental performance of the built environment. These methods, which are called full-scale methods, could use measuring techniques to investigate a performance under a controlled environment (laboratory experiments), or within an ambient situation (on-site/on-field measurement).

The laboratory experiments employ a model of the studied space(s) and place them in a laboratory or a study chamber where the characteristics of ambient conditions are generated (Gray 2009). Such experiments could be applied for assessing thermal comfort or for investigating the effects of exposed environmental conditions, such as wind comfort (as wind tunnel) at several scales, urban or for a single building, such as the studies 2 and 16 in Table 2-18.

The on-site measurements employ measuring techniques to investigate microclimate comfort, similar to the laboratory experiments. However, they are conducted in an existing building or a mock-up model that is built and placed in a real ambient environment (Groat and Wang 2013). These techniques are valuable and acceptable for providing understanding of the phenomenon in realistic situations. For example, an on-site measurement technique was used in the study 8 in Table 2-18, to gain more understanding of the effect of geometry on the thermal performance of the building. Moreover, studies 20 and 22 in Table 2-18 used this technique to collect information regarding the impact of devices and systems (ventilation, heating, cooling and lighting) on the energy consumption in buildings. The combination of both measurements, on-site and laboratory, could offer reliable and trustable results in terms of using on-site measurements and replicating the real situations such as the study by Chun and Tamura, 2005 in Table 2-18.

Although few studies pointed out that both laboratory experiments and on-site measurements present high validity and accurate methods for investigating thermal conditions, such methods can provide information that is more realistic compared to modelling methods. This is due to their high potentials for expressing the phenomenon in a way that is physically much more similar to the reality. However, unexpected errors from the physical experiments and measuring instruments could happen, and this may affect the accuracy of the measured data. In addition, they can be cost-expensive and require time; this is significant for the cases with alterations and parameters (Mak *et al.* 2005).

Simulation, which is useful for developing and testing assumptions, investigates how a physical environment influences some aspects of life, as an intermediate point of knowledge for developing design guidelines. Also, it can be triangulated with data yielded from other methods for more accurate results (Groat and Wang 2013). This could be used as a design tool for generating design alternatives, predicting performance and defining the optimum solution that improves performance. In addition, it could be used for analysing the effect of space(s), system(s) or device(s) at several scales to inform more details (Ohba *et al.* 2010). This process includes setting up a model that represents the overall system that stimulates the reality being studied. This process employs equivalency between the real model and the simulation model, in terms of boundary conditions (e.g. climate condition, shape and temperature) and dimensionless parameters relevant to the actual physical process (Groat and Wang 2013). These are called numerical (mathematical) models. Then a numerical approximation is utilised in simulation to predict thermal and air performance inside and outside buildings, and the energy consumption, thus to obtain solutions for problems. Mathematical problems are formulated so that they can be solved with fundamental arithmetic equations for heat transfer and fluid dynamics. Simulation is applied in vast fields of research. Examples of such studies are 5, 7, 9, 10, 13, 17, and 24 as shown in Table 2-18.

With the broad availability of computers and software simulation packages, the applications of numerical models are gaining more and more attention; in particular they can provide high reliability and accuracy as full-scale methods. They also allow numbers of model alterations to be investigated under controlled ambient conditions with minimum cost and amounts of time. In addition, they allow the construction of parts, strategies or devices that do not exist in reality to be assessed in detail.

For example, Computational Fluid Dynamic (CFD) has contributed to 70% of the literature in recent years (Ai *et al.* 2011). It is a useful numerical tool for studying the airflow performance of sustainable features of buildings due to ventilation. In addition, it can analyse the thermal performance of buildings to meet the energy demands (Calautit and Hughes 2014; Hughes and Mak 2011; Ali and Armstrong 2008; Mak *et al.* 2005; Yau 2002). Other simulation mechanisms can predict the energy performance of buildings including demands and loads such as heating, cooling, ventilation and solar gain. In addition, they allow cost calculation and the provision of feasibility data.

2.5.1 Summary

The previous review strengthens the combination of multiple data sources due to the potentials of each method individually and collectively. Considering the aim and objectives of this study, availability of facilities, and time allowance, two main sources of data are involved in this study. These are case studies and simulation.

Case studies are useful to address the first objective of the study. Therefore, several high-rise office buildings that include skycourts are investigated. This kind of analysis is efficient to allow exploration of skycourts in real estate buildings. The most important benefit is to define the prototypes of skycourts in the research context, and formulate the theoretical models of the buildings. Other benefits include exploring several features of skycourts, such as geometry (the form – shape, height, area, and proportion), orientation, configuration within the vertical section of the building, and the other supported elements such as building form, façade, aerodynamic elements, and atrium and control management systems. In order to minimise the limitations of the approach, objectivity is considered to avoid bias and explore multiple cases that have the same features in the same context. Various methods are used to capture multiple sources of data; these include scrutiny of documents and site visits. The data are evaluated and analysed in the form of a cross-case matrix to compare different issues. This phase is described in chapter three.

A simulation is carried out to investigate the thermal conditions inside the skycourt, and its impact on the energy performance of the building. This method is suitable to achieve the second and third objectives of the study. Then, to define the most affordable prototype of skycourts in high-rise office buildings in terms of the study perspective, simulation is recommended when dealing with questions of scale and complexity. Computer programs can replicate real-world contexts or events (virtual world) for the purpose of studying results of dynamic interaction (synthetic elements) of manipulated factors within the setting. As discussed previously, one of the main types of simulation models to predict thermal and energy performance is the mathematical model. Mathematical models deal with numerical coding. The most powerful modelling is the computer simulation, which offers a useful tactical tool that can process a huge body of information in small periods and does so accurately. Furthermore, it can provide designers with a tool for determining the energy performance. Examples of these models are energy simulations for the building which represent mathematical systems about the performance of equipment under a given set of circumstances as parameters. In addition, CFD can predict detailed and specific data. However, the new direction of building energy simulation is to integrate (couple) models, so the validity of results will be high. These approaches allow a better understanding of the thermal, air performance inside a skycourt to be gained, optimising the design of the skycourt and predicting energy usage. This is discussed in detail in chapter four.

A concurrent triangular strategy would best describe the interconnection of the mixed-methods for this study. Figure 2-12 shows how the concurrent combination between both quantitative and qualitative methods could be effective to investigate the skycourt performance, so allowing the answers from both data sets to be combined and compared. The study will implement mathematical models. Therefore, numerical data, descriptive figures, and matrix tables for comparing variables will be carried out in the research.

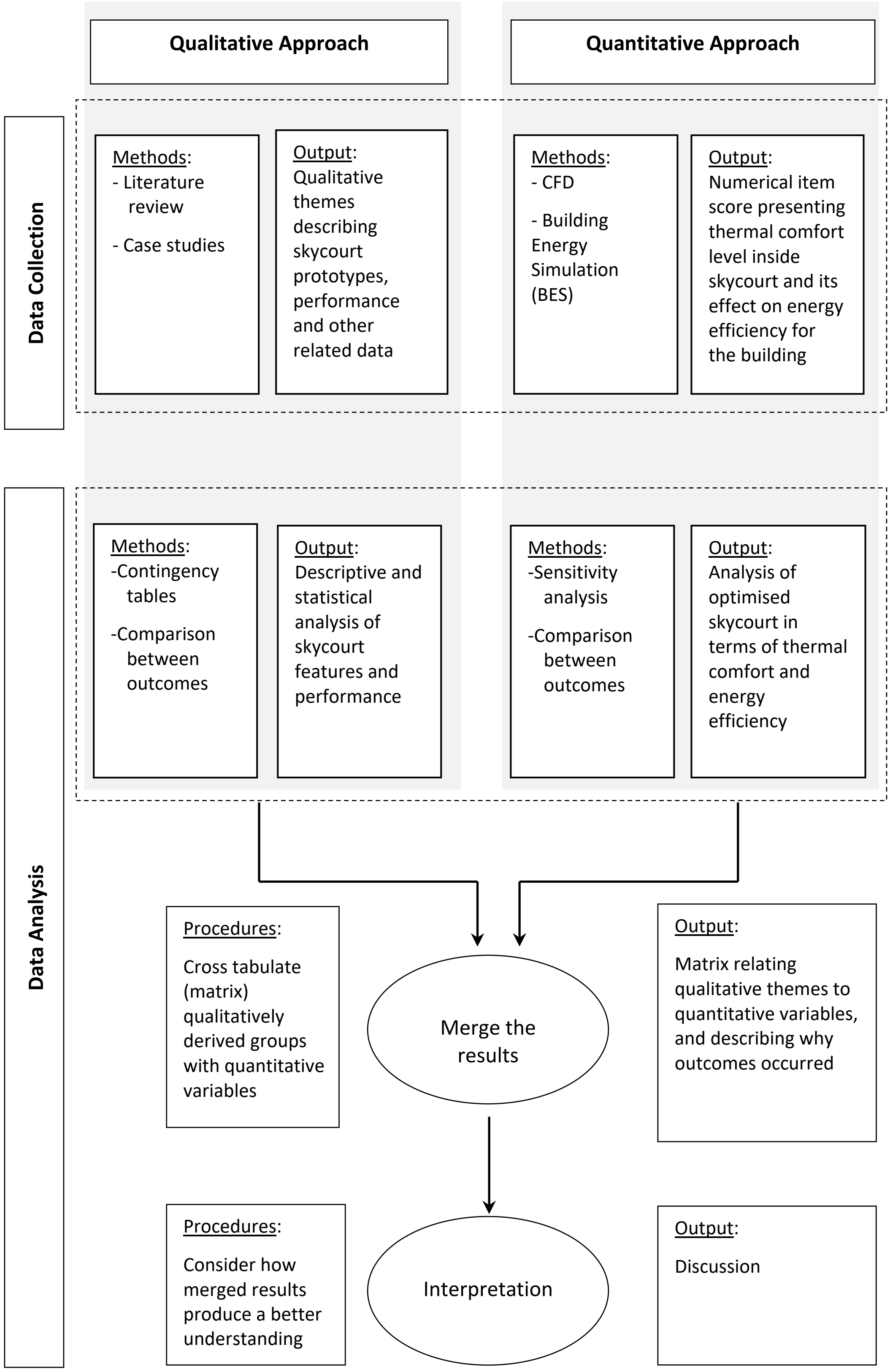


Figure 2-12. The concurrent design of the research

Source: Adapted by researcher from Creswell and Clark (2011)

2.6 SUMMARY AND CONCLUSIONS FOR THE STUDY

This chapter described the evolution of skycourts in high-rise buildings and the various perspectives and functions of skycourts. A skycourt can enhance the environmental design in buildings. Skycourts are perceived as spaces that act as transitional and networking areas. The influence of such areas as ventilated spaces on energy demand in a temperate climate is considered one of the knowledge gaps in respect of office buildings, which requires investigation.

Available data in the literature provide mechanisms to improve energy efficiency of the current ventilation strategies. There is the need to develop new options that can offer a significant impact in minimising energy consumption for heating and cooling in office buildings, and enhancing thermal conditions in ventilated spaces such as the skycourt (Figure 2-13).

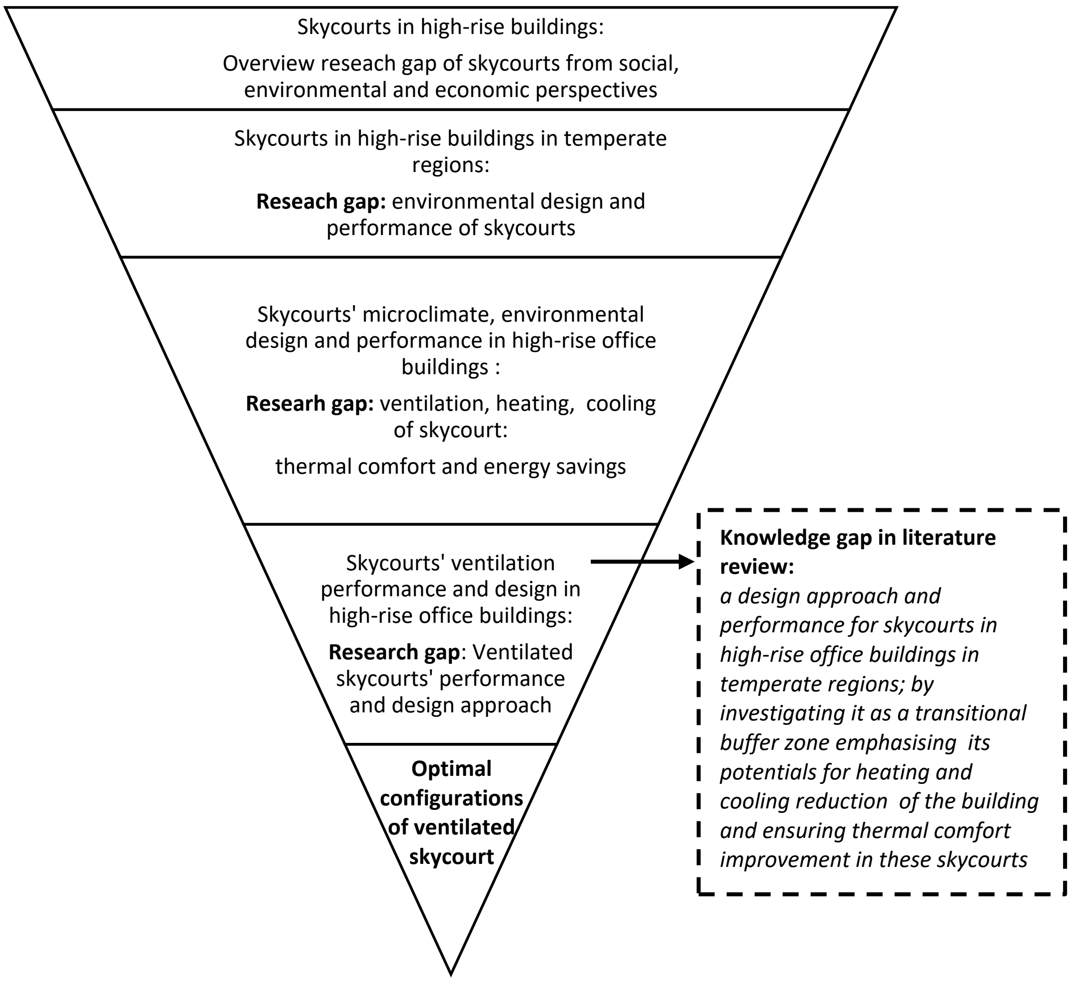


Figure 2-13. Flow chart of topics related to the research and main knowledge gap

Based on the discussion presented in this chapter, an outline for developing a ventilation strategy in skycourts could be concluded. This process involves examination of four main factors; these are the following:

Firstly, external and internal climate variables. External variables include climate parameters of the context in different seasons. In this study, the London climate profile is adopted. Internal variables define the expected thermal comfort range required in the skycourt space by determining the required levels of air temperature and air change rate.

Secondly, the design configuration of the skycourt. This includes geometric parameters such as skycourts' orientation, height, area, length and depth. In addition, this involves the influence of vertical locations and horizontal positions for openings of inlet and outlet air inside skycourts.

Thirdly, methods to predict heating and cooling loads of the building, in addition to the air temperature and airspeed inside the skycourt. The concurrent triangulation of methods is adopted for this study. Simulation is found to be the appropriate method to fulfil the study questions of energy and thermal predictions.

Finally, criteria to assess ventilation effectiveness. This includes the amount of savings of energy demands for heating and cooling for the building. In addition, consideration is given to levels of thermal comfort inside the skycourt to obtain the influence of the proposed approach.

Extracting prototypes of skycourts through analysing their spatial configurations in high-rise office buildings will be discussed in the next chapter.

CHAPTER THREE: PROTOTYPES OF SKYCOURTS IN THE RESEARCH CONTEXT

3 PROTOTYPES OF SKYCOURTS IN THE RESEARCH CONTEXT

3.1 INTRODUCTION

The present study involves investigation of prototypes for skycourts in existing constructions in temperate climates. This process is useful to accomplish the first objective of the research, which is to define the existing patterns and spatial configurations of skycourts that function as transitional buffer spaces in high-rise buildings.

This phase of the research explores the skycourt in the office building typology, worldwide, with the focus on the climatic context of the study. The selection process is based on pre-defined criteria that correspond to the research objectives. This is followed by collecting data about the selected buildings and more focused data about skycourts. Data for the buildings were obtained from design documents. Other resources include interviews with designers and site visits. Then, comparisons between the selected cases are made in the form of drawings and cross tables. The analysis of cases is based on parameters concerning the skycourt. These parameters include spatial configuration, location, height, and function.

The case study analysis includes two stages: the first determines global buildings from different climate zones. Although the research focuses on high-rise buildings in the temperate climate, understanding issues relating to skycourts in other climate contexts will aid identification of the influence of climate on skycourt design. The second stage explores buildings located in regions of temperate climate. The next sections of this chapter present these two stages. The levels of details about the building and the skycourt vary between the two stages. The first stage focuses on general information, while the second provides more details about the skycourt prototype. The analysis is followed by a discussion to conclude main features for the design of the skycourt. Details about the main cases of the second stage and analysis of these cases are presented in Appendix B, Extracting prototypes of skycourts.

3.2 FIRST STAGE: SKYCOURTS AT A GLOBAL LEVEL

The first stage provides information about skycourts in buildings around the world. These buildings are located in different climate zones: arid, tropical, temperate, and cold. The buildings are identified through a study of the literature as their skycourts provide potential benefits for the total performance of the buildings. Selection of the buildings was based on the following criteria. Firstly, these structures should integrate the skycourt. Secondly, these buildings should be classified as high-rise buildings in their contexts, although this term could vary among different contexts. Thirdly, these buildings should function as offices or include office zones in cases of mixed-use buildings, and the skycourt should serve the occupants of these zones. The number of skycourts in each building varies from one to more than 50 skycourts. The following provides a brief of the main case studies.

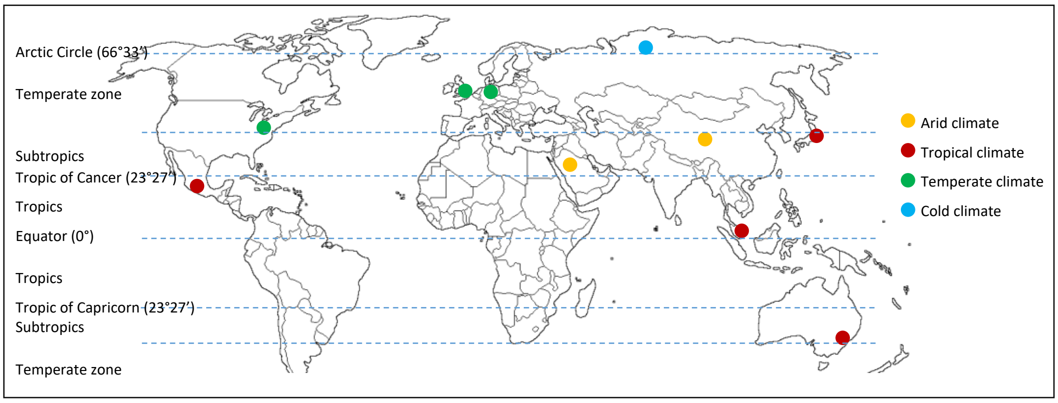


Figure 3-1. Map showing the different geographical zones of the world

National Commercial Bank (NCB), 1983, Jeddah, Saudi Arabia, consists of 27 floors and is one of the first high-rise office buildings that integrates skycourts. The building has a triangle-shaped plan, which includes vegetated skycourts. Skycourts are three stepped alternatively, open to the air and connected with a central court along the whole height. These spaces represent approximately 2.4% of the total built-up area, and perform as spaces for social interaction, viewing, observation, and providing natural light and ventilation.

Shanghai Tower, 2014, Shanghai, China, is a 632 m mixed-use high-rise building that includes offices, hotels and retail zones. The building is separated into nines zones, and contains about 21 skycourts. Skycourts are located at the sides as sky-lobbies of nine-storey height, and among the floors dividing the different zones of the tower. These spaces form about 2.7% of the total built-up area. They are planted and contain entertainment facilities such as cafes, restaurants and retail spaces.

Lotte Tower, 2015, Seoul, South Korea, is another example of a mixed-use building. It is a 123-storey tower that holds offices and hotel zones. Skycourts are a significant part of the tower, and collect approximately 2.4% of the total built-up area. Sky-lobbies are located on the different levels of the building, and used as social and transitional spaces.

Singapore National Library, 2005, Bugis, Singapore, is an example of high-rise buildings with integrated skycourts in the tropical climate area. This building is used as a library. However, it is included in the study due to the significant skycourts, which represent almost 11.3% of the total built-up area, and also due to the similarity of the space layout with office zones. The 14 skycourts introduce green spaces connected with a central atrium, and some of them are open to the outdoor climate. This strategy could enhance the biodiversity and the users' psychology.

Genzyme Centre, 2004, Massachusetts, the USA, is a 12-storey research and development centre, and includes 18 skycourts. These spaces provide greenery in the building, and function as a social gathering space. They have a connection with the full-height atrium.

ACROS Fukuoka Prefectural International Hall, 1991, Fukuoka, Japan, is a 60 m high office building with multi-function facilities. It includes 16 skycourts that have the form of sky-terraces and sky-roof, and constitute more than 13% of the built-up area. They function as gardens and contain about 35,000 plants of different species. These areas support the greenery of the city.

The Shard, 2012, London, the UK, is a 304 m high-rise building, which consists of 95 floors, and is considered as one of the major landmarks of London city. It holds a mix of offices, residential and hotel zones. Offices occupy the lower floors till floor number 26. Each level includes a winter garden, which is like a sky-terrace. These skycourts separate the several zones of the building. The multi-storey skycourts are used for social gatherings, and include restaurants and cafes. Also, they function for viewing the city, particularly the ones that are located on floors 68th to the 72nd. Those at the top are open on the upper part of the facades to the external environment.

Commerzbank, 1997, Frankfurt, Germany, is a well-known high-rise office building due to its triangle form and the environmental design. It contains a central triangular atrium of full height, separated by a skylight every 12 floors. This separation is for fire security as a smoke barrier. Also, this separation encourages fresh air by supporting shorter air circulation. The triangular geometric plan is an equilateral 60 m with convex sides and rounded corners. Two sides of the plan hold offices, and one side features skygardens. The building contains nine skycourts. These changes in orientation from one wing of the triangle to the next as the following sequence: three facing eastwards, three facing southwards and three westwards. The landscape of these spaces depends on solar orientation. The skycourts are used as outdoor public social places and facilitate views, natural light and ventilation.

Heron Tower, 2011, London, the UK, holds 46 floors. It is segmented vertically into ten villages; each segment includes a three-storey skycourt, except one which is a six-storey skycourt. These are in the form of the full-height atrium, and used as spaces for social communication. Also, they allow visual connectivity with the outside and let daylight enter deep into the interior.

Liberty Tower of Meiji University, 1998, Tokyo, Japan, is 119 m high. The wind floor number 17 holds a skycourt with openings on the four sides and three V-shaped glass screens that are connected with a central core atrium, to facilitate social interaction and support air movement inside the building.

The Leadenhall Building, 2014**,** London, the UK, is a 224 m high office building. It has been awarded a BREEAM excellent rating for its essential design, and the Home City of London Prize, 2015. It includes two skycourts; one as a sky-entrance 28 m high on the ground floor, which is used as open space that connects the building to the outdoor context; and the second of two-storey height from level 46 to floor 52. These skycourts function as a public realm and observation decks, and facilitate social interaction, daylighting, and viewing.

30 St. Mary Axe, 2004**,** London, the UK, located in the financial and insurance district. This 180 m high building is well known for its aerodynamic form. The cylindrical form responses to environmental and urban design issues such as fit to the site, reduce the impact of massive scale, and work well with the wind. Also, it minimises heat gain and heat loss over the envelope, as it requires 25% less external surface compared to an equivalent size rectilinear tower. The floor plan has a circular shape; each floor has six rectangular spaces (fingers) that radiate from the centre (the core), and the triangle voids between these fingers create sky-terraces. The building holds spiral (stepped) three 2-storey and four 6-storey sky-terraces. These zones provide additional insulation, regulate internal temperature, and enhance energy reduction. Also, they bring daylight, views, visual connections and social interaction, and are designed to support ventilation. The triangular shape of the skycourts provides rectangular offices.

Post Tower, 2002**,** Bonn, Germany, is one of the magnificent office buildings in Europe; it is 163 m high with 42 floors. It is vertically segmented into four parts, three 2-storey and one 11-story. These components function as skycourts that facilitate social interactions, vertical and horizontal movements, and support airflow by the stack and wind-induced forces.

The Broadgate Tower, 2008**,** London, the UK, is a 35-storey office building of 165 m height and was awarded CTBUH best tall building in Europe for the year 2009. It includes several types of skycourts at the entrance level and the upper floors.

20 Fenchurch Street, 2014**,** London, the UK, is well known as ‘’London’s sky-garden ‘’ and ‘’Walkie Talkie’’ tower. This structure is a significant example of high-rise office buildings in London city that contains several styles of skycourt. The building is of 177 m height, rated BREEAM excellent and nominated as CTBUH best tall building in Europe for 2015. It contains a sky-entrance, sky-terrace, and sky-roof. However, the skycourt at the top is the most significant, and it is used as a retail zone occupied by cafes and restaurants, and provides magnificent views of the city.

51 Lime Street, 2007**,** London, the UK, consists of three overlapping curved parts; the upper has the height of a 28-storey (127 m) structure. It was awarded the CTBUH best tall building in Europe for 2008, and certified BREEAM excellent for its energy efficiency due to its highly efficient services equipment, systems, and high-insulated facades, which reduce glare and solar gain. The building contains a skycourt in the form of a sky-entrance. This space functions as a social and a transitional space of the height of two floors connected with the outdoor context by a public plaza.

The Lloyds Building, 1986**,** London, the UK, is 95 m high office building, which contains a significant skycourt as an atrium of the full height of the building. This functions as a central space that holds all of the vertical transitional facilities such as escalators and elevators. It is covered from the top with a skylight.

Torre Cube, 2005**,** Guadalajara, Mexico, is an example of an office building that saves 100% of the energy consumption for cooling and heating, as it depends on natural ventilation only, with no mechanical systems for heating and cooling. It has a funnel-shaped office space that is connected with a central atrium of the full height of the tower (60 m). Each office wing includes two office zones and one skycourt zone. The total number of skycourts is three, one 4-storey and two 3-storey. These skycourts support social interaction and facilitate fresh air movement to the office zones.

Rothschild Bank Headquarters, 2011**,** London, the UK, is a 75 m high office building consisting of interconnected squares. These include five skycourts of several styles. The ground floor holds the sky-entrance, floors number 1 and 11 contain skycourts, and the roof at the 11^{th} floor facilitates a sky-roof. Also, floor number 15 holds a sky-terrace.

6 Bevis Marks, 2014**,** London, the UK, is another example of office buildings that are rated BREEAM excellent and was nominated CTBUH best tall building in Europe for 2014. It is significant in London due to the green sky-terraces at the upper floors. These facilitate entertainment including cafes and restaurants, and enhance the psycho-physiological issues for the employees through providing daylight, fresh air, and excellent viewing.

1 Bligh Street, 2011, Sydney, Australia is an elliptical 30-storey high-rise office building, which holds two skycourts, one on the 15^{th} floor, and the other on the 30^{th} floor. The one in the middle of the building is connected with a central atrium of the full height of the tower (120 m). The other skycourt is of 10 m height in the form of a sky-roof. This building conserves 100% of its energy consumption for heating and cooling in the atrium, lobby and skycourt areas as these are passive ventilated areas, whereas the office zones are mechanically ventilated.

10 Brock Street, 2013**,** London, the UK, is three slender towers; the middle is 16 floors high connected with the two others, which are 11-storey and 10-storey high. The skycourt is located on all floors of the middle slender tower, while the 11-storey part contains a sky-terrace and sky-roof at the top.

3.2.1 Overview of Skycourts in High-Rise Office Buildings in Several Climates

The skycourt in high-rise office buildings has similar functions and spatial configurations in different climate regions. However, the difference is found in the façade envelope, such as the percentage of opening in the skycourt wall and shading.

Design of skycourts should respect the local climatic conditions. For example, from examination of the examples studied, it was found that completely open skycourt walls are found in high-rise buildings in areas with a hot dry climate, such as the skycourt of the National Commercial Bank (NCB) located in Jeddah. Skycourts in tropical climates are designed based on a 45-degree line and about half of the skycourt wall is open. High-rise buildings in temperate climates present different solutions for skycourt designs. It is uncommon to find open skycourt walls; they are glazed and closed due to the high wind speed and the high temperature variation between summer and winter, and day and night. In addition, shading is required to reduce solar radiation in summer and allow it in winter. Table 3-1 summaries design recommendations for skycourts in hot dry, tropical, temperate and cold climate regions.

Table 3-1. Skycourt design in different climates

	Climate Characteristics	Skycourt Requirements for Environmental Design
Hot dry climate	- High air temperature (over 37°C) - Low humidity - High day/night temperature fluctuation	- Orientation (along east-west axis) to reduce solar gain in morning and afternoon - Protection from solar radiation (heat gain) - Open walls - Increase humidity through greenery and plants - Night-time ventilation - Thermal mass: to delay thermal exchange between interior and exterior and limit internal heat gain - Evaporative cooling: to create humidity
Tropical climate	- High air temperature - High humidity (over 80%) - High solar radiation - Small temperature variation between internal and external /day and night	- Protection from solar radiation (heat gain): shading devices (not to block air movement) - Partially open walls - Natural ventilation - Night-time ventilation - Wing walls - Narrow floor (depth) to enhance cross ventilation - High floor-to-ceiling height (height) to enhance stack-effect
Temperate climate	- Moderate temperature - Warm and sunny but not too hot summer - Cold but not extremely cold winter	- Shading - Closed Walls - Cooling in summer - Heating in winter - Passive heating - High air change rate - Thermal mass insulation/Double skin façade
Cold climate	- Low air temperature - Low solar radiation	- Glazed areas toward intense solar radiation (south) with adjustable shading devices - Sky-garden (winter garden) in the south with prevailing wind direction - Building form: curvilinear, compact shape (deep) - Conservation of heat (passive solar heating) - Building envelope: double, triple glass

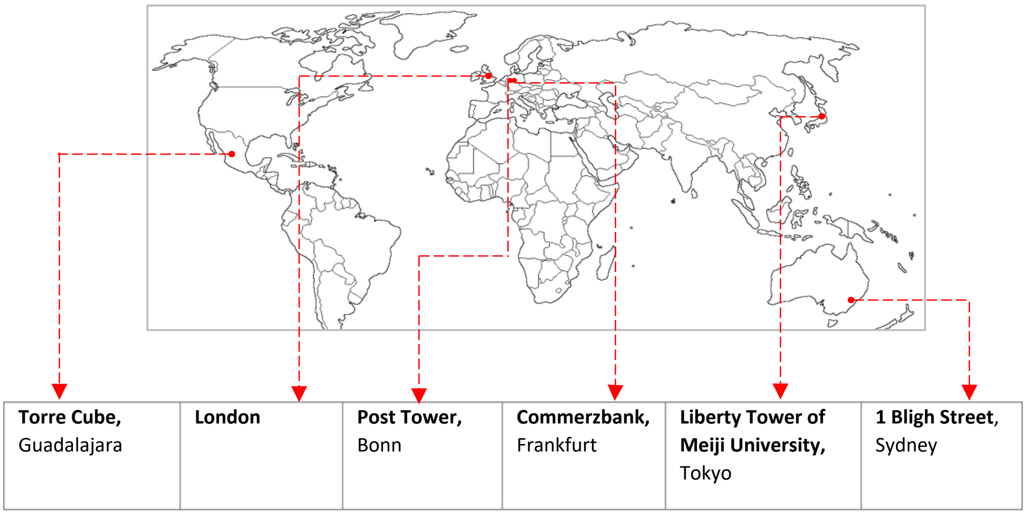


Figure 3-2. Map showing locations of selected high-rise office buildings

Table 3-2. Skycourt attributes in selected high-rise office buildings

Skycourt Characteristics		**Commerzbank,** Frankfurt, Germany	**Liberty Tower of Meiji University,** Tokyo, Japan	**Post Tower,** Bonn, Germany	**Torre Cube,** Guadalajara, Mexico	**1 Bligh Street**, Sydney, Austria
Description	Description of skycourt	Three 4-storey stepped sky- gardens at each segment	Wind floor (one 1-storey sky-garden at floor no. 18 with openings on the four sides and three V-shaped glass screens (wind fences) to prevent outdoor air from disrupting occupants	Three 9-storey sky-gardens at each segment and one 11-storey sky-garden at the upper segment	One 4-storey Two 3-storey stepped sky gardens	One 1-storey sky-garden floor at floor no. 15/ mid-height of the atrium One 10 m high at the top
	Total number	12	1	4	3	2
Type /style	Sky-roof/ garden					1 (top floor/ 10 m height)
	Sky- terrace/ balcony					
	Skycourt/ floor	3 each village/segment	1	Three 9-storey and one 11-storey	1 each office wing (3 wings)	1 (floor no. 15)
Function	Social space	√ yes		√ yes	√ yes	√ yes
	Psycho-hysiological /wellbeing (thermal comfort and visual) enhancer	√ yes				
	Transitional space	√ yes	√ yes	√ yes	√ yes	√ yes
	Environmental filter	√ yes				
	Biodiversity enhancer					

Skycourt Characteristics		Commerzbank, Frankfurt, Germany	Liberty Tower of Meiji University, Tokyo, Japan	Post Tower, Bonn, Germany	Torre Cube, Guadalajara, Mexico	1 Bligh Street, Sydney, Austria
Function	Passive design element (means for reducing the energy consumption)	√ yes	√ yes	√ yes	√ yes	√ yes
	Income generator					
	Productivity enhancer	√ yes				
Spatial configuration	Hollowed-out space	√ yes			√ yes	√ yes
	Corner space			√ yes		
	Sided space	√ yes				
	Interstitial space		√ yes			
	Chimney					
	Infill space			√ yes		

Most of these buildings are located in London, these are: the Shard, Heron Tower, Leadenhall Building, 30 St. Mary Axe, Broadgate Tower, 20 Fenchurch Street, 51 Lime Street, the Lloyds Building, Rothschild Bank headquarters, 6 Bevis Marks and 10 Brock Street (Figure 3-3). The tallest building is the Shard with approximately 304 m height (75 floors); the offices occupied the lower part of the tower (floors numbers 2 to 28). The lowest height building is 10 Brock Street of 72 m height (Table 3-3).

Other buildings are the Commerzbank in Frankfurt; the Liberty Tower of Meiji University in Tokyo; and the Post Tower in Bonn (Figure 3-2, and Table 3-2).

The Shard	Heron Tower	Leadenhall Building	30 St. Mary Axe	Broadgate Tower	20 Fenchurch Street
51 Lime Street	The Lloyds Building	Rothschild Bank Headquarter	6 Bevis Marks	10 Brock Street	

Figure 3-3. Map showing locations of the selected buildings in the second stage – London

Table 3-3. Skycourt attributes in the selected high-rise office buildings in London

Skycourt		**The Shard**	**Heron Tower**	**Leadenhall Building**	**30 St. Mary Axe**	**Broadgate Tower**	**20 Fenchurch Street**	**51 Lime Street**	**Lloyds Building**	**Rothschild Bank**	**6 Bevis Marks**	**10 Brock Street**
Type/Style												
Sky-roof/ garden	Quantity	[1]	[3]			[1]	[1]			[1]	[2]	[1]
	Floor(s) No.	(73-75)	(36), (39), (45)			(35)	(36-38)			(11)	(15), (16)	(9)
Sky-terrace/ balcony	Quantity	[50]			[5] /floor		[1]				[1] (11)	
	Floor(s) No.	[26]: (floors 1-26): winter gardens, [24]: (floors 53-65)			(5-36)		(36)					
Skycourt	Quantity	[2]	[10]	[5]		[1]			[1]	[3]		[2]
	Floor(s) No.	(31-33) restaurant (68-72) observatory	[1]: (floors 4-9) [9] (10-36)	(46-47), (48), (49), (50), (51-52)		(34-35)			(0-14) atrium	(1), (11), (15)		(0), (2-15)
Sky-entrance	Quantity	[1]	[1]	[1]	[1]	[1] (	[1]	[1]		[1]	[1]	[1]
	Floor(s) No.	(0)	(0-3)	(0-4) galleria	(0-1)	0-7)	(0-2)	(0-2)		(0)	(0)	(0)
Total Number		54	14	6	6	3	3	1	1	5	4	4

Skycourt	**The Shard**	**Heron Tower**	**Leadenhall Building**	**30 St. Mary Axe**	**Broadgate Tower**	**20 Fenchurch Street**	**51 Lime Street**	**Lloyds Building**	**Rothschild Bank**	**6 Bevis Marks**	**10 Brock Street**
Function											
Social space concerning the different levels of interaction between people (Floor(s) No.)	√	√	√	√	√	√	√	√	√	√	√
Psycho-physiological well-being (thermal comfort and visual) enhancer (Floor(s) No.)	√				√	√				√	
Transitional space (Floor(s) No.)	√	√	√	√	√	√	√	√	√	√	√
Environmental filter (greenery)	√	√	√			√				√	√
Biodiversity enhancer			√								
Passive design element (means for reducing the energy consumption) (Floor(s) No.)	√	√	√	√	√			√	√	√	√
Income generator (Floor(s) No.)	√	√	√	√	√	√			√	√	
Productivity enhancer (Floor(s) No.)	√	√	√	√		√			√	√	

Skycourt	The Shard	Heron Tower	Leadenhall Building	30 St. Mary Axe	Broadgate Tower	20 Fenchurch Street	51 Lime Street	Lloyds Building	Rothschild Bank	6 Bevis Marks	10 Brock Street
Spatial Configuration											
Hollowed-out space (Floor(s) No.)		√ (0-3) (4-9) (10-12) (13-15) (16-18) (19-21) (22-24) (25-27) (28-30) (31-33) (34-36)	√ (46-47) (48) (49) (50) (51-52)	√ (0-1) (5-36)		√ (36)				√ (0)	√ (16)
Corner space (Floor(s) No.)	√ (1-26) (53-65)								√ (15)		
Sided space (Floor(s) No.)			√ (2-4)		√ (0-7) (34-35)	√ (37-38)	√ (0-2)		√ (11)	√ (11)	√ (9)
Interstitial space (Floor(s) No.)	√ (0) (31-33) (68-72) (73-75)			√ (40)	√ (35) roof	√ (0-2)				√ (15)	√ (0)
Chimney (Floor(s) No.)								√ (0-14)		√ (16)	√ (2-15)
Infill space (Floor(s) No.)		√ fragmented (36) (39) (45)							√ (0) (1)	√ (16)	√ (9)

3.2.2 Overview of Skycourts in High-Rise Office Buildings in London and Other Temperate Climate Regions

According to the research study investigations, a skycourt that is located between the floors of the building is the most common type in office buildings, then the sky-roof and sky-entrance. The sky-terrace is common in residential typologies rather than offices. The skycourt is positioned mostly between the office zones and the external walls.

The location of skycourts is connected with its function; for example, skycourts on the middle floors of the building could enhance occupants' interactions and provide natural light and fresh air; skycourts on upper floors function as viewing desks. Skycourts could separate the different zones in the mixed-use typologies. The sky-roof spaces are mostly used as viewing desks and contain restaurants and cafes, and are open to public, such as those situated at 6 Bevis Marks and 20 Fenchurch Street. Sky-roofs have greenery landscape in almost all the cases. They were found fragmented as infill or stepped levels. Sky-entrances are frequent in the large tall buildings. They connect the building with the outdoor context (the public realm in some cases) and provide prestigious lit entrances for buildings such as the Leadenhall, Broadgate and 51 Lime Street. They contain transitional elements and support the contact between people. These spaces are of multi-storey height interstitial or hollowed out of stepped levels. Sky-terraces function as private verandas for the residential units, such as in the case of the Shard Tower, or are found as parts of skycourts.

The hollowed-out space is widely used as a spatial configuration (prototype) for skycourts in the selected cases (Figure 3-4). This is defined as a glazed void connected with the exterior by one edge of the building. Other prototypes include the two-edged (corner), three-edged (sided) prototypes. The Heron Tower, the Leadenhall Building, 30 St. Mary Axe, the Commerzbank and Broadgate Tower are examples of buildings that hold these prototypes. Moreover, the hollowed-out form was found to be the most common spatial configuration (prototype) of skycourts worldwide in several climatic regions, such as the National Commercial Bank, Jeddah; Lotte Tower, Seoul; Genzyme Centre, Massachusetts; ACROS Fukuoka Prefectural International Hall, Fukuoka.

The four-edged (interstitial) skycourt was also found in temperate cases such as the upper skycourts of the Shard, the Leadenhall Building, 30 St. Mary Axe and the Broadgate Tower.

However, this prototype functions significantly as an observation desk and viewing space to the city.

Infill skycourts are found in Rothschild Bank building and Post Tower. Stepped organisation, which consists of multi-skycourts, defines the skycourts in 30 St. Mary Axe starting from floor number 5 to floor number 36 and the Commerzbank buildings. However, the skycourt space in these buildings has a hollowed-out configuration. In addition, a stepping pattern defines the sky-entrances of the Leadenhall and the Broadgate buildings as well as the sky-roof and sky-terraces of the 20 Fenchurch Street and the 6 Bevis Marks. The skycourt as a chimney is not common, yet it is found in the Lloyds Building and 6 Bevis Marks as a central atrium.

The hollowed-out skycourt could be classified into two patterns; one involves an atrium and the other does not contain an atrium (Figure 3-5). Most of the sample buildings in London integrate the second pattern, in which the skycourt is not connected with an atrium, such as the spaces found in Heron Tower, 30 St. Mary Axe, the Leadenhall Building, 20 Fenchurch Street, 51 Lime Street and 10 Brock Street. The other pattern is found in other temperate climate regions such as the skycourts of Commerzbank and Post Tower buildings.

The skycourt configuration along the vertical section in buildings located in London shows that the height of the skycourt ranges between two-floor to six-floor (Heron Tower, Leadenhall Building, Broadgate Tower, 20 Fenchurch Street). Nine-floor height is found in buildings in temperate climates such as in the case of the Post Tower in Bonn. However, this height is not recommended because of problems related to control of airflow (Wood and Salib 2013).

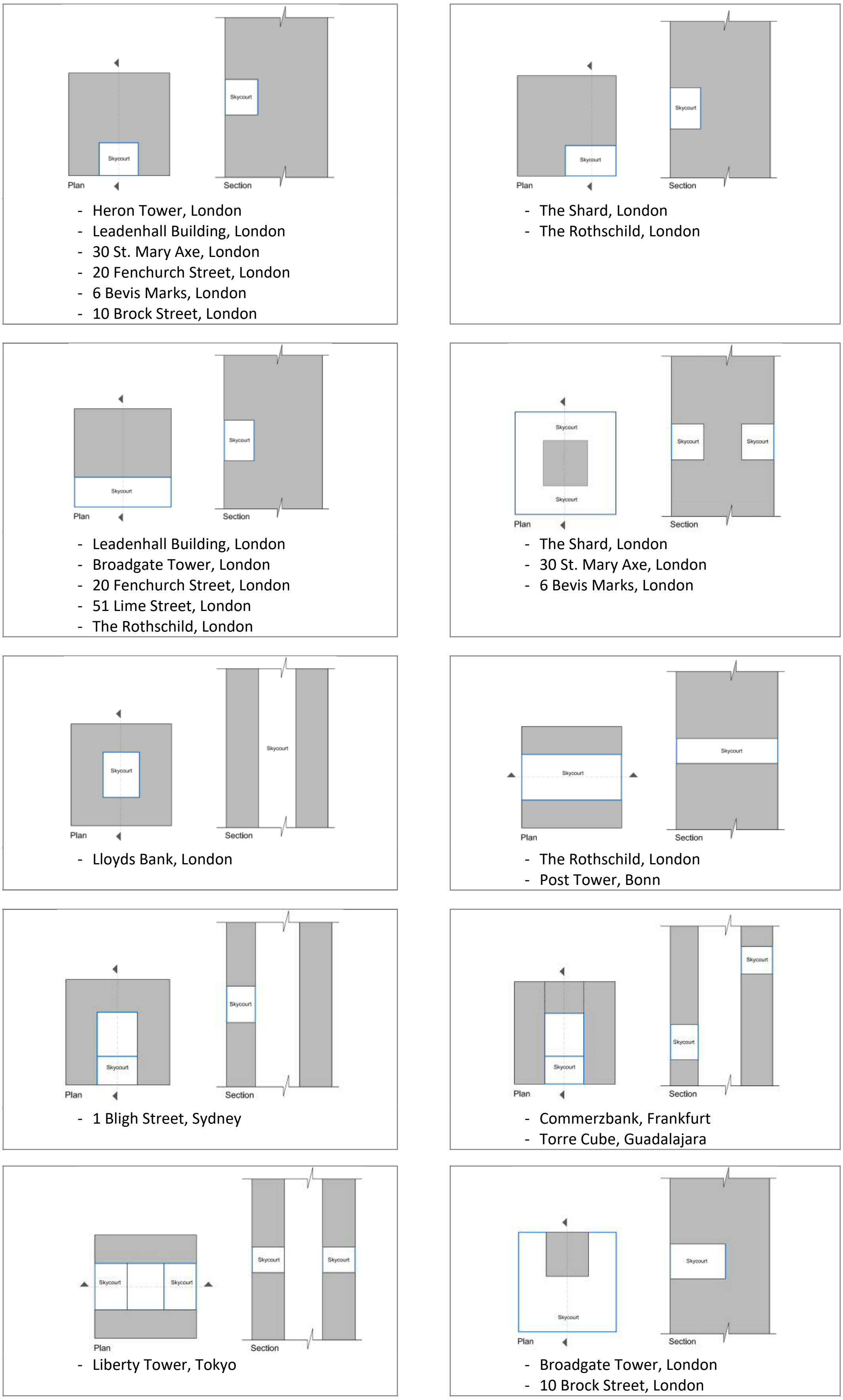


Figure 3-4. Patterns of skycourts in high-rise office buildings (the white shading defines skycourts)

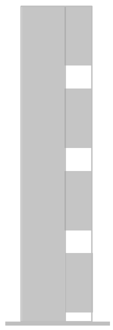
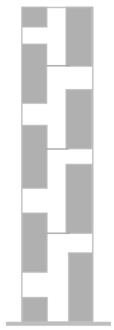
Pattern	A	B
Solid - Void		
	. Hollowed skycourt . No atrium	. Hollowed skycourt . Connected to an atrium

Figure 3-5. Patterns of skycourts in terms of vertical section based on the sample buildings

3.3 CONCLUSIONS FOR THE STUDY

An investigation of skycourt prototypes in existing buildings was described. These cases show potentials of adequate performance in previous studies. The study filtered standard features for the design of skycourts, including spatial patterns, geometry, and functions. These affect the thermal and energy performance of skycourts in high-rise office buildings. The following points are highlighted:

(i) The importance of considering the local climate conditions during the design of skycourts to facilitate a holistic sustainable design and performance of high-rise buildings.

(ii) The skycourt is partially occupied; it is used mostly as a transitional and interaction zone located between the inside and the outside (a buffer zone).

(iii) Skycourts have significant environmental benefits, and thus can contribute to improve the overall performance of high-rise office buildings depending on the climate context. However, there are limited investigations about potentials of such elements in the energy performance of the total energy consumption. The percentage of the annual energy saving for buildings is a result of a combination between several design features and systems, such as building form, façade, vertical segmentation, atrium, internal layout, shading devices, landscape, building management system, and human behaviour.

(iv) The skycourt is a multi-storey area with full-height glazed facades in London. The skycourt, which is located between floors, is widely integrated in high-rise office buildings. In addition, the hollowed-out layout is the most common prototype of skycourts. This buffer zone is connected to the exterior by one edge. Other prototypes include two-edged (corner), and three-edged (sided) forms. The four-edged prototype, which is constructed mostly at the top of mixed-use buildings as a conversation desk for the public, is not commonly used by occupants. In addition, it is not connected with office zones.

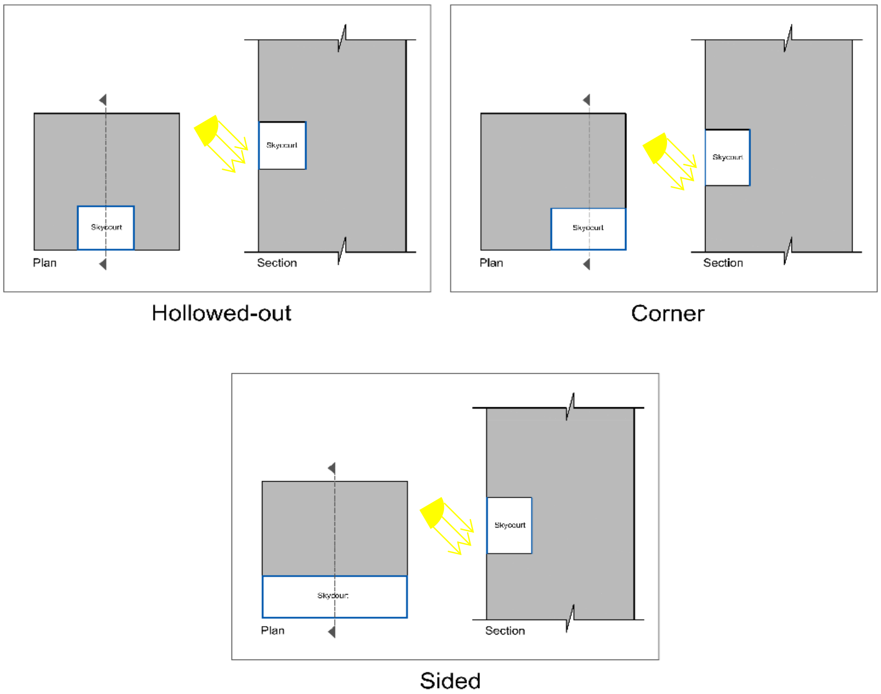


Figure 3-6. Prototypes of skycourts as a buffer zones in office high-rise buildings in London

(v) According to the findings of this phase of the research, the most common prototypes of skycourts in high-rise office buildings in London were defined. These are as follows: the hollowed-out, the corner and the sided skycourt. Accordingly, the hypothetical models will be formulated for skycourts. A skycourt is considered as an integrated transitional buffer space located at the mid-level of an office building in London. Further details about setting up the hypothetical building are discussed in the next chapter.

The next chapter will describe the method that is carried out to test the research assumption and the research design that is created to fulfil the research questions of the present study.

CHAPTER FOUR: METHODOLOGY AND RESEARCH DESIGN

4 METHODOLOGY AND RESEARCH DESIGN

4.1 INTRODUCTION

As declared in chapter two, the method of simulation will be used as the method to fulfil the study questions of energy and thermal predictions. The method of simulation is selected to test the influence of skycourts as a transitional buffer zone. Three prototypes of skycourts are considered in this research study: the hollowed-out, the corner, and the sided forms. Simulations were carried out to answer the following objectives. Firstly, to explore the impact of integrating an air-conditioned skycourt into a high-rise office building. Secondly, to examine the influence of the skycourt when it is an unheated and uncooled zone. Thirdly, to investigate the effect of key design parameters of skycourts on the performance of the unheated/uncooled skycourts. Finally, to optimise the design of these skycourts.

This chapter introduces the simulation approach and software that are selected for the present study. It also describes the research design that is constructed to accomplish the above objectives. This includes setting up the hypothetical model that is adopted in the study; criteria for assessing the assumption of the study; the simulation settings; and stages of the simulation. Finally, the approach that is used for presenting the simulation results is defined.

4.2 THE COUPLING MODELS APPROACH: BUILDING ENERGY SIMULATION AND COMPUTATIONAL FLUID DYNAMICS

Generally, simulation methods in construction could be classified into two modules: (i) Building Energy Simulation (BES); and (ii) Computational Fluid Dynamics (CFD).

BES stands on the principles of energy (heat) balance equations that consider the internal heat transfer between the air in the space and surfaces. These include energy balance equations for the space air, for the surface (e.g. wall and window), and for radiative heat flux (Zhai *et al.* 2002). Therefore, BES can provide thermal and energy analysis for the whole building and the HVAC systems, such as mean air temperature, air velocity, in addition to heating, cooling, ventilation, solar, and fabric loads. This simulation can be obtained on an hourly basis for the whole year.

However, BES assumes air to be well-mixed. Therefore, it is unable to provide detailed predictions of spaces' indoor air properties, such as the distribution of air velocity and temperature, relative humidity and contaminant concentrations (Zhai and Yan 2003).

CFD has been recently recognised as the most accurate and detailed model among the airflow models. CFD stands on numerical techniques to solve the equations for the fluid flow, the mass of containment species, thermal comfort and the indoor air quality analysis. It can solve these aspects by dividing the spatial continuum into cells among a grid, which requires iterations to achieve a converged solution (Zhai *et al.* 2002). Therefore, it can provide detailed predictions for indoor air properties, such as the distribution of air velocity and temperature, internal and external airflows, and contaminant concentrations (Barbason and Reiter 2014).

On the other hand, fully CFD simulation requires long calculation times. Furthermore, airflow models need thermal and flow boundary conditions that can be obtained from BES.

Thus, it is argued that integrating BES and CFD together can produce complementary information about energy consumption and indoor thermal conditions for buildings. Moreover, it is agreed that the coupled simulation can predict results that are more accurate, detailed and quick compared to the separate simulation (Barbason and Reiter 2014; Zhai and Chen 2005; Wang and Wong 2008).

Recently, a trend for carrying out building thermal and energy simulations in buildings has been established in scholarly database. This approach is known as the “coupling models”, which refers to the interrelation of two models. Coupling simulation is highly recommended in ventilation studies due to its accuracy and efficiency. It can improve predictions about cooling and heating loads by at least 10% (Zhai *et al.* 2002). Furthermore, it can reduce the simulation time and its requirements. For example, a full CFD requires about 12 hours to be completed using parallel workstation, while a coupling

CFD requires less than one hour using a 1 Gbytes computer to evaluate the same indoor environment (Wang and Wong 2009).

Integration between BES and CFD has been optimised with other methods such as numerical methods, theoretical analysis and experimental work. That is exemplified in the works undertaken by Barbason and Reiter (2014); Cropper *et al*. (2010); Wang and Wong (2008); and Bartak *et al*. (2002). The validation process in these studies showed that the iteration between BES and CFD produces correct and converged solutions, and informs accurate and efficient predictions for thermal and airflow patterns in a short time of execution. Consequently, coupling models can be considered as an advanced simulation tool to test the built environment.

The coupling approach stands on providing the interior surface temperatures and the heat extraction rate that are obtained from the BES model, to the CFD model, so the airflow simulation can calculate specific air thermal conditions. The CFD model can receive more exact and real-time internal thermal conditions. Therefore, it can predict the dynamic indoor thermal conditions. This procedure is essential for the assessment of indoor air quality and thermal comfort. Moreover, the BES model can obtain a more accurate convection heat transfer coefficient from the boundary envelope. This process produces more precise calculations for energy demands, and full thermal behaviours for the building enclosure. In addition, using this mechanism of integration can eliminate the few assumptions that are handled via each separate application, and reduce the computational time of CFD (Wang and Wong 2008), (Figure 4-1).

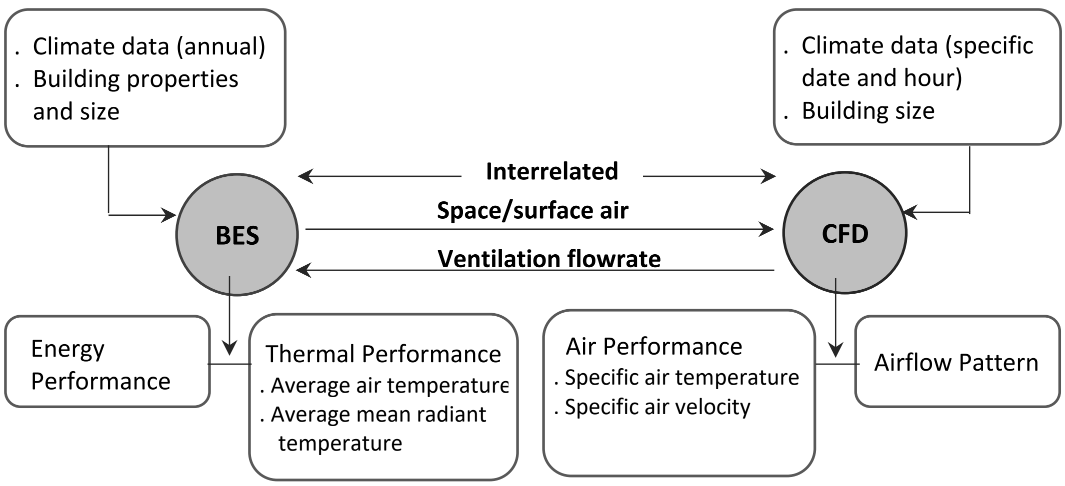


Figure 4-1. BES and CFD coupling models

There are two major approaches for coupling energy and CFD simulations: static coupling and dynamic coupling. However, Zhai *et al*. (2002) distinguished a third strategy for coupling simulation, known as bin coupling. The static coupling process includes a one-step or two-step data exchange between BES and CFD programs. The process can be performed manually with a few coupling iterations and does not require hard modifications of the individual BES and CFD programs. On the other hand, the dynamic coupling process requires continuous coupling between BES and CFD at each time step. This method may occur in a one-time step, quasi-dynamic or full-dynamic steps. The one-time-step focuses on the coupling at one specific time step of interest. At that point step, the iteration between BES and CFD is carried out to reach a converged solution. However, coupling might happen without iteration at each time step in a period such as in the quasi-dynamic. In this type, the CFD simulation obtains the boundary conditions from the previous BES calculation at the specific time step, then returns the thermal information of indoor air to BES of the next time step. The full-dynamic coupling involves iteration between BES and CFD to reach a converged solution at each coupling time step before moving on to the next step. In the bin coupling process, BES receives information that is pre-calculated by CFD and saves it in the bins to be used for subsequent energy computation.

Generally, approaches for exchanging data between BES and CFD models may be classified into three methods based on the type of data transfer. In the first method, the indoor surface temperatures transfer from BES to CFD, then the convective heat coefficient and indoor air temperature from CFD to BES. The second approach considers transferring the indoor surface temperature from BES to CFD, and then convective heat flux from CFD to BES. The third method includes transferring interior convective heat flux from BES to CFD, and then returns convective heat coefficient and indoor air temperature gradients from CFD to BES. Method one is considered the most appropriate one due to its stability. However, method two is the most expensive since it requires explicit BES and implicit CFD models. Method three is not recommended since it is unable to control the air temperature during the exchanging process (Zhai and Chen 2005; Zhai and Yan 2003).

In order to choose a tool for this study, there are main factors for consideration. These include availability of facilities, advantages of the tool, experience of the user, in addition to cost and time consuming. There are several simulation software, such as Design Builder, Energy Plus, ESP-r with ANSYS Fluent, Grasshopper with Ladybug, and HTB2 with

WinAir that have capabilities for producing energy simulation and CFD calculations using coupling approach and exchanging data based on transferring indoor surface temperatures from BES to CFD.

Industrial graphic interface tools, such as Design Builder, which are considered user-friendly software, require extra attention as these tools include default settings and values that allow the tool to run simulation and provide results without knowing a lot of details (Myers 1995).

HTB2, the energy simulation, and WinAir, the CFD tool, are numerical models that have advantages of flexibility and ease of modification. In these text–based interface tools, users type commands' lines, and the operating system responds to those commands. Although text-based method is determined an old method in modern industrial simulation tools and may require repeat of modelling process, several advantages are found for such a method. These include creating faster output results (Chi et al. 2017) without the need to high memory or high processing computer devices (Singh and Sivaswamy 2010). Therefore, text–based interface tools provide an opportunity to develop understanding of building physics, which makes them well suited for use in this study. In addition, HTB2 calculates heat transfer through a complete layered building surface that makes it as the best choice for simulating heating and cooling loads for energy demand simulation analysis (Alexander 1996). The next section describes these tools in details and discusses the process of coupling the two tools.

4.2.1 Integrating HTB2 and WinAir

HTB2 software (version 10) was used to inform thermal performance and energy efficiency, while WinAir (version 4) was adopted as the CFD simulation to inform the ventilation performance inside the skycourt. These two programs were developed by Welsh School of Architecture (WSA), Cardiff University.

HTB2 is a numerical model that can predict the indoor thermal performance, and estimate the energy demands for buildings during both the preliminary design stage and occupancy period (Lewis and Alexander 1990). HTB2 is recommended due to its high validity since it has been developed over thirty years. Furthermore, it has undergone a series of broad testing including the IEA Annex 1 (Oscar Faber and Partners 1980); IEA Task 12 (Lomas *et al.* 1994); and IEA BESTEST (Neymark *et al.* 2011). Also, it has been validated under the

American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) standards and used to develop benchmarks for other standards (Alexander and Jenkins 2015). In addition, HTB2 has flexibility and ease of modification, which makes it well suited for use in the field of energy efficiency and sustainable design of buildings (Xing *et al.* 2012).

Generally, the required input data for HTB2 include the weather data for the research context, the building model, and the design conditions. The input files in the HTB2 model are text files that describe the building, its services, its operation and its environment. In addition, these descriptions include information to control the simulation itself, such as the duration of the simulation. These files are structured in hierarchical order into three levels according to their functions (Alexander 1996), (Figure 4-2). The top file defines run parameters of the simulation including the length of the time step, the run length, the subsystem to be used, the name of the data file that is used from the second and the third levels, and the output required files. The second level files define the main subsystems including the physical building, its services and incidental gains, scheduling information, and the external conditions. The third level describes characteristics of the subsystems, including the building material thermal properties, the construction of materials, the building layout, the heating system characteristics, the lighting gain characteristics, the small incidental sources of heat, the occupancy characteristics, the ventilation properties and the daily usage patterns.

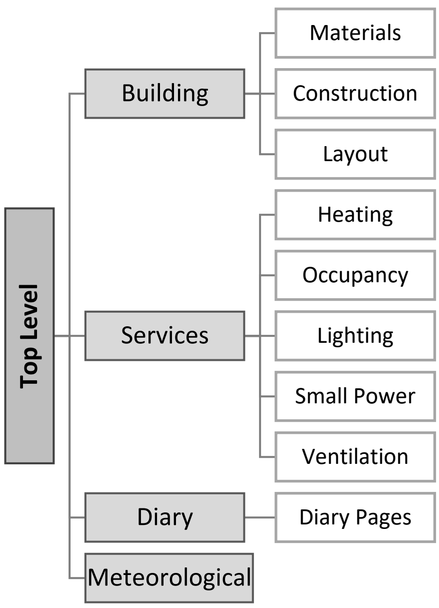


Figure 4-2. Structure of HTB2 hierarchy input data file

Source: Alexander (1996)

The output data files of the HTB2 model are very flexible; they may hold average daily, monthly or yearly conditions. These data are categorised into thermal conditions and energy performance. The thermal results include internal air temperature, mean radiant temperature, the temperature of the surfaces. The energy performance is embodied by the total physical solar entry through transparent openings (solar gain), the total energy movement due to infiltration and ventilation (ventilation gain), the convective part of the fabric transfer only, the across "internal" surfaces of space (fabric gain) and the estimation of the total of all cooling and heating systems to the space. The output information could be in the form of power (W) or energy (kWh) (Alexander 1996).

WinAir has been developed for conducting ventilation research to predict airflow distribution, air temperature and air velocity. However, it is not commercially available yet. It is generally considered reliable; several ventilation studies have been performed by WinAir and showed accuracy in results. Examples of such studies for existing projects carried out by research teams in WSA, Cardiff University, include: (i) Residential block, Zurich; (ii) Dock B, Zurich; (iii) Inselspital, Bern; and (iv) Train station, Olten.

In addition, WinAir can be used to perform CFD analysis and calculate the airflow for other programs, such as ECOTECT, which is unable to carry out such calculations, and then import the results back into ECOTECT. The code uses the standard K-epsilon (κ-ε) turbulence model for the prediction of the airflow. Despite the mentioned advantages, WinAir has certain limitations. It was designed mainly as an application that can only analyse a single wind direction and a single wind speed at a time, which is a shortcoming in comparative studies. Therefore, WinAir may be more suitable for ventilation simulations rather than the more general-purpose codes (Gelil and Badawy 2015). However, the use of WinAir is appropriate for the aim of this study (Figure 4-3).

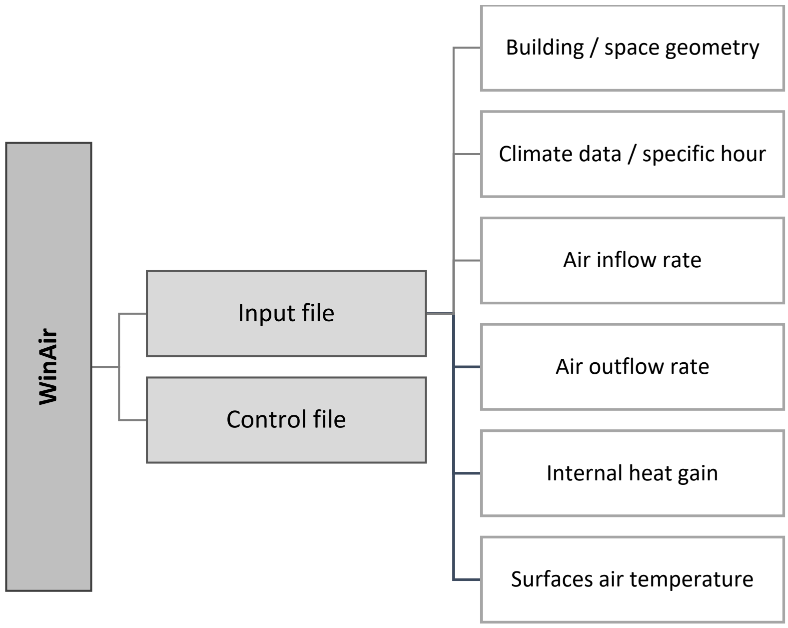


Figure 4-3. Structure of WinAir data file

The climate data relates to a specific time at a specific date. In the simulations, the measured mean surface temperatures of the surfaces in the space are considered as boundary conditions. CFD geometry is defined in blocks of topics. When a case is loaded, the following information is provided for the whole domain:

- Domain Active Volume: the total volume of the unblocked cells, in m^3;
- Forced Inflow: the total of fixed inlet flows, in kg/s;
- Total Outflow: the total of fixed outlets, in kg/s;
- Total Heat Gains: the total of fixed heat gains, kW;
- Total Heat Loss: the total of variable heat gains, ΣUA, kW;

The output data comprises mass and energy inflow and outflow results. These are categorised in three panels. The first is the mean panel that displays average field data for the region including air temperature, and air velocity. The second is the flow panel, which displays flows in and out of the region. The third, the energy panel, displays the energy flows in and out of the region including fixed gain/loss heat sources, pressure boundaries and fabric.

Coupling HTB2 with WinAir can accomplish graduated and accurate information about the air temperature, air velocity and air concentration. In addition, it can show the airflow pattern (Jones and Kopitsis 2001; Jones and Kippenberg 2000). In the present study, HTB2 and WinAir models were coupled to investigate the thermal conditions in the skycourt.

The WinAir input data are established from previously calculated values using the HTB2 model, including temperatures of the internal surfaces, heat gain, heat loss, and air inflow and outflow rates. Figure 4-4 illustrates the HTB2 and WinAir coupling approach conducted in the study.

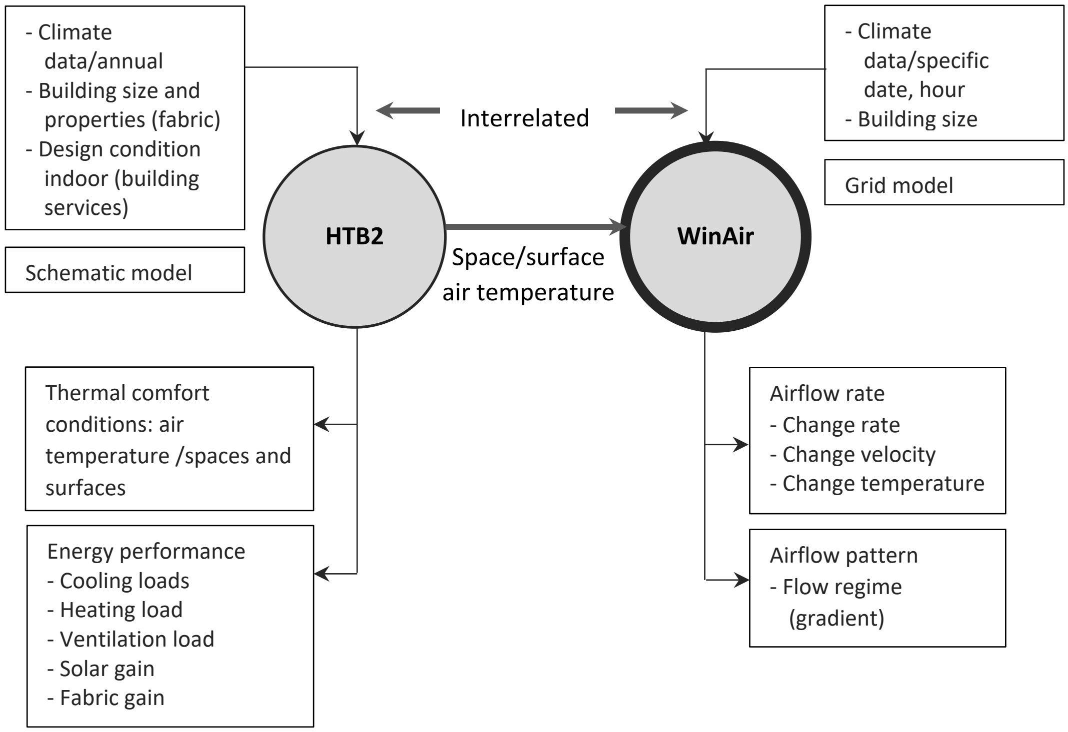


Figure 4-4. HTB2 and WinAir coupling models

In this study, an external coupling was adopted to ensure accurate predictions of the indoor environment for the skycourt, and to reduce the time taken by calculations. Therefore, two models were built separately in HTB2 and WinAir. A schematic model was developed in HTB2 to predict the thermal conditions inside the skycourt space and the energy consumption for the heating and cooling of the building. This considers that the skycourt space consists of two zones; lower zone (from skycourt floor to 3m height) and upper zone. Furthermore, a grid model was built in WinAir to investigate in details the airflow – air temperature and velocity.

Data exchange for boundary conditions is needed to bridge the two programs. The static coupling strategy is used to couple the two simulations. Thermal conditions for CFD (WinAir) simulations were obtained from previously calculated values from the energy modelling software (HTB2). These include the internal surfaces' temperature, the inlet (supply) air, the outlet (exhaust) air, and the internal heat gains involved inside the skycourt. Then, the resulting temperature from the WinAir simulation was compared with the average skycourt temperature from BES to measure the predicted temperature difference.

4.3 SETTING UP THE MODEL

The simulation model is the overall system that simulates the reality being studied (Groat and Wang 2013). The easiest method to assess improvements in building design is to compare the performance with a reference case (Ternoey *et al.* 1985). In the present research study, the simulation models were formulated for the purpose of testing the assumption and achieving the research objectives. The hypothetical models were established based on two issues. Firstly, design guidelines for office buildings that represent the typical characteristics of high-rise office buildings in London. Secondly, findings extracted from the previous phase of the research regarding the spatial configurations (prototypes) of skycourts.

4.3.1 Establishing the Hypothetical Building for the Study

The hypothetical model is an office building of 150 m height, as this is commonly found in the cities of Europe, including London (Fazlic 2008). Characteristics of the building layout and plan details were defined based on the design guidelines suggested by the British Council for Offices (BCO). The floor layout is open offices; the distribution of columns is based on a planning grid of 7.5 m × 7.5 m. The height of each floor is 3 m (BCO Guide 2014), (Figure 4-5 and Table 4-1).

The floor layout of the offices contains the following elements: (i) the core and (ii) the office zones. The core is located at the centre of the layout and includes the operational components of the building that provide vertical circulation, toilets, and distribution of mechanical, electrical and plumbing services. The office zones are distributed according to the density of occupation.

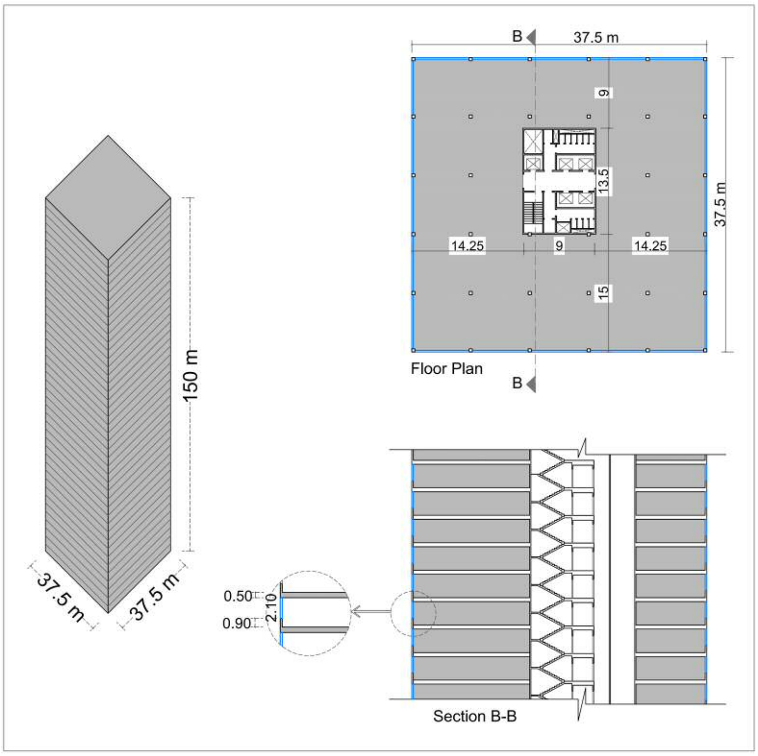


Figure 4-5. Hypothetical office model layout without skycourt for the study

Table 4-1. Guidance for space configuration for office buildings

Building Elements		**Specifications according to BCO Guides (2009 and 2014)**
Deep plan	Window to window (or atrium)	15–21 m
	Window to core	6–12 m
Floor to ceiling	New-build	2.75 m or 3 m
Grids	Planning grid	1.5 m × 1.5 m
	Column grid	7.5 m, 9 m or 12 m
Circulation	Percentage of primary circulation to net internal area (NIA)	15% to 22%

Source: BCO Guides (2009 and 2014)

Dimensions of the floor plan are fixed in all cases (37.5m × 37.5m). In addition, the core and escape stairs dimensions are fixed. These are the following: the area of the core is 121.5 m^2 (9 m length, and 13.5 m depth). The total gross area (GIA) of the office zones on each floor equals 1284.75 m^2.

4.3.2 Establishing the Reference Models that Included Skycourts

According to phase two of this research (chapter three), three main spatial configurations (prototypes) of skycourts were found to be widely constructed in the research context. These are: the hollowed-out space, the corner space and the sided space (Figure 4-6). These prototypes reveal the function of the skycourt when it acts as a buffer zone between the inside (the air-conditioned office zones) and the outside (the external environment). They are connected with the outdoors by a one-edged (hollowed-out) skycourt, a two-edged (corner) skycourt, and a three-edged (sided) skycourt. In addition, they are located at the mid-level of the building. Therefore, three reference models were developed to present these three protytypes of skycourts. These are as follows

- Prototype (A) model, which represents the office building with a hollowed-out skycourt;
- Prototype (B) model, which represents the office building with a corner skycourt;
- Prototype (C) model that represents the office building with a sided skycourt.

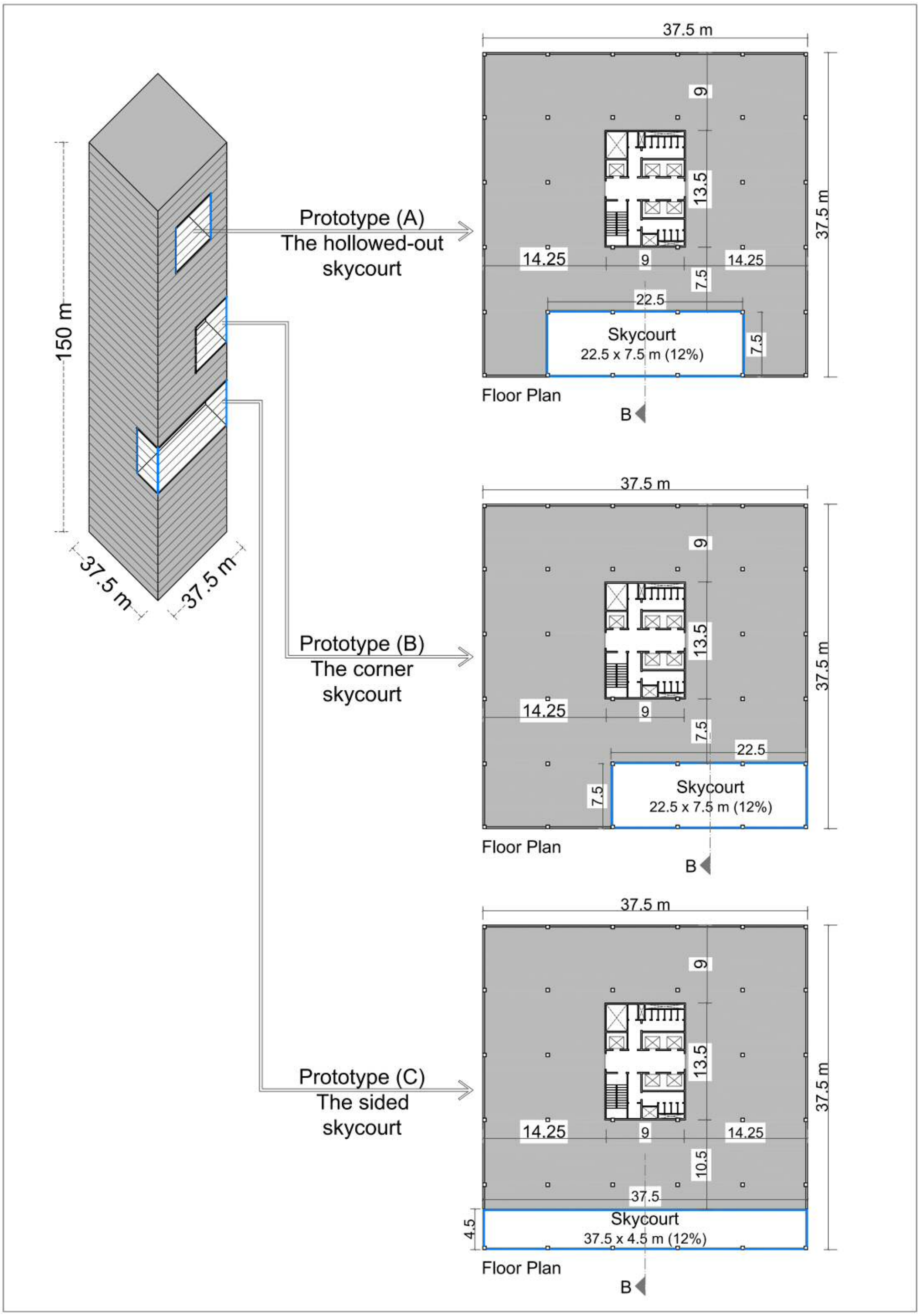


Figure 4-6. Prototypes (spatial configurations) of skycourt models considered in the study: (A) hollowed-out, (B) corner, and (C) sided prototypes

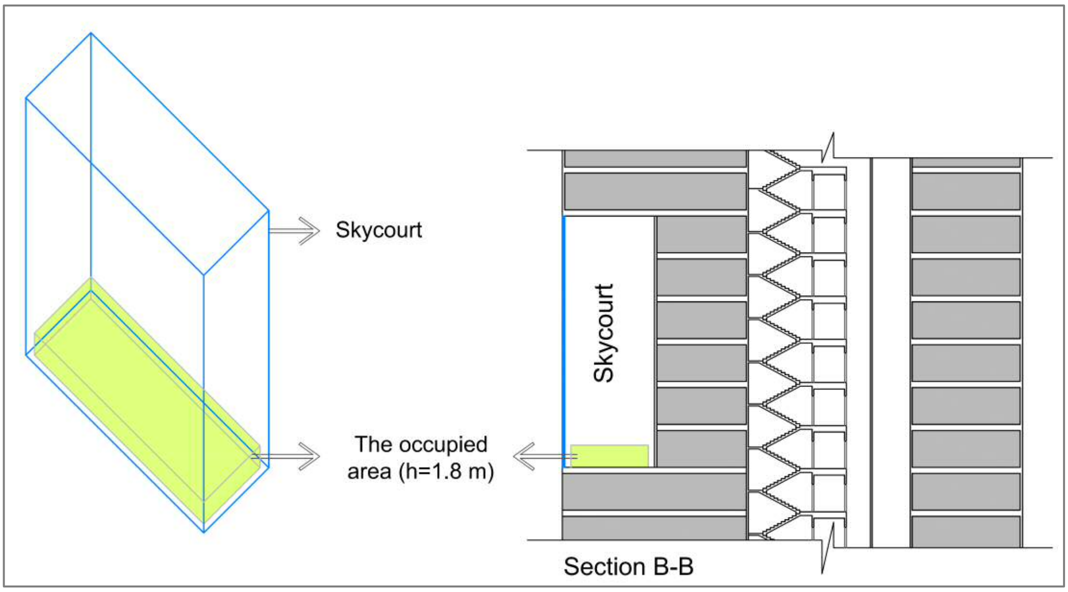


Figure 4-7. Section for the skycourt showing the occupied area

The area of the office floor was defined based on the required percentage to the net internal area of the floor, and the floor plate efficiency. The plan efficiency (NIA: GIA) is the ratio of the net internal area (NIA) to the gross internal area (GIA). For a typical office floor plan for a building up to nine floors in height, the plan efficiency should be between 80% and 85%. The considered elements in the suggested floor plan are the core, and the skycourt. The percentage of the core to the net internal area equals 8%. This means that the maximum area of the skycourt should not exceed 12% of the net internal area of the floor, which equals 168.75 m^2. Accordingly, the office area on each floor for the reference models equals 1116 m^2. However, dimensions of the skycourt differ in the reference cases based on the prototype. In reference case (A), the hollowed-out skycourt, the skycourt is of 22.5 m length and 7.5 m depth. For the corner skycourt, reference model (B), the length and depth are the same as model (A). Dimensions for the sided skycourt, model (C), are 4.5 m in length and 37.5 m in depth. Table 4-2 shows the geometry of each element in the reference and base cases of the study.

To reduce the simulation time needed for each simulation run, the simulation was not conducted for the entire high-rise building. The reference models were constructed to include the skycourt section. This process can also help easy recognition of any problem in the modelling process or domain settings, since the height of the skycourt is limited to a specific number of floors. An eight-floor height for the building was used in the study, as a six-floor height is common for skycourts in the research context. The section of the reference models includes the skycourt, the floors of the adjacent offices of the skycourt, the office floors above the ceiling of the skycourt, and the office floors below the floor of the skycourt (Figure 4-7). The upper floor, the lower floor, and the core were set up as constant temperature blocks, as no heat is assumed to be transferred through the interior spaces. In addition, the skycourt was set up at the south façade at the mid-part of the building.

Table 4-2. Geometrical properties of the reference models per floor

	Height	Floor Plan Dimensions	Core Dimension	Office Area	Skycourt Dimension	Skycourt Area (12% to GIA)
Hypothetical model without skycourt	Six-floor	37.5 × 37.5 m	9 × 13.5 m	1284.75 m^2	-	-
Reference model A: with skycourt prototype (A)	Six-floor	37.5 × 37.5 m	9 × 13.5 m	1116 m^2	22.5 × 7.5 m	168.75 m^2
Reference model B: with skycourt prototype (B)	Six-floor	37.5 × 37.5 m	9 × 13.5 m	1116 m^2	22.5 × 7.5 m	168.75 m^2
Reference model C: with skycourt prototype (C)	Six-floor	37.5 × 37.5 m	9 × 13.5 m	1116 m^2	4.5 × 37.5 m	168.75 m^2

The CFD model offers detailed thermal information on the specific conditions at particular parts of the building. These are concerned with the skycourt space. Therefore, the CFD model was constructed to obtain the skycourt space, while the floors of the adjacent offices were presented as blocks. The internal and external boundary conditions around the skycourt were considered to improve the estimation of the airflow. These included indoor thermal conditions and external climate conditions (temperature and humidity).

As this study considers investigations about an enclosed skycourt that adopts mechanical ventilation, impact of variation of vertical location of skycourt along the height of the building is not included in the simulation. Elshaer *et al.* (2016) found that differences of heating and cooling loads due to the impact of vertical location of mechanical systems are lower in high-rise buildings that are located in urban areas.

4.4 CRITERIA OF THE STUDY

All energy simulations were carried out for a period of one year using the climate data of London derived from Energy Plus. However, the CFD simulation was performed based on three specific hours; the hottest external air temperature in summer, the coldest external air temperature in winter, and a typical temperature in mid-season. The main criteria to assess the study's assumptions are:

(i) The annual heating and cooling energy consumption (kWh/m^2.yr) for the building.

(ii) The comfort level of the indoor air temperature (°C), and the air velocity at the occupied level of the skycourt.

Heating and cooling demands for the offices and the skycourt zone were considered in order to compare the energy performance, whereas the core zone demand was neglected. Thermal conditions at the skycourt were assessed for the occupied region up to 1.8 m height above the floor level of the skycourt (Figure 4-7). The comfort standards for air temperature and airspeed at general office spaces were determined using the BCO Guide (2014). According to this guide, comfort air temperature ranges are 24°C ± 2°C in summer, 20°C ± 2°C in winter, and airspeed varies between 0.1 m/s and 0.2 m/s. The closer values to the thermal comfort standards would indicate more effective performance by the ventilation strategy (Figure 4-8).

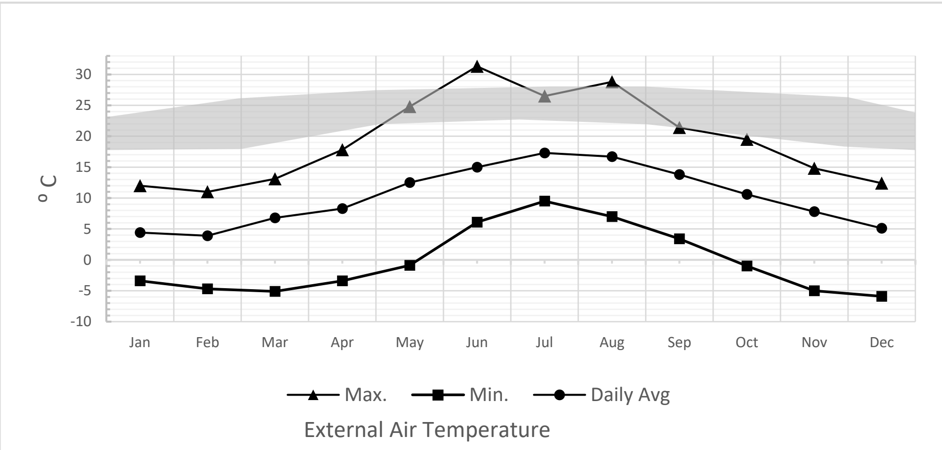


Figure 4-8. Indoor air temperature comfort range (the shaded area) in offices according to BCO Guide (2014), and external air temperature

Source: Energy Plus

There are other criteria that are required for achieving the research study's main objectives, such as the surface air temperature. In addition, it considers the different sources of loads' gains and losses for the skycourt, e.g. solar, incidental and heating gains; and cooling, ventilation and fabric losses. This helps to identify the effect of integrating the different prototypes of skycourts on the energy performance of the building.

4.5 SIMULATION SETTINGS

The accuracy of the results that are predicted by the simulation process depends heavily on the accuracy of the input, and the applicability of the model configurations. For this study, the simulation settings and assumptions were kept identical throughout the different cases to ensure that the attained results are influenced only by the considered variable(s).

However, the following values were defined based on review of key building standards and benchmarks: workplace density, comfort criteria, indoor design conditions regarding building services, including heating, ventilation, internal gain from people, lighting and appliances, energy efficiency standards for air infiltration, U-values for construction materials for the building elements, and operating schedule for spaces.

The benchmarks include the British Council for Offices Guides (2014 and 2009), CIBSE Guides A: Environmental Design (2015), CIBSE Guide F: Energy Efficiency in Buildings (2012), the Target CO_2 Emission Rate (TER), the Building Control Body (BCB) and the Concurrent Notional Building Specification in the L2A Building Regulations – Approved Document L2A: Conservation of fuel and power in new buildings other than dwellings for England (2016) , and ASHRAE (2013).

4.5.1 Framework and Assumptions for Energy Simulation (HTB2)

The input data required for the HTB2 model comprises information of both the regional climate data and the building. The building data include information regarding the building size, construction materials, small power, building services (heating, lighting, ventilation and occupancy) during the occupation and vacation periods, and the diary of application. The following presents the main assumptions that were made in this study.

Climate conditions of London: London is located at 51°28'N Latitude, 0°19'W Longitude. It has a marine temperate climate that is mild with no dry season, and warm summers. It has a light rainfall during the year. Heavy precipitation occurs during mild winters which are dominated by mid-latitude cyclones. The Köppen-Geiger climate classification considered the London climate as a temperate oceanic climate (Cfb) (Peel *et al.* 2007). Generally, the temperate oceanic climate zone has an average temperature below 22°C in all months and at least averaging above 10°C in four months. However, the coldest months record average temperature above 0°C and there is no significant precipitation difference between seasons. In London, the average annual temperature is 11.1°C, and the average monthly temperature varies by 13.5°C. During summer, temperatures rarely rise above 30°C, though higher temperatures have become more common recently. The average high temperature is 22°C, and the average low temperature is 12.3°C, with an average relative humidity of 66%,[1] (Figure 4-9).

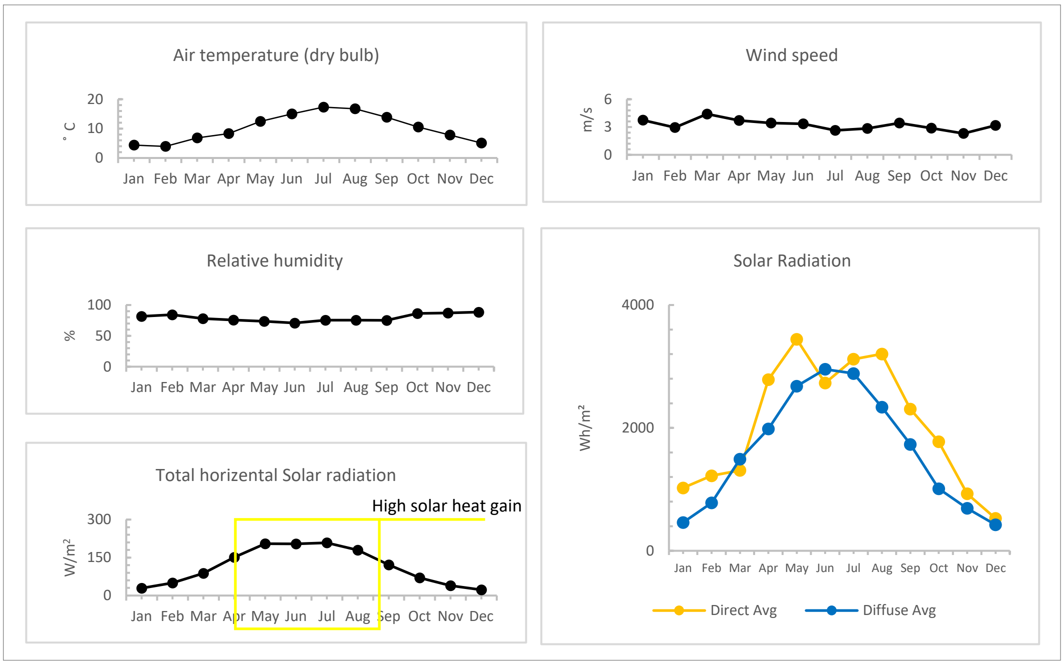


Figure 4-9. Weather data for London

In winter, the daytime temperature reaches 6.7°C on average, falling to 2.3°C overnight. The average relative humidity is high, and records as between 81% and 95% in the coldest days. Transitional seasons (autumn and spring) in London achieve average temperatures between 13.3°C and 14.3°C during the day, and 8°C to 5.3°C overnight.

Construction materials: These were selected based on two factors. The first is the common use in industry in the research context. The second is the limiting fabric thermal

[1] https://www.energyplus.net/weather

transmittance (U-value) in standards. Table 4-3 illustrates the allowance U-value for roof, wall, floor and windows according to the Approved Document L2A (2016)

Table 4-3. Benchmark allowance of the fabric parameter U-value

Description	Target CO_2 Emission Rate (TER)	The Concurrent Notional Building Specification	Building Control Body (BCB)
Roof U-value (W/m^2.C)	0.25	0.18	0.15
Wall U-value (W/m^2.C)	0.35	0.26	0.23
Floor U-value (W/m^2.C)	0.25	0.22	0.2
Windows U-value (W/m^2.C)	2.2	1.6 (10% off)	1.5
Windows g-value (%)		40	

Source: Approved Document L2A (2016)

Specifications for the construction materials that were used in creating the model are illustrated in Table 4-4. The selected constructions for walls, floors and windows achieve the requirements of thermal properties according to the Building Control Body (BCB), and the Concurrent Notional Building Specification.

Table 4-4. Thermal properties of the model construction materials (thickness, U-value) for the study

Element name	**Layer Order**		**Layer Name**	**Thickness** (m)	**Resistance** (m^2/W.C)	**Indicative U-value** (W/m^2.C)
Skycourt external wall	External →‖→ Internal	Double glazing	Window glass	0.006	0.471	1.535
			Cavity	0.0046		
			Window glass	0.006		
Skycourt floor/ceiling	Top ↓ ═ ↓ Bottom	Floor / ceiling slab	Board – flooring	0.04	4.681	0.206
			Gap	0.09		
			Concrete	0.3		
			Insulation – polyurethane foam board	0.12		
			Plastic – P.V.C/asbestos tiles	0.001		
Skycourt internal wall	Internal →‖→ Internal	Double glazing	Window glass	0.006	0.471	1.535
			Cavity	0.0046		
			Window glass	0.006		
Office external wall	External →‖→ Internal	External wall	Refectory insulating concrete	0.1	5.368	0.180
			Insulation – polystyrene	0.06		
			Board – fibre board	0.048		
			Insulation – polyurethane foam board	0.06		
			Board – gypsum plasterboard	0.032		
Office external window	External →‖→ Internal	Double glazing	Window glass	0.006	0.471	1.535
			Cavity wall	0.0046		
			Window glass	0.006		
Office internal wall	Internal →‖→ Internal	Internal wall	Board – gypsum plaster	0.06	4.3368	0.221
			Insulation	0.8		
			Board – gypsum plaster	0.06		
Office floor/ceiling	Top ↓ ═ ↓ Bottom	Floor / ceiling slab	Board – flooring	0.04	4.681	0.206
			Gap	0.09		
			Concrete	0.3		
			Insulation – polyurethane foam board	0.12		
			Plastic – P.V.C/asbestos tiles	0.001		
Core wall	Internal →‖→ Internal	Internal wall	Board – gypsum plaster	0.06	4.3368	0.221
			Insulation	0.8		
			Board – gypsum plaster	0.06		

A double skin façade is recommended for temperate climates. Such a façade can improve the thermal resistance of the envelope of the building. In addition, it can minimise the effect of wind speed, noise of wind and solar radiation (Goncalves and Umakoshi 2010). This role is effective for transitional spaces and vertical circulation elements (Eisele and Kloft 2003). Therefore, double glazing of 0.4 g-value was assumed for the exterior walls of the skycourt, windows of offices, and internal walls that separate the skycourt and the office zones. However, shading devices were not defined for the skycourt walls, or the external windows of the office building in the simulation. The thermal transmittance (U-value) of these windows accounts for about 1.5 W/m^2.C.

External walls for offices were assumed to be cavity walls of 0.18 W/m^2.C thermal transmittance (U-value). Concrete floors and ceilings were assumed for the building. These accounted for about 0.21 W/m^2.C thermal transmittance (U-value).

The solar radiation (solar patching) through the skycourt's external windows was assumed to affect the internal walls and the floor level of the skycourt and adjacent floors. However, solar radiation through the external windows of office zones was assumed to affect the floor level of the offices (Table 4-5).

Table 4-5. Glazing properties of windows

	Glass Type	G-value	Solar Patching
Skycourt external window/wall	Double glazing	0.4	- on skycourt floor - on surfaces of skycourt internal walls - on office floors
Office external windows	Double glazing	0.4	- on office floors

Ventilation rate: The CIBSE Guide A (2015) determines the minimum ventilation rate (outdoor airflow required) for several building types to maintain an accepted air quality based on the number of occupants in the spaces. In this respect, the recommended air supply rate (L/s) per person in general offices is 10 L/s per person. Therefore, it is important to define the occupancy density in spaces. Table 4-6 shows the standard allowance for occupancy in different spaces in office buildings according to the BCO Guides (2009 and 2014), and CIBSE Guide A (2015) based on the area of the space (m^2).

The study determined the standards for the skycourt as a general space, as there are no recommended standards for transitional areas. The occupancy profile used in the study is

12 m^2 per person. The equation used to calculate the required fresh (outdoor) airflow per number of occupants is:

$$Vbz = Rp \times Pz$$

Where *Vbz* is the breathing zone outdoor (fresh) airflow (m^3/s), *Rp* is the outdoor (fresh) rate required per person, *Pz* is the number of people expected to occupy the zone during typical usage.

Table 4-6. Benchmark allowance of occupancy standards in office building

Occupancy /Capacity	BCO Guide 2009	BCO Guide 2014	CIBSE Guide A
Workplace density (NIA per workspace)	8–13 m^2 /person	8–13 m^2/person	12 m^2 /person
On floor services (NIA per person)	10 m^2	8–10 m^2	
Core elements (NIA per person)	12 m^2	10–12 m^2	
Toilet (NIA per person)	12 m^2	10 m^2	
Lift (NIA per person)	12 m^2	10–12 m^2	

Source: BCO Guides (2009 and 2014); CIBSE Guide A (2015)

However, the uncontrolled inward leakage of outdoor air through the building envelope such as through cracks, interstices or other unintentional openings, was considered for calculating the outdoor airflow into the building. This is known as the infiltration rate, and it is calculated by the following equation:

$$\text{Infiltration rate } (m^3/hr) = Ra \times Az$$

Where *Ra* (airtightness) is the resistance to inward or outward air leakage per unit area ($m^3/m^2.hr$), *Az* is the zone façade area (m^2).

A comparison for airtightness (air permeability) is shown in Table 4-7. The value used in the study for airtightness is 3.5 $m^3/ m^2.hr$ at 50pa. However, air infiltration was set up at the perimeter of the building.

Table 4-7. Benchmark allowance for air supply rate and airtightness in office building

	BCO Guide 2009	BCO Guide 2014	CIBSE Guide A	The Concurrent Notional Building Specification
Air supply rate (L/s per person)	10	10	10	
Airtightness (Air permeability) (m^3/m^2.hr) at 50pa	3.5	3.5	5	3

Source: BCO Guides (2009 and 2014); CIBSE Guide A (2015); Approved Document L2A (2016)

Internal heat gains: These include lighting, equipment (appliances) and occupant gains. The benchmark allowances in watt per area (m^2) to peak sensible heat loads in general office buildings according to the BCO Guides (2009 and 2014) and CIBSE Guide A (2015) are defined in Table 4-8.

Table 4-8. Benchmark allowance for internal heat gain in office building

	BCO Guide 2009	BCO Guide 2014	CIBSE Guide A *
People	-	-	6.7 W/m²
Equipment	-	-	15 W/m²
Lighting: Electrical Load Allowance	12 W/m²	10 W/m²	8–12 W/m²
Small Power: Loading diversified on floor distribution (based on one workspace per 10 m²)	25 W/m²	20 –25 W/m²	

* These values are defined at density of occupation equals 12 person per m^2

Source: BCO Guides (2009 and 2014); CIBSE Guide A (2015)

In the study, the internal heat gains were estimated according to CIBSE Guide A (2015) as these values were combined with occupant densities. The expected number of occupants in this building during a typical usage per area (m^2) is one person per 12 m^2. Accordingly, the used allowances sensible gains are 12 W/m^2 for lighting, 15 W/m^2 and 6.7 W/m^2 for occupants. It should be mentioned here that the above method for calculating the internal heat gains and the occupancy capacity was used for the different cases in the study. Therefore, the estimated value for the internal gains varies according to the area of spaces in the different cases during the simulation stages.

Operating schedule: Five days per week, Monday to Friday, starting at 09.00 to 18.00, were assumed as an operating schedule for the building. The occupancy profile was assumed to be 100% for the skycourt and the core. However, the occupancy profile for the offices is different. Office spaces were assumed to be 100% occupied between 09:00-13:00 and 14:00-18:00, while, in the break hour, 13:00-14:00, it was assumed to be 70% occupied.

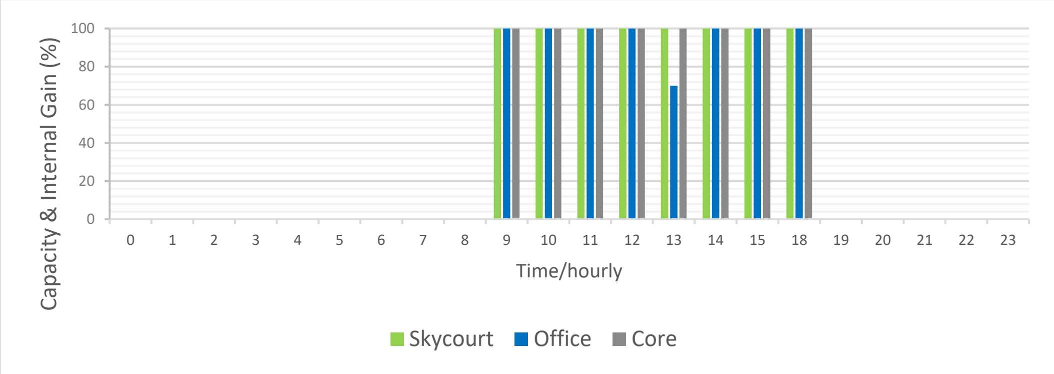


Figure 4-10. Estimated capacity and internal gains percentages on hourly bases

The operating time schedule for heating and cooling is five days per week, Monday to Friday (08.00–18.00). In practice, the supply air temperature is not normally allowed to be lower than about 18°C for comfort purposes (Awbi 1998a). The BCO Guide (2014) defined comfort ranges in office buildings and general spaces as the following: summer dry resultant temperature is 24°C ± 2°C, and 20°C ± 2°C in winter. Therefore, the heating and cooling schedule during the simulation was set to heating set point to 18°C and cooling set point to 25°C.

The output data of the HTB2 model includes energy performance embodied by energy demands for heating and cooling (kWh), based on the yearly database for the building including offices and skycourt. Furthermore, thermal conditions were represented by mean air temperature and the surface temperature of elements. This data was integrated into the CFD model as input data for the WinAir model.

4.5.2 Framework and Assumptions for CFD (WinAir)

The WinAir simulation was carried out considering the climate data for the peak summer hour, the coldest winter hour and the mid-temperature hour. In addition, input data combines surface temperatures of the internal spaces (skycourt and offices) in these hours. These values were extracted from the HTB2 model. Three cases were defined for each model; see Figure 4-11 and Table 4-9. These include:

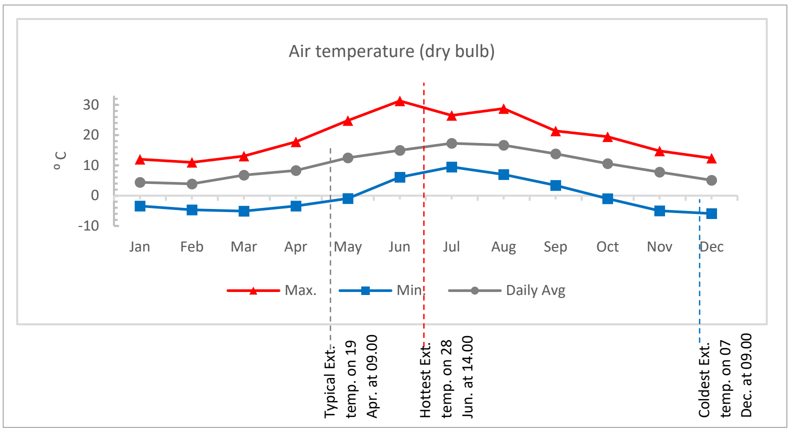


Figure 4-11. Selected times considered for CFD and the external air temperature

- The summer case, the external temperature is 28.3°C, the relative humidity is 42%; internal temperatures are coupled from HTB2 on June 28th at 14.00 pm;
- The winter case, the external temperature is -5°C and the relative humidity is 95%; internal temperatures are coupled from HTB2 on December 7th at 9.00 am;
- The transitional case, the external temperature is 13.2°C and the relative humidity is 91%, and internal temperatures are coupled from HTB2 on April 19th at 9.00 am.

The internal gain, and the inlet and outlet airflow rates were defined based on the case from the HTB2 output. Figure 4-12 shows an outline for the skycourt model on WinAir.

Table 4-9. External climatic conditions employed for CFD simulation

Weather Data	**Summer Season Case (Hottest Ext. Temp)**	**Winter Season Case (Coldest Ext. Temp)**	**Mid-season Case (Typical Ext. Temp)**
Dry-bulb temperature (°C)	28.3	-5	13.2
Relative humidity (%)	42	95	91

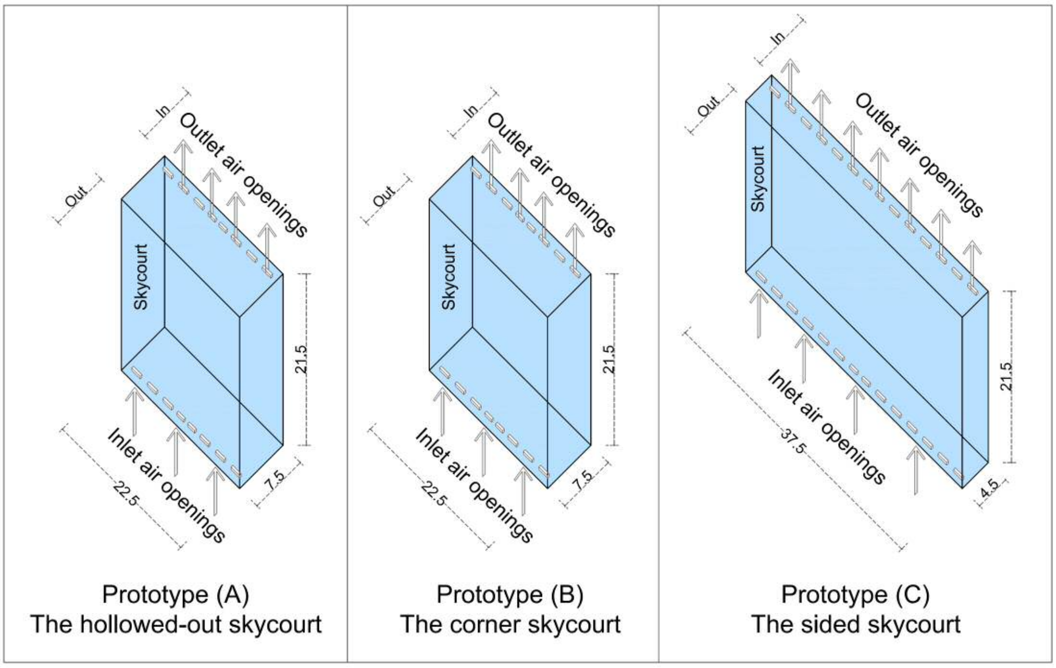


Figure 4-12. Reference models for the skycourts for WinAir in the study

4.5.3 Summary of the Simulation Settings

The simulation was carried out for periods all over the year under different seasons, summer, winter and mid-seasons, using HTB2. However, CFD was performed considering the climate data for the peak summer hour, the coldest winter hour and the mid-temperature hour. The adapted settings and conditions of the simulation process are summarised in Table 4-10. Similar conditions were adopted for all models.

Table 4-10. Summary of main simulation settings and assumptions of the study

	Settings			Reference
	Skycourt	**Office Zones**	**Core**	
External conditions	Temperate climate, London			Energy Plus
Building layout	Vary according to the model under investigation	Vary according to the model under investigation	Fixed	
Building material	As defined in Table 4-4	As defined in Table 4-4	As defined in Table 4-4	
Workplace density (NIA per workspace)	12 m²/person	12 m²/person	12 m²/person	CIBSE Guide A
Internal heat gain*:				
People	6.7 w/m²	6.7 w/m²	6.7 w/m²	CIBSE Guide A
Equipment	-	15 w/m²	-	CIBSE Guide A
Lighting	12 w/m²	12 w/m²	12 w/m²	CIBSE Guide A
Thermal comfort:				
Air temperature - Winter	20°C ± 2°C	20°C ± 2°C	20°C ± 2°C	BCO Guide CIBSE Guide A
Air temperature - Summer	24°C ± 2°C	24°C ± 2°C	24°C ± 2°C	
Airspeed	0.1 m/s – 0.2 m/s	0.1 m/s – 0.2 m/s	0.1 m/s – 0.2 m/s	
Fabric parameter:				
Windows g-value	40%	40%	-	BCB (2016) BCO Guide
Windows U-value	1.53 W/m².C	1.53 W/m².C	-	
Window to Wall ratio	70%	70%	-	
External wall U-value	1.53 W/m².C	0.18 W/m².C	-	BCB (2016)
Internal wall U-value	1.53 W/m².C	0.22 W/m².C	0.22 W/m².C	BCB (2016)
Floor U-value	0.2 W/m².C	0.2 W/m².C	0.2 W/m².C	BCB (2016)
Ventilation settings:				
Infiltration rate at 50 Pa	3.5 m³/m².hr	3.5 m³/m².hr	-	BCO Guide (2014)
Air supply rate	10 L/s per person	10 L/s per person	10 L/s per person	CIBSE Guide A
Heating set point	18°C	18°C	18°C	
Cooling set point	25°C	25°C	25°C	
Operating time	08:00–18:00	08:00–18:00	08:00–18:00	
Total simulation time:				
Energy building simulation	All over the year	All over the year	All over the year	HTB2
CFD simulation	Three peak hours (hottest, coldest and typical external temperatures)	-	-	WinAir

4.5.4 Verification of the Hypothetical Models

Validation, calibration and verification are important steps in any simulation study. Several studies provide guidelines for the validation process of simulation models (Zeigler and Nutaro 2016; Hora and Campos 2015; Murray-Smith 2015; Qudrat-Ullah 2012; Rehman and Pedersen 2012; Sargent 2011 and Dee 1995). These processes aim to ensure that the simulation model is correctly formulated and accurately represents the real system, to confirm whether a simulation model is valid or reject this model.

Verification of the hypothetical simulation model includes formulating the model correctly and comparing the simulation model and its outcome results to results of other valid models. These comparisons can be implemented using a variety of techniques including: (i) checking simulation output for reasonableness and (ii) comparing simulation output with analytical results (Hora and Campos 2015).

In this study, the hypothetical models were established based on design guidelines for office buildings that represent the typical characteristics of high-rise office buildings in London. In addition, the simulation settings were defined based on valid benchmark as mentioned in section 4.5 simulation settings.

The hypothetical model is verified by analysing the energy consumption of the building, and examining the indoor air temperature of offices and skycourt zone in selected hours in summer, winter and mid-seasons. These are discussed below.

Firstly, the annual energy simulation for the hypothetical model of the study that does not integrate a skycourt shows coherence with CIBSE Guide F (2012), energy consumption and system benchmarks for air-conditioned offices. For example:

(i) According to Table 20.1, CIBSE Guide F, energy benchmarks for good practice of air-conditioned standard offices in the UK count about 111 kWh/m^2.yr of treated floor area for HVAC (CIBSE Guide F 2012). The model in the present study counted about 106 kWh/m^2.yr of treated floor area for heating, cooling and ventilation.

(ii) According to Table 20.9, CIBSE Guide F, good practice for air-conditioned standard offices in the UK count about 50 kWh/m^2.yr for lighting and equipment. The model in the study counts about 49 kWh/m^2.yr for lighting and equipment.

Differences of values for energy consumption and systems between the good practice model according to CIBSE Guide F and the model of the present study are considered marginal as these are thought to be largely due to the different settings. For example, the good practice model according to CIBSE Guide F considers a benchmark value of 5 m^3/m^2.hr (at 50 Pa) for infiltration rate. However, the model of the study considers a benchmark value of 3.5 m^3/m^2.hr (at 50 Pa) for infiltration rate, as this is average value on the considered benchmarks. In addition, internal gains are calculated based on a benchmark value of 14 W/m^2 for office equipment (CIBSE Guide F 2012), whereas the current study considered a benchmark value of 15 W/m^2 for office equipment. This comparison ensures the capability of the hypothetical model of the study and the validity of the simulation results.

Secondly, comparison of weekly energy loads including heating, cooling, ventilation, incidental, solar and fabric loads and air temperature at the office zone in selected weekdays in summer, winter and mid-season, shows that maximum cooling occurred in summer days, heating in winter days, and no overheating or overcooling occurred in mid-season. In addition, these loads correspond with the air temperature. The selected summer weekdays are 26 -30 June, the selected winter weekdays are 4-8 December and the selected mid-season weekdays are 17-21 April. Therefore, the output energy consumption data of the prototypical model are reasonable, and the model can be used for further research (Figure 4-13).

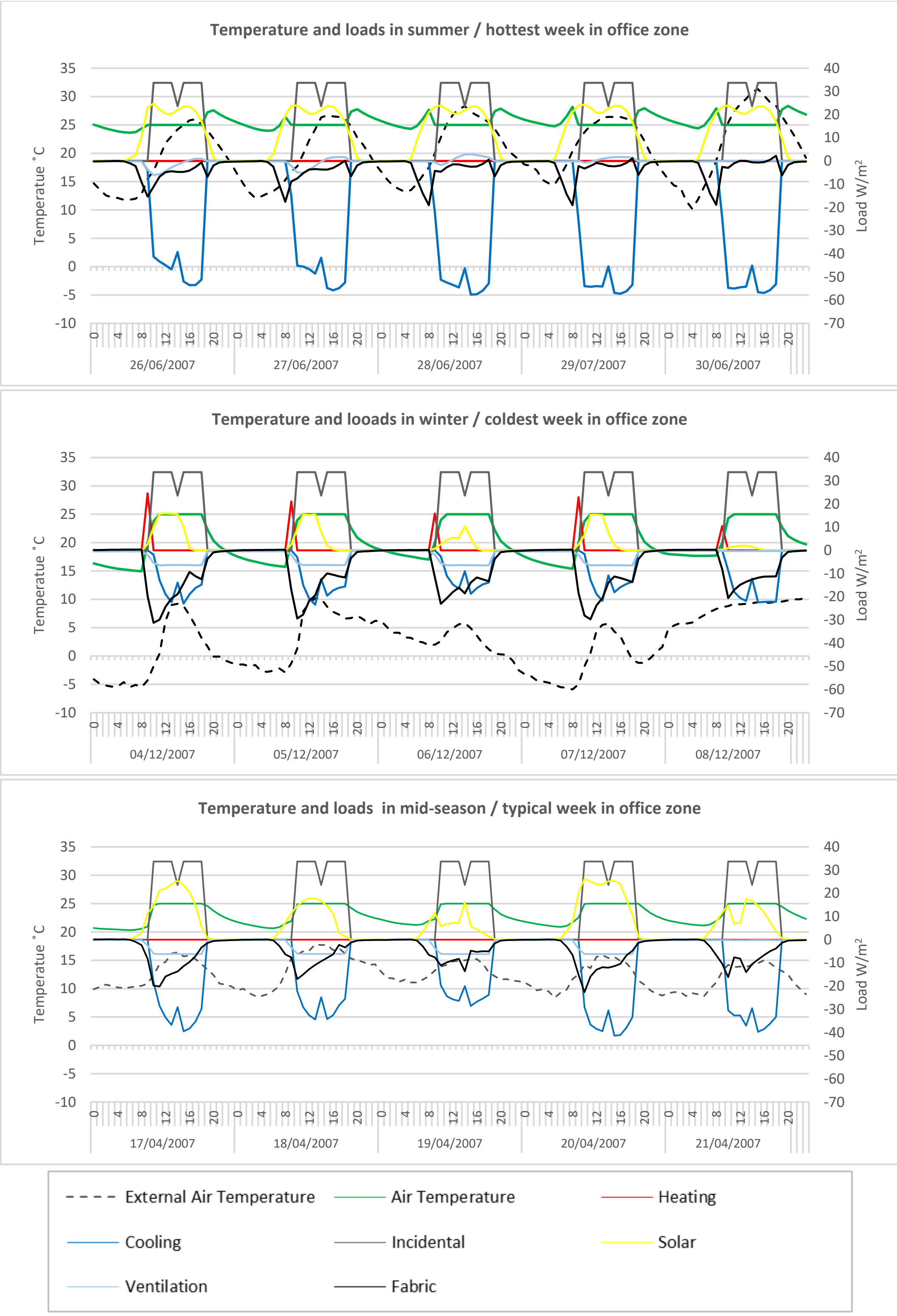


Figure 4-13. Breakdown of energy loads and air temperature in selected summer, winter and mid-season weeks at office zone

Thirdly, comparison of hourly air temperature between BES and CFD simulation results from HTB2 and WinAir for the hypothetical models that integrate air conditioned skycourts is highlighted in Table 4-11. CFD simulation can provide accurate information at the occupancy level of the skycourt, while BES provides an average temperature. Therefore, to further improve the accuracy of the results, segmentation of the skycourt space in the BES model into more than one space is considered, to obtain more specific results to feed to the CFD model. The skycourt model in HTB2 was constructed to include two zones; lower zone and upper zone. The lower zone represents the occupied volume of the skycourt, which is the focus zone in this study. It is anticipated that the coupling between HTB2 and WinAir produce minimum temperature difference (nearly 1°C) at the occupied area of the skycourt. That small difference is usually accepted for ventilation cases to continue the simulation for the next time step (Wang and Wong 2008). This result acknowledges the corresponding and compatibility between the two software.

Table 4-11. Comparison of hourly results of thermal conditions between HTB2 and WinAir at skycourts' occupied zones

Skycourt Prototype	Simulation	Air Temperature (°C) at Occupancy Level of Skycourt	Airspeed (m/s) at Occupancy Level of Skycourt
Simulation at hot day at summer/ 28 June –14.00, external air temperature: 28.3° C, RH: 42%			
Hollowed-out (A)	HTB2	25	-
	WinAir	18.2-27.5 (25)	0.08
Corner (B)	HTB2	25	-
	WinAir	18.2-27.5 (25)	0.09
Sided (C)	HTB2	25	-
	WinAir	18.2-28 (25)	0.08
Simulation at cold day at winter/ 7 December –09.00 am, external air temperature: -5° C, RH: 95%			
Hollowed-out (A)	HTB2	20	-
	WinAir	17.3-24.1 (19.1)	0.3
Corner (B)	HTB2	20	-
	WinAir	16.8-23.9 (19)	0.3
Sided (C)	HTB2	20	-
	WinAir	16.3-23.6 (19)	0.3
Simulation at typical day at mid-season/ 19 April –09.00 am, external air temperature: 13.2° C, RH: 91%			
Hollowed-out (A)	HTB2	22	-
	WinAir	20-22.2 (21.1)	0.06
Corner (B)	HTB2	21	-
	WinAir	19.3-21.5 (21.2)	0.06
Sided (C)	HTB2	22	-
	WinAir	20.3-21.2 (20.6)	0.05

More comparisons about the validity of other predicted results to relative research studies in the literature review are provided throughout presenting the simulation results in chapter five and discussing the results in chapter six.

4.6 SIMULATION STAGES

This section presents the stages for the research study process that were conducted to achieve the research objectives and to assess the research study's assumption. The procedure is divided into four main stages; each one has a particular aim. These comprise firstly, the effect of integrating air-conditioned skycourts in high-rise office buildings. Secondly, the optimum ventilation strategy for the unheated and uncooled skycourt. Thirdly, the sensitivity analysis. Fourthly, the optimisation of the skycourt design. The major focus of the study is the thermal performance of the skycourt and the energy consumption of the building. It should be mentioned that in each stage the predicted air temperature for the investigated spaces using the energy simulation software, HTB2, was compared against the measured data from the CFD simulation process using WinAir.

4.6.1 Stage One: Integrating a Heated and Cooled Skycourt

The first stage was conducted to investigate the impact of integrating a heated and a cooled skycourt in a high-rise office building. This includes examining the thermal performance of the skycourt, and energy performance of the building. The provision of air conditioning, heating, cooling and ventilation in skycourts is based on the current practice. Offices are heated, cooled, and ventilated mechanically as in the case of existing real estate. Air is filtered and pre-heated or re-cooled in these spaces. This stage of the investigation was conducted in two steps. The first step considered the model without the skycourt, and the second step involved the reference models that included skycourts.

4.6.1.1 Step 1a: The Model without Skycourt

A hypothetical office building without a skycourt was simulated, using HTB2 software, to predict the energy demand of heating and cooling of the building during the occupation (Figure 4-14).

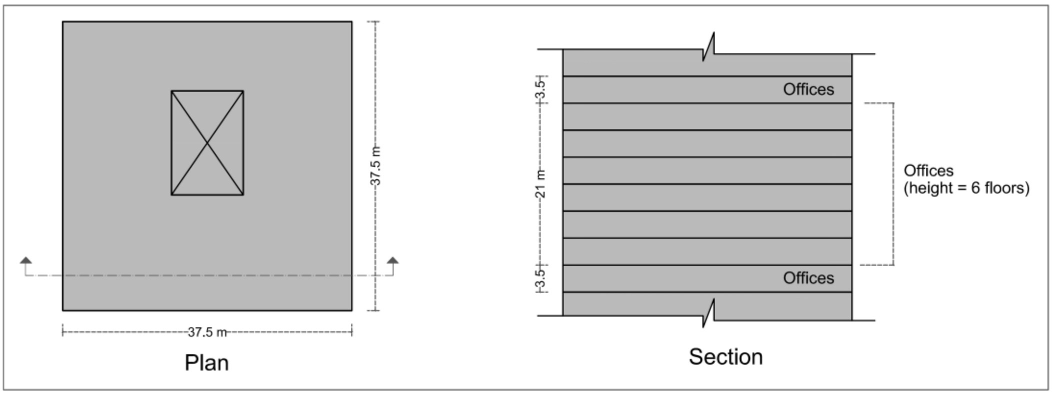


Figure 4-14. Model of building without skycourt for stage one, step 1a

4.6.1.2 Step 1b: The Reference Models that Include Skycourts

The reference case is the same hypothetical building with a skycourt. The study established three models, each one of them represents a prototype of a skycourt. Reference model (A) represents a building with prototype (A), the hollowed-out skycourt; reference model (B) is for a building with prototype (B), the corner space; and finally, reference model (C) is for a building integrated prototype (C), the sided skycourt. Figure 4-15 illustrates the reference models of the study. Both spaces, the skycourt and the adjacent offices, are isolated, and heated, cooled, and ventilated mechanically as shown in Figure 4-16.

The adopted settings and conditions of the simulation process are the ones defined in the previous section (Table 4-10). The thermal conditions of the skycourts were tested under three critical hours in summer, winter and mid-seasons. These involve the effect of the dry-bulb air temperatures and solar radiations. These parameters have effects on heat gain and loss in the building, and the internal thermal conditions. Fixed and independent variables for this stage are summarised in Table 4-12.

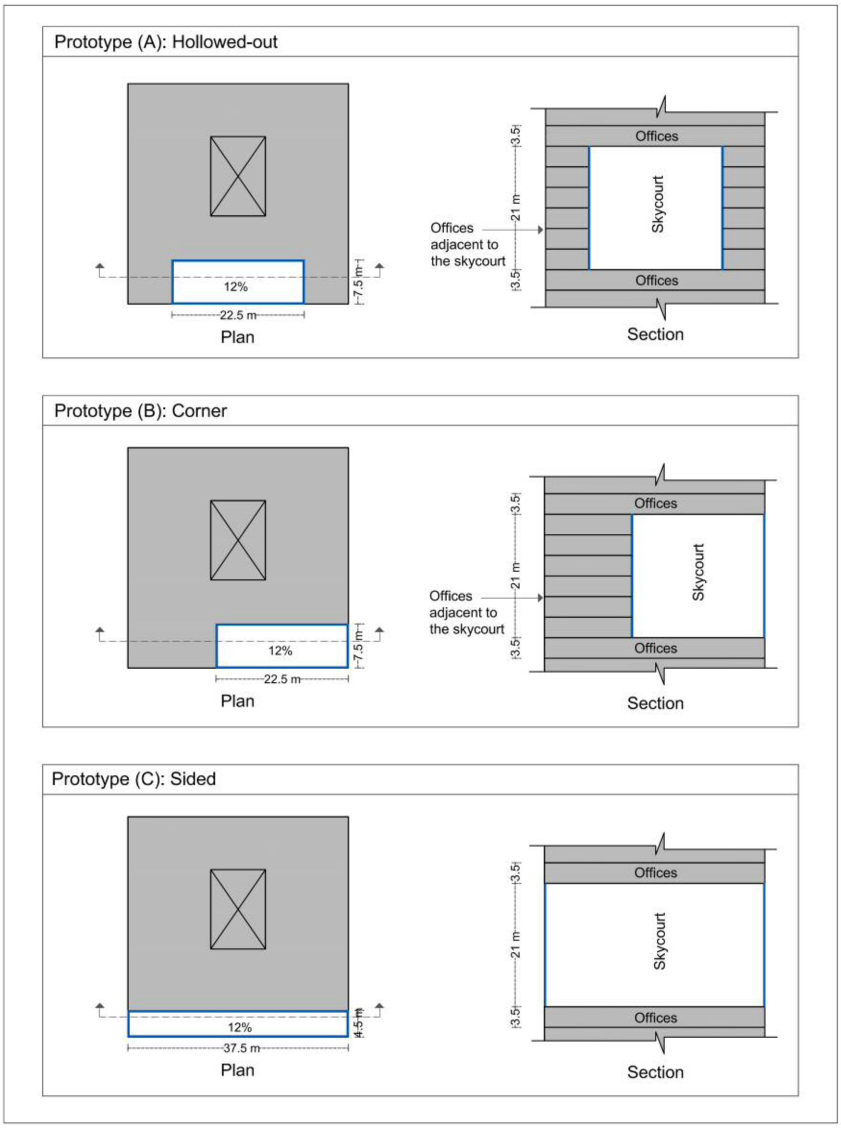


Figure 4-15. Reference models for office buildings that integrate skycourts for stage one, step 1b

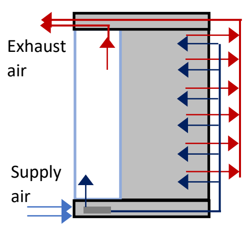
Skycourt is an air-conditioned isolatable space	
Reference Case	
Skycourt and adjacent offices are air-conditioned: ventilated, heated and cooled separately	
- Inlet air volume rate is about 1 L/s per person - Inlet air volume rate for each office floor is 0.93 m^3/s at 18°C - Inlet air volume rate for skycourt prototypes (A) and (B) is 0.85 m^3/s at 18°C - Inlet air volume rate for skycourt prototype (C) is 1.26 m^3/s at 18°C	

Figure 4-16. Proposed ventilation strategy for the skycourt for stage one

Table 4-12. Fixed and independent settings for stage one

Fixed Parameters	**Details**
Climate conditions	London climate
Geometrical properties of the models	As defined in Table 4-2
Energy simulation conditions	As defined in Table 4-10
CFD simulation conditions	As defined in Table 4-9
Independent Variables	**Details**
Tested cases/models	Four models: One model of the building without skycourt Three reference models* for the buildings with skycourt's prototypes: Prototype (A): hollowed-out space Prototype (B): corner space Prototype (C): sided space
Weather seasons	Three times in weather seasons, these are: Summer (Jun., Jul., Aug.) - Hottest hour: 28 Jun. at 14.00 Winter (Dec., Jan., Feb.) - Coldest hour: 7 Dec. at 9.00 am Mid-seasons (Mar., Apr., May, Sep., Oct., Nov.) - Typical: 19 Apr. at 9.00 am

* Reference Model: building with ventilated, heated and cooled skycourt

After obtaining the simulation of the reference buildings, the results of thermal conditions of the skycourts, and the energy performance of the building were undertaken. For the purposes of conducting the comparison between the calculated data using HTB2, and the measured data using WinAir, the CFD simulation uses the climate data for the peak summer hour, the coldest winter hour and the mid-temperature hour. In total, 13 simulation cases were performed.

4.6.2 Stage Two: Incorporating an Unheated and Uncooled Skycourt

In this stage, the research study examines the potential of the skycourt when it acts as an unheated and uncooled transitional buffer area that does not consume energy for heating nor cooling. In order to achieve energy savings for the building and better indoor thermal conditions in the skycourt, the study suggests three scenarios. In the first scenario, the skycourt use infiltration only (Figure 4-17). In the second scenario, the air extracted from the offices is driven through the office outlets and pushed into the skycourt inlets (Figure 4-18). In the third scenario, the fresh air is supplied to the skycourt space, then it is forced to extract into the adjacent offices (Figure 4-19).

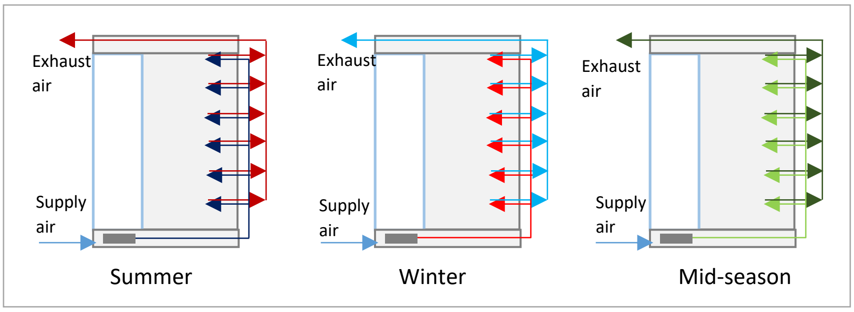


Figure 4-17. Scenario one for unheated and uncooled skycourt: skycourt is a sealed space

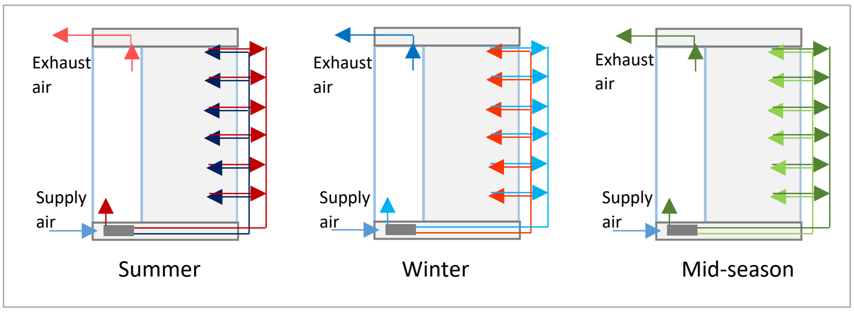


Figure 4-18. Scenario two for unheated and uncooled skycourt: skycourt is ventilated by the exhaust air from the office spaces

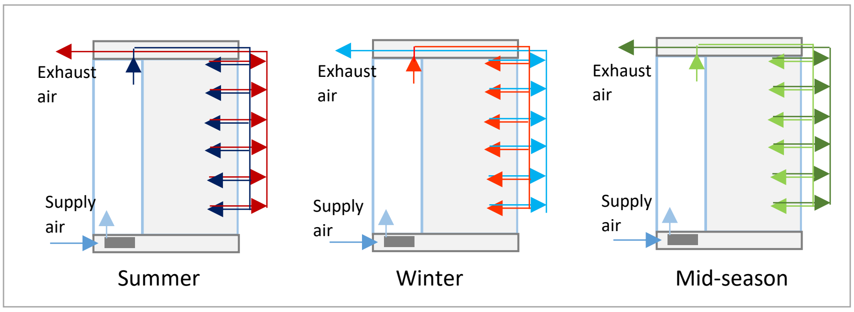


Figure 4-19. Scenario three for unheated and uncooled skycourt: skycourt is ventilated by the supply air to the offices

Five ventilation strategies were suggested under the previous scenarios. The purpose is to identify the appropriate ventilation strategy for each prototype of skycourts in summer, winter and mid-seasons with respect to energy consumption and thermal comfort. The proposed ventilation strategies are:

(i) Sealed-skycourt ventilation strategy one (V1): this is based on infiltration only.

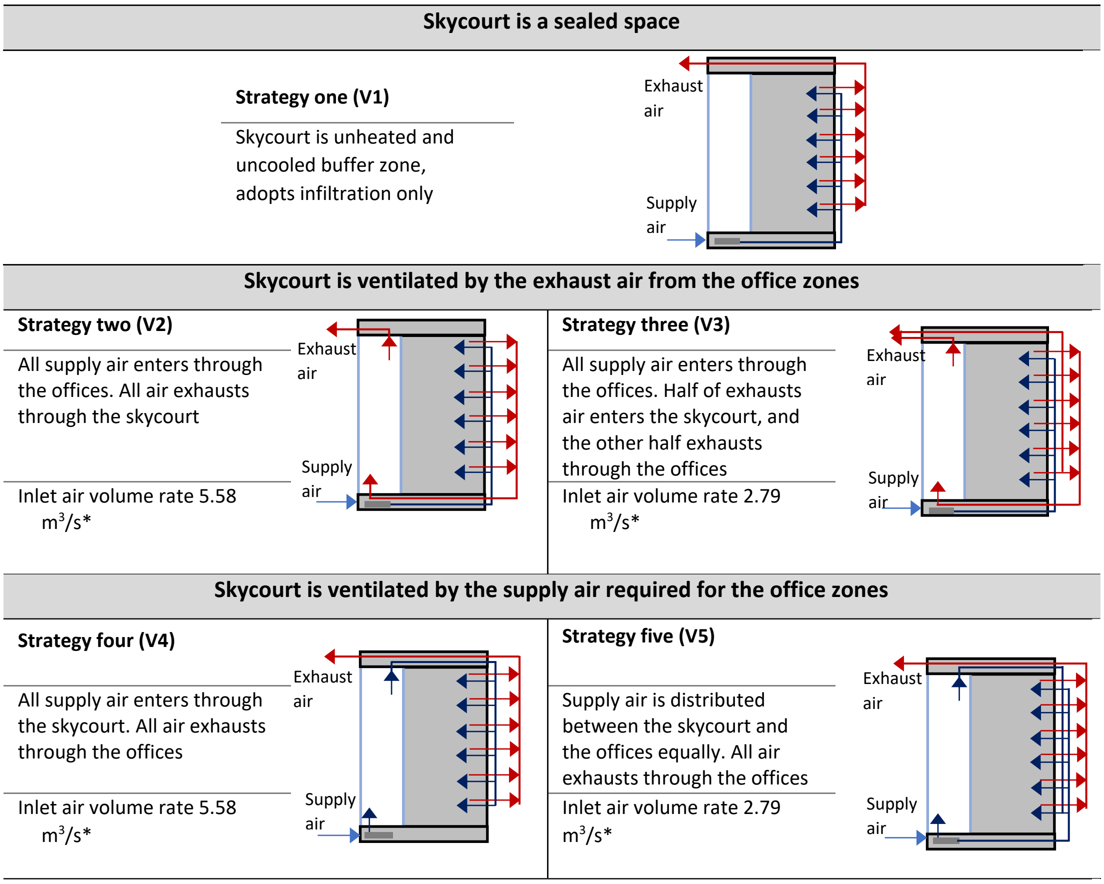
(ii) Combined-exhaust ventilation strategy two (V2): the skycourt is ventilated by the exhaust air from the office spaces, all air enters through the office zone. Then, all air exhausts through the skycourt.

(iii) Combined-exhaust ventilation strategy three (V3): the skycourt is ventilated by half of the exhaust air from the office spaces, air enters through the office zone. Then, half of the air exhausts through the skycourt, and the other half through the office zone.

(iv) Combined-supply ventilation strategy four (V4): the skycourt is ventilated by the supply fresh air to the office spaces. All air enters through the skycourt zone, and then, the air exhausts through the office zone.

(v) Combined-supply ventilation strategy five (V5): the skycourt is ventilated by half of the supply fresh air to the office spaces. Half of the fresh air enters through the skycourt zone, and the other half through the office zone. Then, all air exhausts through the office zone.

Figure 4-20 illustrates these strategies, air movement, and simulation settings for the skycourt.



* These settings are defined for the skycourt

Figure 4-20. Proposed ventilation strategies for the skycourt for stage two

The proposed location of air inlet and air outlet openings in this stage are the same in all cases. Air inlet openings are inserted at the floor level of the skycourt, and air outlet openings are inserted at the ceiling level of the skycourt. Displacement ventilation is assumed to determine air distribution in the skycourt when air enters the skycourt. It is anticipated that this system can be an efficient alternative in the skycourt.

Supply air temperature is based on the principle of the case under study. For example, in the case of the combined-exhaust strategies, supply air temperature depends on the air temperature extracted from the offices, while, for combined-supply strategies, it is assumed to be 18°C or more based on the external air temperature.

The study involves modifying each of the ventilation strategies in the input data while keeping the other parameters fixed. Each ventilation strategy was tested under three seasons: summer, winter and transitional seasons. The total number of the simulation cases in this stage is 60. Fixed and independent variables are summarised in Table 4-12. These are:

- Three prototypes (spatial configurations) of skycourts:
  Prototype (A): hollowed-out space
  Prototype (B): corner space
  Prototype (C): sided space
- Five ventilation strategies, which have been defined previously
- Three times for CFD simulation:
  The hottest hour in summer months (June, July and August)
  The coldest hour in winter months (December, January and February)
  A typical hour in mid-season months (March, April, May, September, October and November)

Table 4-13. Fixed and independent settings for stage two

Fixed Parameters	Details
Climate conditions	London climate
Geometrical properties of the models	As defined in Table 4-2
Energy simulation conditions	As defined in Table 4-10 and Figure 4-15
CFD simulation conditions	As defined in Table 4-9
Independent variables	**Details**
Tested prototypes/models	Three models: Prototype (A): hollowed-out space Prototype (B): corner space Prototype (C): sided space
Ventilation strategies	Five strategies: Strategy one (V1) Strategy two (V2) Strategy three (V3) Strategy four (V4) Strategy five (V5)
Weather seasons	Three times in weather seasons, these are: Summer (Jun., Jul., Aug.) - Hottest hour: 28 Jun. at 14.00 Winter (Dec., Jan., Feb.) - Coldest hour: 7 Dec. at 9.00 am Mid-seasons (Mar., Apr., May, Sep., Oct., Nov.) - Typical: 19 Apr. at 9.00 am

The air temperature and the air speed for the skycourt (calculated using the thermal simulation software, HTB2) were compared against the measured data from the CFD simulation process using WinAir.

This stage aims to identify the most suitable ventilation strategy to be utilised inside the skycourt. This strategy will obtain the most energy savings with respect to heating and cooling loads of the building, and in addition provide thermal comfort for the occupants of the skycourt. The most suitable alternative will also positively affect the adjacent offices. The result will greatly simplify further investigation of the key parameters to determine the most critical ventilation conditions in the next stage.

4.6.3 Stage Three: Sensitivity Analysis: The Generation of Ventilated Skycourt Alternatives

For this stage, the optimum ventilation strategy for each prototype of the skycourts, identified in the previous stage, was used to investigate the performance of the skycourt with the variation of main parameters. These parameters can affect the thermal comfort in ventilated spaces and the energy demands of buildings. These parameters were discussed previously in section four in chapter two. This stage aims to define the key factors in skycourt design connected with the optimal ventilation strategy for each skycourt prototype. Therefore, the model with the optimum ventilation strategy was used as a base case here while comparing the impact of each parameter. In addition, it should be mentioned that during the investigation of a single parameter, all the other parameters maintain the default settings. The investigation in this stage involves two issues. The first is the skycourt geometry in terms of orientation, height, percentage of area to GIA, and length to width. The second considers improvements of the ventilation strategy in terms of vertical distribution and horizontal position of air inlet and outlet openings. The fixed variables for this stage are illustrated in Table 4-14. These are:

- Three prototypes (spatial configurations) of skycourts:
  Prototype (A): hollowed-out space
  Prototype (B): corner space
  Prototype (C): sided space
- One ventilation strategy, according to the results of stage two
- Three times in weather seasons, these are:
  The hottest hour in summer months (June, July and August)
  The coldest hour in winter months (December, January and February)
  A typical hour in mid-season months (March, April, May, September, October and November)

Table 4-14. Fixed settings for stage three

Fixed Parameters	**Details**
Climate conditions	London climate
Geometrical properties of the models	Vary according to the model under investigation
Energy simulation conditions	As defined in Table 4-10
CFD simulation conditions	As defined in Table 4-9
Ventilation strategies Prototype (A): hollowed-out space Prototype (B): corner space Prototype (C): sided space	 : According to the results of stage two : According to the results of stage two : According to the results of stage two

4.6.3.1 Step 3a: Optimising the Skycourt Geometry

This stage aims to study the effect of the geometrical parameters of the skycourt on the energy consumption of the building and the thermal comfort at the skycourt based on the ventilation strategy found from stage two. These parameters are the skycourt orientation, height, area to GIA, and length and depth.

Orientations were tested, ranging from south to east (Figure 4-21). Three heights were examined, three-floor height, six-floor height, and nine-floor height (Figure 4-22). Three areas with a considered percentage to GIA have been investigated, which account for 12% of GIA, 8% of GIA, and 4% of GIA (Figure 4-23). Length and depth have been tested including (i) 22.5 m × 7.5 m, (ii) 15 m × 7.5 m, (iii) 7.5 m × 15 m, (iv) 7.5 m × 7.5 m, (v) 37.5 m × 4.5 m, and (vi) 37.5 m × 3 m, (Figure 4-24).

The independent variables are summarised in Table 4-15. The total number of simulation cases in this step is 156; 39 runs using HTB2, and 117 using WinAir.

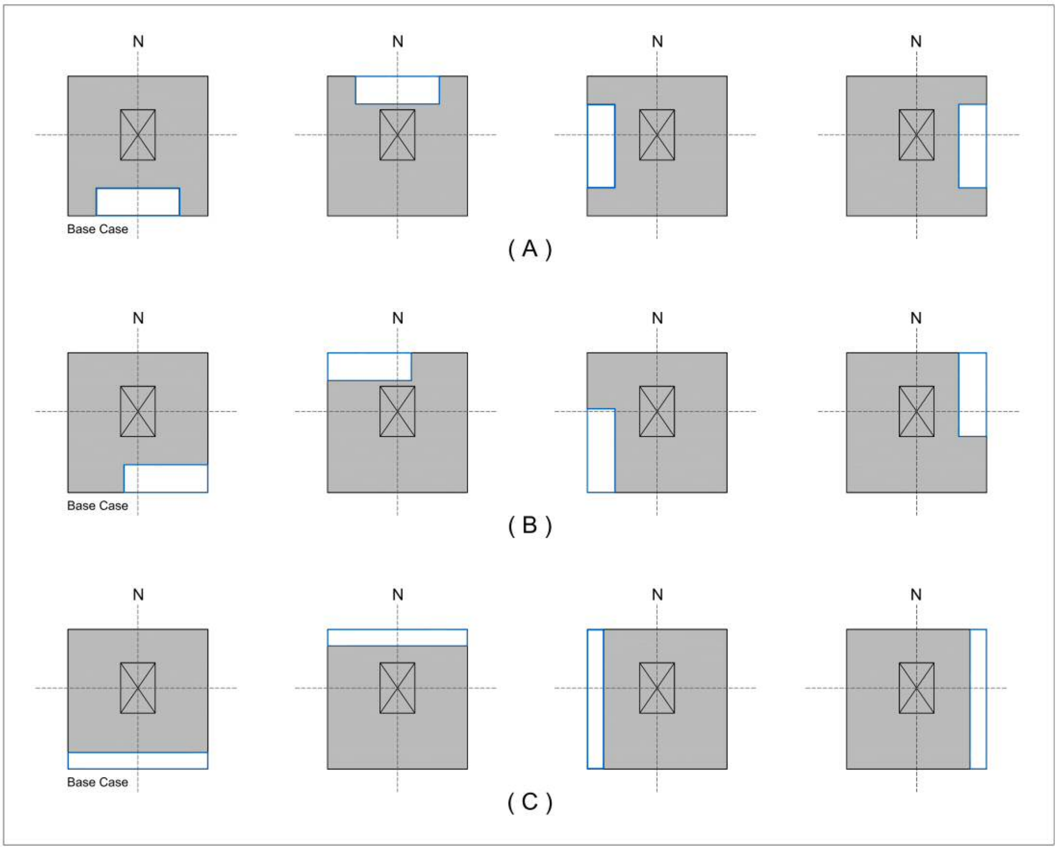


Figure 4-21. Schematic diagrams of orientation comparative models for stage three, step 3a: (A) hollowed-out, (B) corner and (C) sided

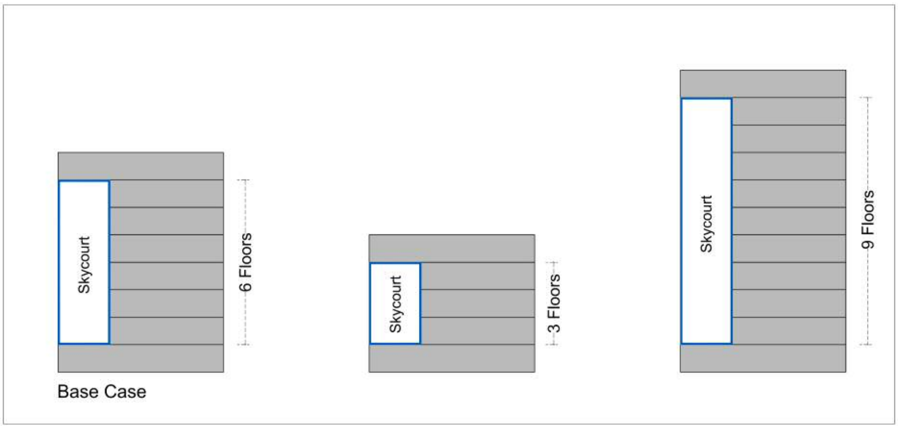


Figure 4-22. Schematic diagrams of heights comparative models for stage three, step 3a

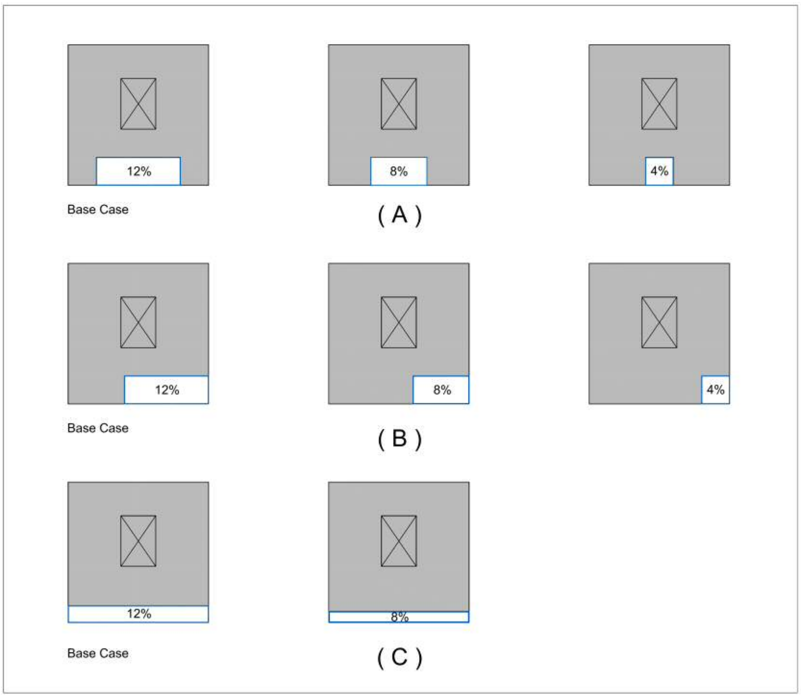


Figure 4-23. Schematic diagrams of area comparative models for stage three, step 3a: (A) hollowed-out, (B) corner and (C) sided

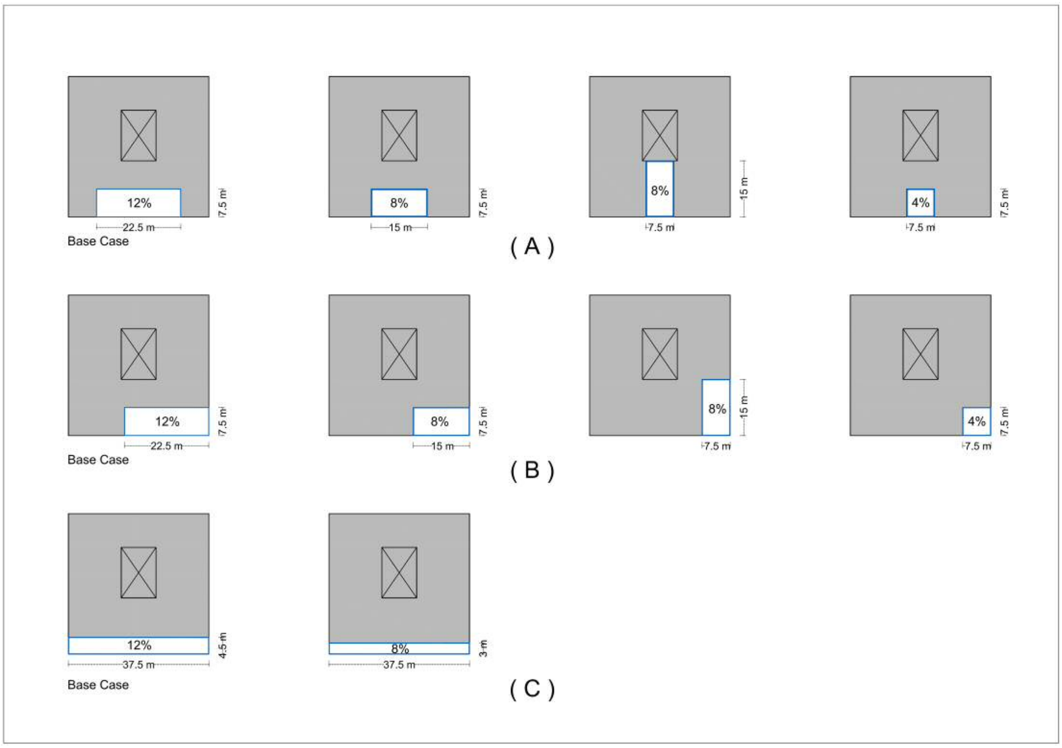


Figure 4-24. Schematic diagrams of length and depth comparative models for stage three, step 3a: (A) hollowed-out, (B) corner and (C) sided

Table 4-15. Independent settings for stage three, step 3a

Independent Variables	Details
Weather seasons	Three times in weather seasons, these are: Summer (Jun., Jul., Aug.) - Hottest hour: 28 Jun. at 14.00 Winter (Dec., Jan., Feb.) - Coldest hour: 7 Dec. at 9.00 am Mid-seasons (Mar., Apr., May, Sep., Oct., Nov.) - Typical: 19 Apr. at 9.00 am
Height of skycourt	
Prototype (A): hollowed-out space	: Three values: Six-floor height Three-floor height Nine-floor height
Prototype (B): corner space	: Three values: Six-floor height Three-floor height Nine-floor height
Prototype (C): sided space	: Three values: Six-floor height Three-floor height Nine-floor height
Orientation of skycourt	
Prototype (A): hollowed-out space	: Four values: South North West East
Prototype (B): corner space	: Four values: South-east North-west West-south East-north
Prototype (C): sided space	: Four values: South-east-west North-east-west West-south-north East-south-north
Percentage of area to GIA	
Prototype (A): hollowed-out space	: Three values: 12% of GIA 8% of GIA 4% of GIA
Prototype (B): corner space	: Three values: 12% of GIA 8% of GIA 4% of GIA
Prototype (C): sided space	: Two values: 12% of GIA 8% of GIA
Length and Depth of skycourt (L × D)	
Prototype (A): hollowed-out space	: Four values: 22.5 m × 7.5 m 15 m × 7.5 m 7.5 m × 15 m 7.5 m × 7.5 m
Prototype (B): corner space	: Four values: 22.5 m × 7.5 m 15 m × 7.5 m 7.5 m × 15 m 7.5 m × 7.5 m
Prototype (C): sided space	: Two values: 37.5 m × 4.5 m 37.5 m × 3 m

4.6.3.2 Step 3b: Optimising the Ventilation Openings

In this stage, the vertical locations and horizontal positions of openings for air inlets and air outlets were investigated to improve the airflow performance within the skycourt space. The study suggests alternatives for improvement when considering the vertical location (distribution) of air inlet and air outlet openings between the floor level, and the ceiling level of the skycourt. Another arrangement considered includes the horizontal positions of inlet and outlet openings. These alternatives are the following:

First, vertical locations of air inlet and air outlet openings regarding their relation with the floor and the ceiling of the skycourt (Figure 4-25):

(a) All air inlet openings are located at the floor level of the skycourt, while the all air outlet openings are located at the ceiling level of the skycourt.

(b) Air inlet openings are located at both floor and ceiling level of the skycourt, and the air outlet openings are located at both floor and ceiling level of the skycourt.

(c) All air inlet openings are located at the floor level of the skycourt, while the air outlet openings are located at the floor level and at the ceiling level of the skycourt.

(d) Air inlet openings are located at the floor level and the ceiling level of the skycourt, while all air outlet openings are located at the ceiling of the skycourt.

(e) Air inlet openings are located at the floor and ceiling level of the skycourt, while all air outlet openings are located at the floor of the skycourt.

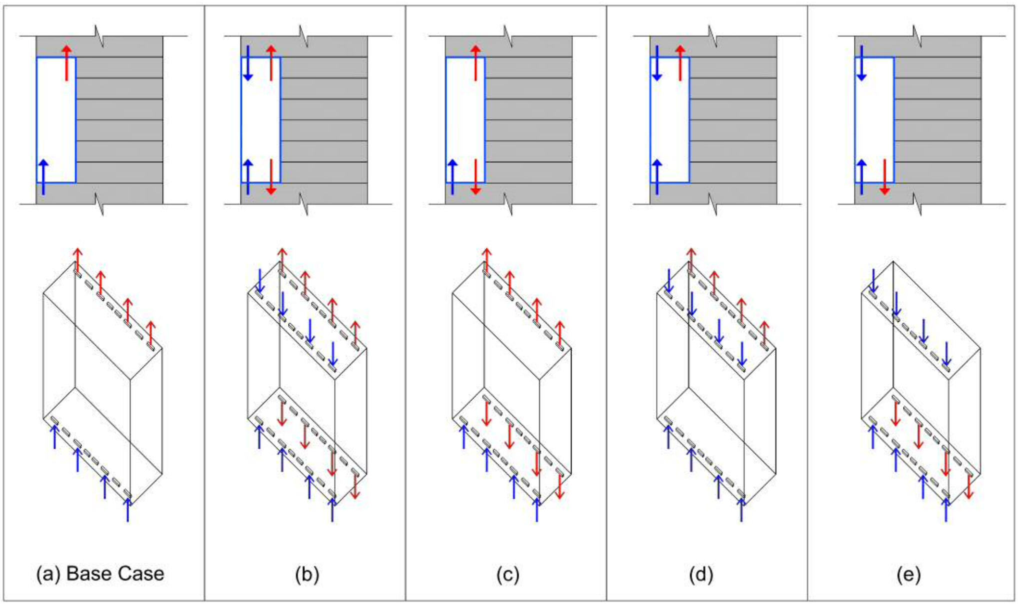


Figure 4-25. Schematic diagrams of vertical locations of air inlet and air outlet openings comparative models for stage 3, step 3b

Second, horizontal positions of air inlet and air outlet openings regarding their relation with the external façade and internal wall of the skycourt (Figure 4-26):

(a) Air inlet openings are closer to the external walls (which are connected with the external environment) of the skycourt, while the air outlet openings are closer to the internal walls of the skycourt (which are connected with the office zone).

(b) Air inlet openings are closer to the internal walls of the skycourt (which are connected with the office zone), while the air outlet openings are closer to the external walls (which are connected with the external environment) of the skycourt.

(c) Air inlet and outlet openings are closer to the external walls (that are connected with the external environment) of the skycourt.

(d) Air inlet and outlet openings are closer to the internal walls of the skycourt (which are connected with the office zone).

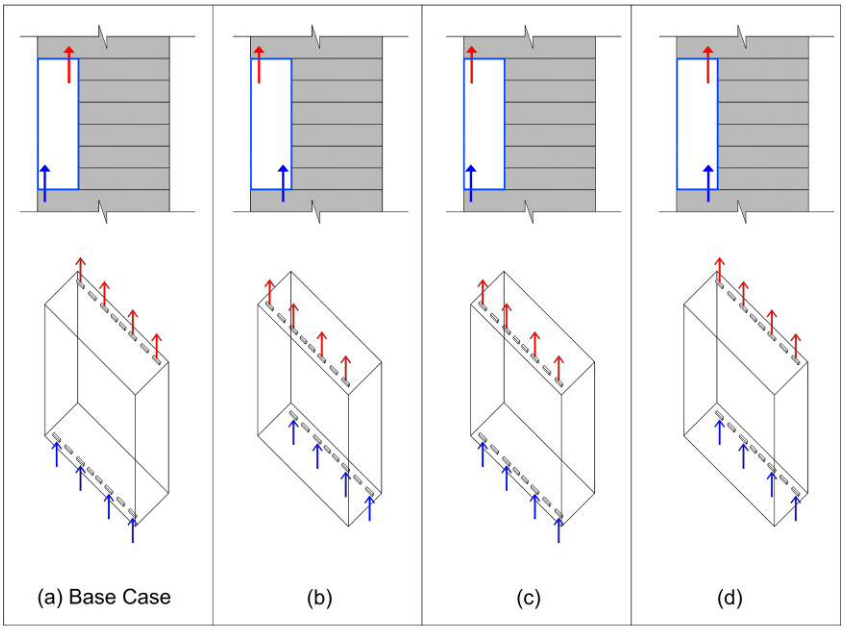


Figure 4-26. Schematic diagrams of horizontal position of air inlet and air outlet openings comparative models for stage 3, step 3b

The independent variables are summarised in Table 4-16. The total number of simulation cases in this step is 84; 3 runs in HTB2, and 81 runs in WinAir.

Table 4-16. Independent settings for stage three, step 3b

Independent Variables	Details
Weather seasons	Three times in weather seasons, these are: Summer (Jun., Jul., Aug.) - Hottest hour: 28 Jun. at 14.00 Winter (Dec., Jan., Feb.) - Coldest hour: 7 Dec. at 9.00 am Mid-seasons (Mar., Apr., May, Sep., Oct., Nov.) - Typical: 19 Apr. at 9.00 am
Air inlet and outlet location:	
Prototype (A): hollowed-out space	: Five values: Air openings Location (a) Air openings Location (b) Air openings Location (c) Air openings Location (d) Air openings Location (e)
Prototype (B): corner space	: Five values: Air openings Location (a) Air openings Location (b) Air openings Location (c) Air openings Location (d) Air openings Location (e)
Prototype (C): sided space	: Five values: Air openings Location (a) Air openings Location (b) Air openings Location (c) Air openings Location (d) Air openings Location (e)
Air inlet and outlet position:	
Prototype (A): hollowed-out space	: Four values: Air openings Position (a) Air openings Position (b) Air openings Position (c) Air openings Position (d)
Prototype (B): corner space	: Four values: Air openings Position (a) Air openings Position (b) Air openings Position (c) Air openings Position (d)
Prototype (C): sided space	: Four values: Air openings Position (a) Air openings Position (b) Air openings Position (c) Air openings Position (d)

4.6.4 Stage Four: Applying of the Improved Configurations

After the optimum configurations of the skycourt were identified from the previous stage the parameters were correlated. Optimisation considers the orientation, height, area, length, and depth of the skycourts, in addition to the vertical locations and horizontal positions of air inlet and outlet openings for each prototype.

The correlations are useful to assess the actual improvement that the new skycourt configuration could achieve in terms of thermal conditions of skycourts and the energy performance of the building. Fixed and independent variables are summarised in Table 4-17. The total number of simulation cases in this stage is 48.

Table 4-17. Fixed and independent settings for stage four

Fixed Parameters	**Details**
Climate conditions	London climate
Geometrical properties of the models	Vary according to the model under investigation
Energy simulation conditions	As defined in Table 4-10
CFD simulation conditions	As defined in Table 4-9
Independent Variables	**Details**
Prototype (A): hollowed-out space	Ventilation strategy: according to results of stage two Skycourt geometry: according to results of stage three, step (3a) Air openings place: according to results of stage three, step (3b)
Prototype (B): corner space	Ventilation strategy: according to results of stage two Skycourt geometry: according to results of stage three, step (3a) Air openings place: according to results of stage three, step (3b)
Prototype (C): sided space	Ventilation strategy: according to results of stage two Skycourt geometry: according to results of stage three, step (3a) Air openings place: according to results of stage three, step (3b)

4.7 APPROACH FOR PRESENTING RESULTS OF THE STUDY

After providing the input data, results will be generated as a detailed report of thermal condition parameters considering: air temperature, surface air temperatures, and airspeed. In addition, heating, cooling, ventilation, solar gain, fabric loads, and incident loads in terms of annual breakdown are produced. Therefore, due to the large number of simulated case studies and to avoid redundancy, the results of the simulations and the analyses are presented in the next two chapters according to the following approach:

Results outline: The results are organised and presented in five sections. Each section delivers the simulation results of a stage. Section one discusses the results obtained from thermal and energy simulations of the reference cases. Section two illustrates results of simulations for the proposed ventilation strategies. Section three presents thermal and energy performance results of optimising the skycourt design and ventilation strategy. Parameters include skycourts' height, orientation, area, length and depth. In addition, results are provided for optimisation of ventilation openings that include vertical locations and horizontal positions of air inlet and outlet openings within the skycourt. Section four deliberates the simulation results for the optimum configurations of each prototype. Section five illustrates the efficiency of the optimal skycourt compared to the original (reference) configuration.

For each comparison, two levels of analysis are conducted. The first level involves comparing the results for each model of the three prototypes of skycourts separately (chapter five). The second level of the analysis involves comparing the results of the three models that represent the three skycourt prototypes altogether (chapter six). The major focus of the comparison is on the following two output criteria: (i) energy performance of the building; and (ii) thermal comfort conditions in the skycourt.

Energy Performance Analysis: For this study, a major focus of the analysis is on the total annual energy demands for heating and cooling in the building. The total annual energy demand for heating and cooling (kWh/m^2.yr) of the skycourt and adjacent offices zones is used as a term of comparison between the cases. Then the percentage of total energy demand reduction is calculated (Table 4-18). Other energy results include the energy loads (kWh/m^2.yr) of heating gain, cooling gain, incident gain, solar gain, ventilation gain and fabric gain of the skycourt. These loads are compared in terms of a yearly basis to identify the effect of integrating each prototype of the skycourt on the energy performance of the building.

Table 4-18. Framework for the energy performance comparison

Criteria	Energy Performance
The total heating and cooling demand for the building (skycourt and adjacent offices) per year	Heating energy (kWh/m^2.yr) Cooling energy (kWh/m^2.yr)
The reduction of heating and cooling demand for the building	Percentage (%)

Thermal Performance Analysis: These results are analysed based on the concept of thermal conditions at specific times/hours. The level of thermal comfort for the different cases are compared among three hours of the year; each hour represents a season. These are:

- Summer case: the hottest external temperature (28.3°C) on 28th of June at 14.00 pm;
- Winter case: the coldest external temperature (-5°C) on 7th of December at 9.00 am;

- Mid-seasons' case: the mid-temperature (13.2°C) on April 19th at 9.00 am.

Air temperature (°C) and airspeed (m/s) in the occupied area of the skycourt are the main results that are considered in the analysis (Table 4-19).

Table 4-19. Framework for the thermal performance comparison

Criteria	Selected Times for CFD	Thermal Conditions
Summer case: The peak hour	The hottest external temperature on June 28th at 14.00	- Internal air temperature in the skycourt at occupancy level (up to 1.8 m height from the floor level) (C°) - Internal airspeed in the skycourt at occupancy level (up to 1.8 m height from the floor level) (m/s)
Winter case: The coldest hour	The coldest external temperature on December 7th at 9.00 am	
Mid-season case: The typical hour	The typical temperature on April 19th at 9.00 am	

4.8 SUMMARY

This chapter presented a description of the coupling simulation method and the research design undertaken to test the assumption and achieve the objectives of this study.

The process of setting up the hypothetical models was described. Design requirements that are recommended for office buildings in the UK by the British Council for Offices were considered to formulate the reference model with and without the skycourt. The tested prototypes of skycourts were selected according to the prototype analysis, which was developed in chapter three.

Then, criteria for assessing the results were defined. The main criteria adopted for comparison of the results were (i) The annual energy demand for heating and cooling for the building, and (ii) air temperature (°C) and airspeed (m/s) conditions at the occupied area of the skycourt in three peak hours.

The framework and the different settings for the simulation cases were introduced and summarised for both software, HTB2 and WinAir.

Finally, four main stages for implementing the simulation process were described in detail: stage one, integrating a skycourt when it obtains isolated air conditioning; stage two, incorporating an unheated and uncooled ventilation strategy in the skycourt; stage three, sensitivity analysis; stage four, applying the improved configurations of skycourts.

Figure 4-27 illustrates the outline of the study. Table 4-20 summaries the whole simulation process. In the next chapter, results of simulation will be presented accordingly.

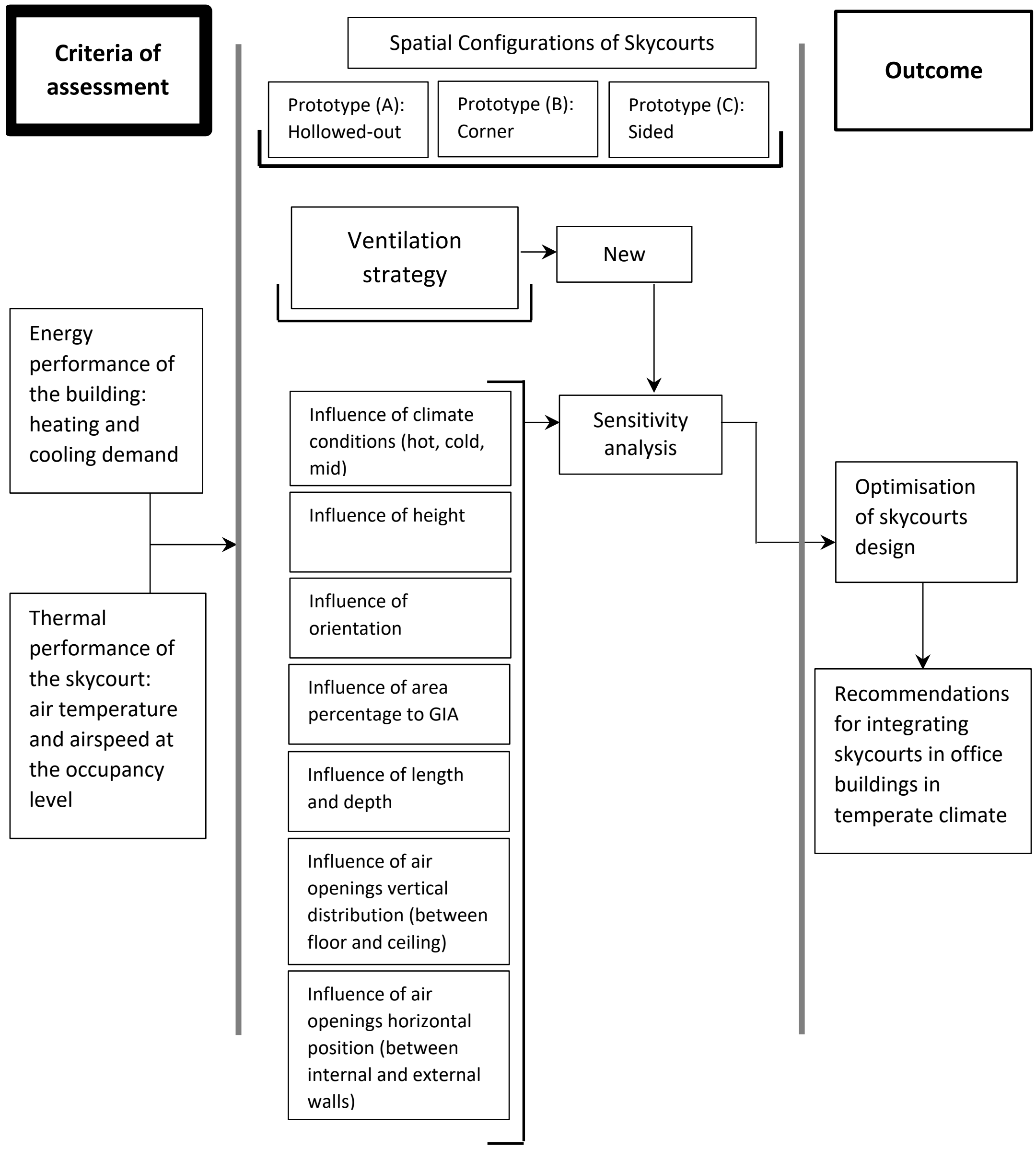


Figure 4-27. Research design

Table 4-20. Summary of modelling and simulation process

Stage	Aim	Settings	No. of Models		No. of Runs		Criteria for Assessment
			HTB2	WinAir	HTB2	WinAir	
One	To investigate the impact of integrating skycourts in high-rise office buildings	Table 4-12 Figures 4-14, 4-15, 4-16	4	3	4	9	- Total annul energy demand for heating and cooling for the whole building (kWh/m^2.yr)
Two	To identify the most suitable ventilation strategy	Table 4-13 Figure 4-20	15	15	15	45	- Air temperature at occupancy level in the skycourt (C°) at specific hours
Three	To define the optimum skycourt configuration for the optimal ventilation strategy	Tables 4-14, 4-15, 4-16 Figures 4-21, 4-22, 4-23, 4-24, 4-25, 4-26	42	66	42	198	
Four	To correlate the optimal parameters to assess the actual improvement	Table 4-17 7	12	12	12	36	- Airspeed at occupancy level in the skycourt (m/s) at specific hours
Total			**169**		**361**		

CHAPTER FIVE: RESULTS

5 RESULTS

5.1 INTRODUCTION

This chapter describes the results obtained from energy simulation (BES) regarding the energy demands for heating and cooling, and CFD air temperature and airspeed. These results will be used to examine the established assumptions in the study.

The chapter is divided into three main sections. Section one presents the simulation results obtained for prototype (A), the hollowed-out skycourt. Sections two and three present an overview of the main simulation results for prototype (B), the corner skycourt, and prototype (C), the sided skycourt, respectively. Detailed results for these prototypes are shown in appendix D in the appendices section. Each section presents the results based on the sequence of the simulation stages for each prototype, and concludes by summarising the key findings of each prototype.

5.2 SKYCOURT PROTOTYPE (A): THE HOLLOWED-OUT SKYCOURT

This section presents the results of the skycourt prototype (A), including four simulation stages and a concluding comparison stage. A summary of results is provided at the end of the section.

5.2.1 The Heated and Cooled Skycourt Results

The performance of the skycourt as an air-conditioned, heated and cooled space was examined. Both areas, the skycourt and the adjacent offices, are mechanically ventilated, cooled and heated separately (isolated ventilation strategy). This model is considered the reference case for the skycourt prototype (A), the hollowed-out skycourt, as this ventilation strategy presents the common approach for cooling and heating the skycourt.

To define the impact of integrating a skycourt in the design of an office building, a comparison of annual heating and cooling demands between this building and the building that does not include a skycourt is provided.

Energy performance: The comparison of energy performance between the model without a skycourt and the model with hollowed-out skycourt (A) showed that:

The annual total energy demand for heating and cooling of the building without a skycourt is less than the half of the demand of the building with a skycourt (Figure 5-1). A possible explanation for this result is that the skycourt volume is a glazed space. Therefore, it receives high solar gain through the external façade, and this requires a high-energy demand to cool the skycourt. The above result agrees with the findings of previous studies, which found that transitional buffer zones consume more energy than other spaces of similar size to accomplish the same level of thermal comfort (Pitts *et al.* 2008; Göçer *et al.* 2006). This may be as high as three times per unit area or volume of ordinary indoor spaces (Pitts and Saleh 2006).

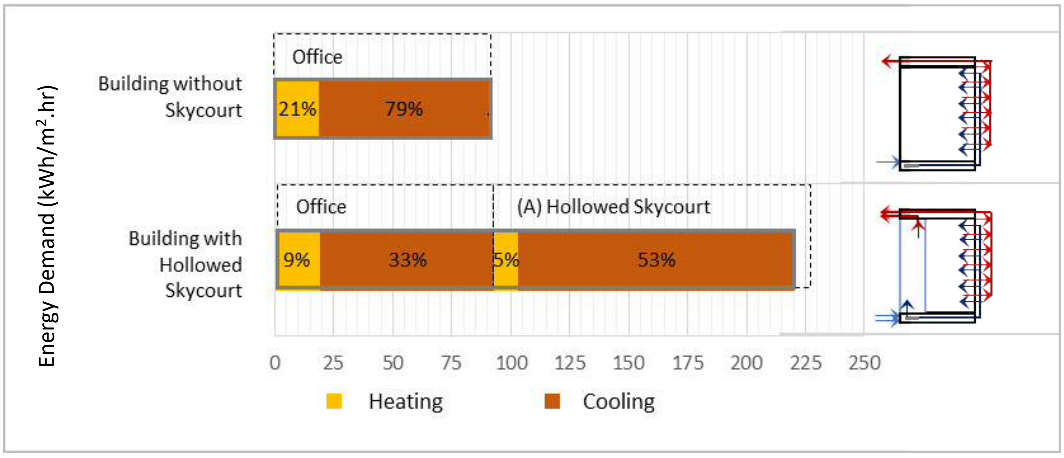


Figure 5-1. Annual heating and cooling demand comparison between building without a skycourt, and building with a hollowed-out skycourt: heated and cooled skycourt

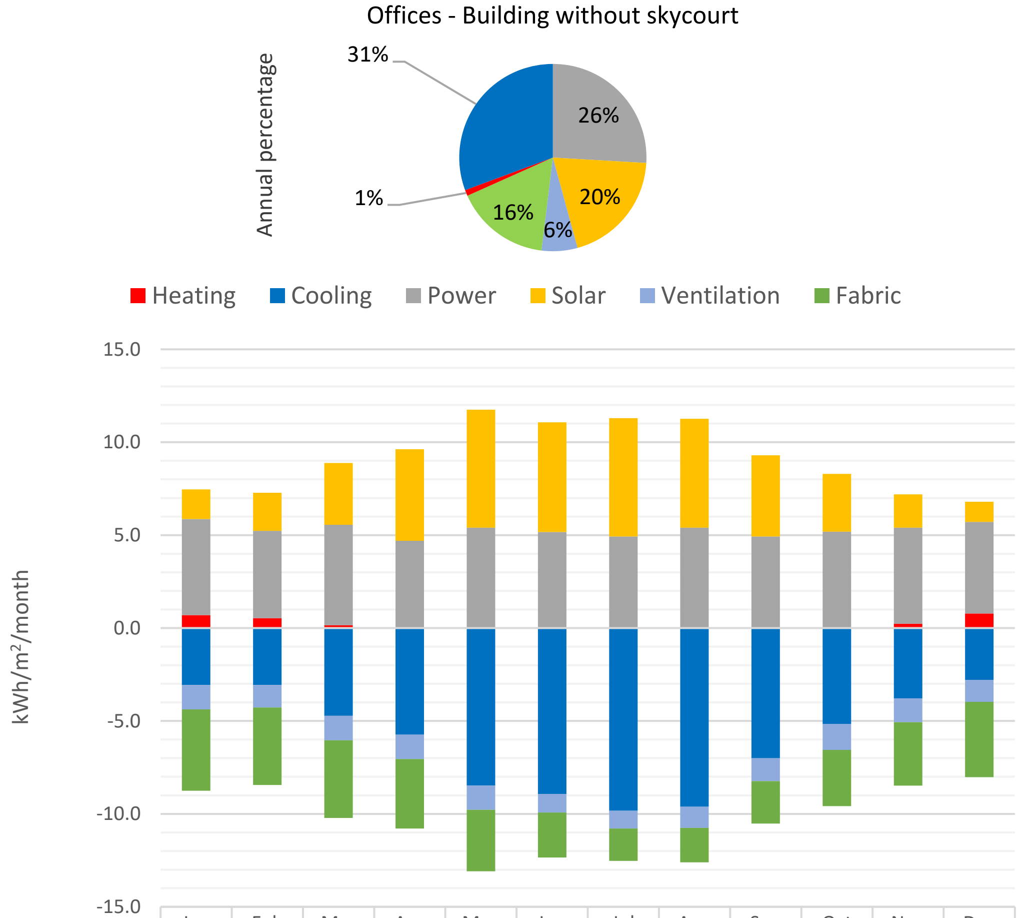
Also, it is clear that the cooling demand accounts for a high portion of energy consumption in both buildings; i.e. about 80% of the total heating and cooling demand. This result agrees with previous studies, which reported that cooling becomes dominant in contemporary buildings in the UK (Hitchin and Pout 2001). Annual heating and cooling demands for the reference skycourt (A) building equal 220.5 kWh/m^2.yr; more than 85% of the total demand is for cooling.

Breakdown of the annual energy loads, including power, solar, ventilation and fabric for offices in the building without a skycourt (Figure 5-2) and the building with a skycourt (Figure 5-3) showed that:

(i) Power gain due to lighting and office equipment requires over 25% of the total loads.

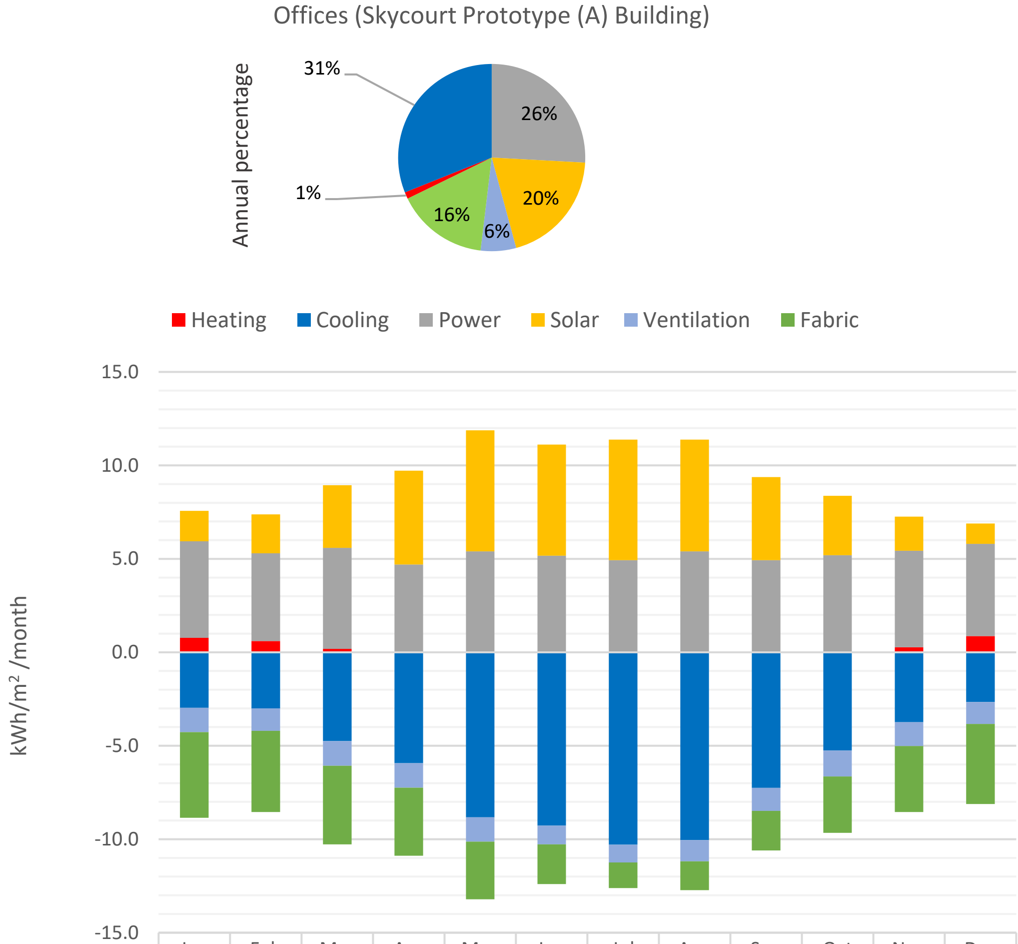
(ii) Solar gain accounts for about 20% of the total loads.

(iii) High cooling demands account for over 30%. Cooling is required all over the year. However, cooling demands recorded the highest amount of energy consumption between May and September. Large glazed facades, high internal gains and the high insulated facades of the model contribute to such high cooling demands (Spasis 2007).



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Fabric	-4.37	-4.17	-4.18	-3.74	-3.31	-2.42	-1.74	-1.85	-2.29	-3.03	-3.41	-4.05
Ventilation	-1.31	-1.20	-1.32	-1.31	-1.30	-1.00	-0.95	-1.14	-1.23	-1.39	-1.28	-1.18
Solar	1.60	2.05	3.32	4.92	6.35	5.90	6.36	5.86	4.36	3.11	1.80	1.08
Power	5.17	4.70	5.40	4.70	5.40	5.17	4.93	5.40	4.93	5.17	5.17	4.93
Cooling	-3.07	-3.07	-4.72	-5.74	-8.47	-8.92	-9.83	-9.62	-7.00	-5.17	-3.79	-2.80
Heating	0.70	0.53	0.15	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.23	0.78

Figure 5-2. Heating, cooling, power, solar, ventilation and fabric loads comparison for office building without a skycourt



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Fabric	-4.58	-4.34	-4.21	-3.64	-3.09	-2.12	-1.36	-1.54	-2.11	-3.01	-3.53	-4.29
Ventilation	-1.31	-1.20	-1.32	-1.31	-1.30	-1.00	-0.95	-1.14	-1.23	-1.39	-1.28	-1.17
Solar	1.63	2.08	3.35	5.02	6.47	5.95	6.45	5.98	4.44	3.17	1.82	1.09
Power	5.17	4.70	5.40	4.70	5.40	5.17	4.93	5.40	4.93	5.17	5.17	4.93
Cooling	-2.96	-3.00	-4.75	-5.93	-8.82	-9.27	-10.30	-10.04	-7.25	-5.26	-3.74	-2.66
Heating	0.77	0.60	0.18	0.01	0.00	0.00	0.00	0.00	0.00	0.03	0.27	0.87

Figure 5-3. Monthly heating, cooling, power, solar, ventilation and fabric loads comparison for office in the building with a hollowed-out skycourt (A): heated and cooled skycourt

The comparison between cooling demands for adjacent offices to the skycourt, individually, showed that these offices consume similar energy in general. However, the offices alongside the lower and the top parts of the skycourt have 1% less cooling demands. This decrease can be due to the influence of the skycourt as a shelter element (Figure 5-4).

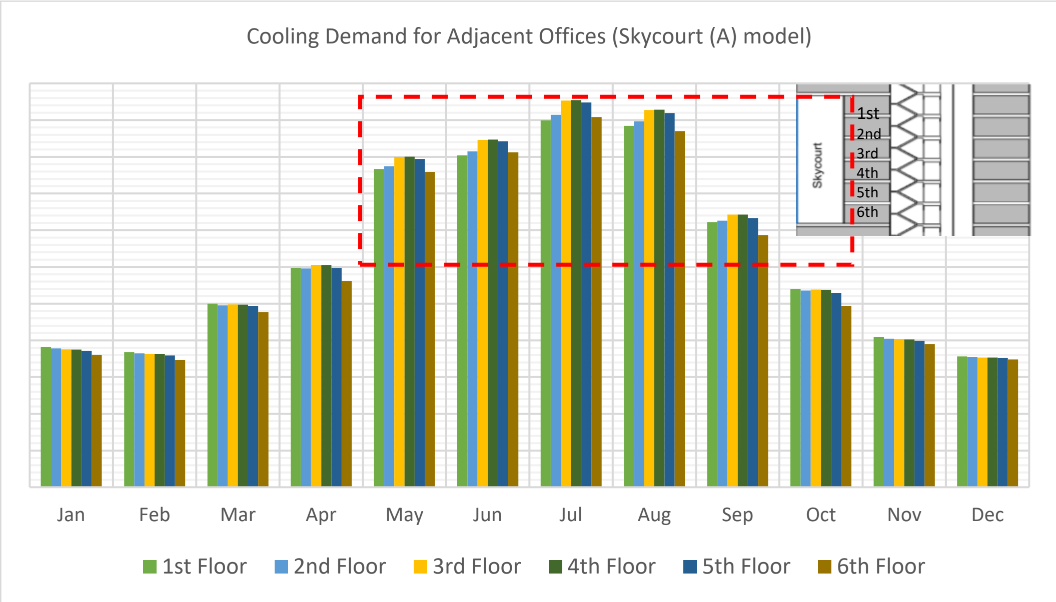
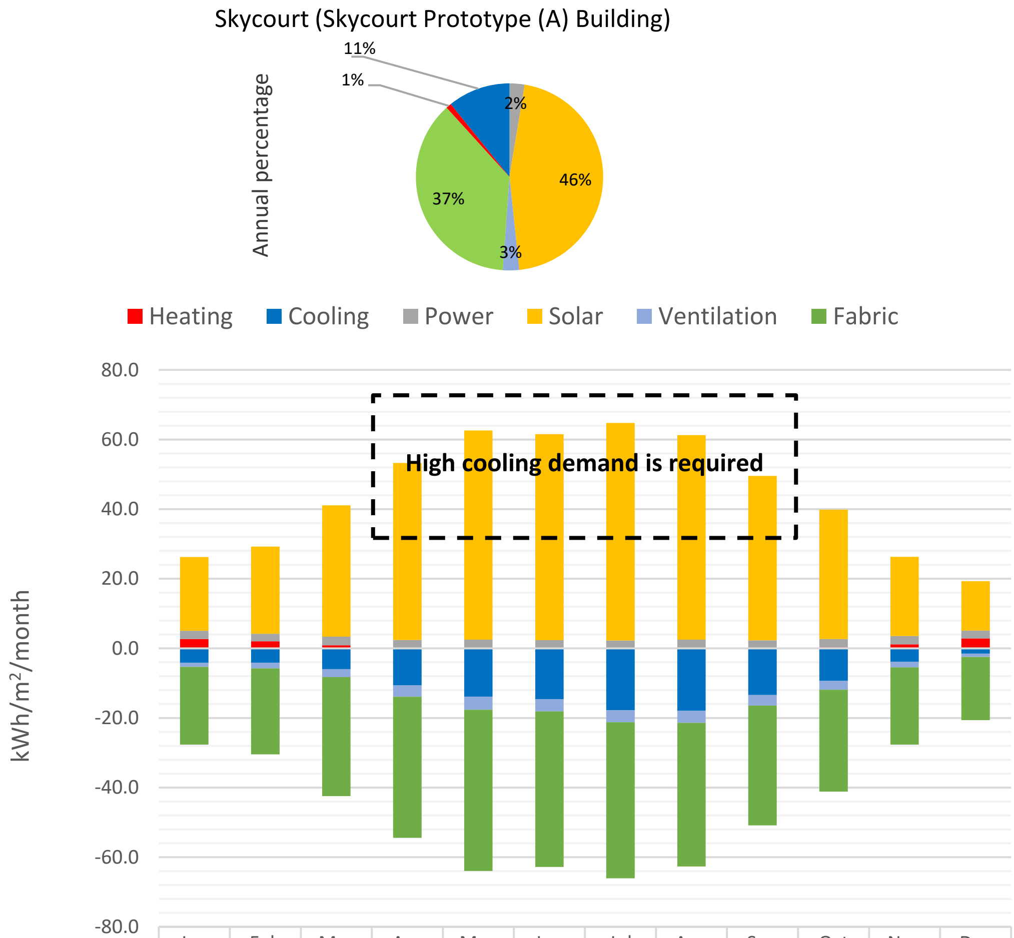


Figure 5-4. Diagram showing monthly cooling demand comparison for offices in the building with a hollowed-out skycourt (A)

The breakdown of the skycourt's monthly energy loads (Figure 5-4) showed that solar gain accounts for the highest heat in summer and transitional seasons. It recorded about half of the total loads, i.e. 500 kWh/m^2.yr. This result can be explained due to the fact that solar heat gain is affected by the orientation and envelope of the building. Thus, maximum gain occurs at the south façade in spring and autumn (Danielski *et al.* 2016) as the lower angle of the sun causes direct radiation onto the vertical surfaces. The skycourt in the reference case is oriented to the south, and it is fully glazed. This indicates that a high cooling demand is required to mediate the indoor thermal conditions of such skycourts.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Fabric	-22.34	-24.72	-34.22	-40.54	-46.32	-44.73	-44.83	-41.23	-34.39	-29.28	-22.22	-18.13
Ventilation	-1.14	-1.60	-2.31	-3.27	-3.78	-3.50	-3.45	-3.46	-3.04	-2.54	-1.56	-0.99
Solar	21.22	25.04	37.71	50.87	60.11	59.15	62.49	58.77	47.26	37.16	22.77	14.20
Power	2.38	2.16	2.49	2.16	2.49	2.38	2.27	2.49	2.27	2.38	2.38	2.27
Cooling	-4.17	-4.11	-5.95	-10.63	-13.86	-14.60	-17.78	-17.96	-13.42	-9.35	-3.87	-1.48
Heating	2.68	2.05	0.89	0.22	0.00	0.00	0.00	0.00	0.03	0.31	1.16	2.86

Figure 5-5. Monthly heating, cooling, power, solar, ventilation and fabric loads comparison for skycourt of the building with a hollowed-out skycourt (A): heated and cooled skycourt

On the other hand, the ventilation load was low, i.e. 30.7 $kWh/m^2.yr$. This can be explained due to the low air change rate in this case. The ventilation rate was calculated depending on the number of occupants, i.e. 10 L/s per person. This accounted for about 0.85 m^3/s volume rate for the skycourt, which is considered a low rate for such spaces.

The fabric load was high, i.e. 450 $kWh/m^2.yr$ due to the difference in temperatures between the inside of the skycourt and the outside environment. This variation in temperature causes transmission of heat through the envelope of the skycourt, particularly through its external wall. Heating and cooling loads accounted for about 12% of the total energy loads of the skycourt.

These results indicate the inefficient use of the isolated mechanical ventilation strategy for the integrated skycourt in an office building. Air-conditioned skycourts consume high portion of the total energy for cooling and heating of the building.

Thermal performance: It is apparent that the occupied area of the skycourt was thermally comfortable under this ventilation strategy (Figure 5-6 and Figure 5-7). It recorded air temperature in summer, i.e. 25°C with average airspeed of 0.08 m/s. Temperature in winter was about 19°C with high speed, i.e. 0.3 m/s. In a typical hour of the transitional seasons, the temperature recorded about 21°C and airspeed was 0.06 m/s.

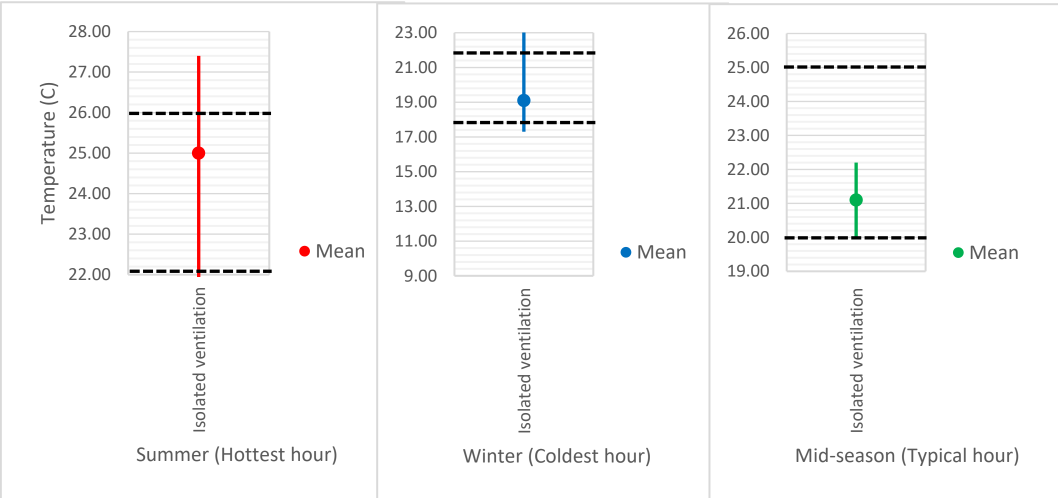


Figure 5-6. Air temperature at the occupancy level in skycourt (A) (dashed lines show comfort air temperature ranges): heated and cooled skycourt

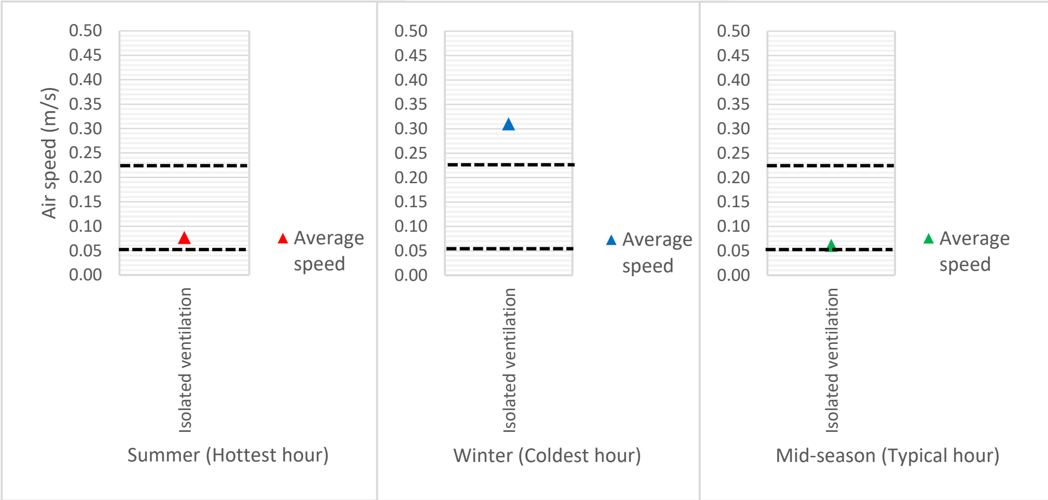


Figure 5-7. Airspeed comparison at the occupancy level in skycourt (A) (dashed lines show comfort airspeed ranges): heated and cooled skycourt

The CFD gradient of temperatures and airspeed inside the skycourt are illustrated in Figure 5-8. The section line is located at the midpoint of the skycourt; the dashed lines indicate the limits of the occupied area of the skycourt, which is the focus of the study.

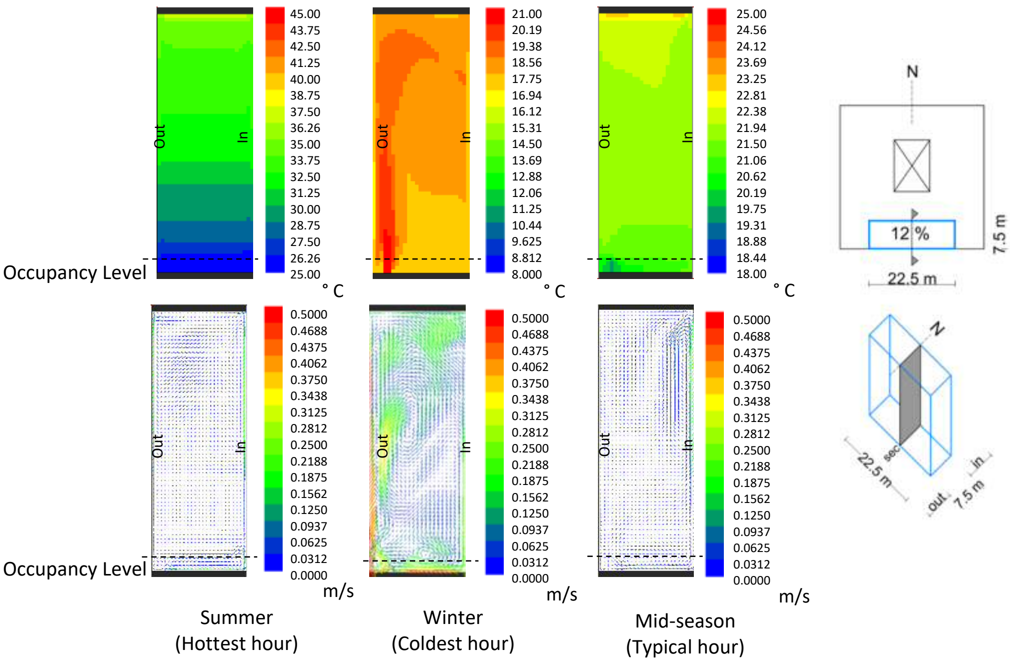


Figure 5-8. Thermal conditions in skycourt (A) at the hottest hour in summer, the coldest hour in winter and typical hour in mid-season: heated and cooled skycourt

Overall, energy and thermal performance results under the air-conditioned ventilation strategy for the skycourt demonstrate the ineffectiveness of this approach to achieve energy savings for the building.

The next section shows the results of the five proposed ventilation strategies.

5.2.2 The Unheated and Uncooled Skycourt Results

This stage aims to decide the most efficient ventilation strategy to be used for the skycourt. Five ventilation strategies were investigated under the assumption that the skycourt is unheated and uncooled. The most suitable strategy yields the highest energy savings for the building, and the most accepted thermal comfort conditions for the skycourt. The positive effect on adjacent offices is considered as well. The model from stage one was used as a reference to evaluate the energy and thermal performance when different ventilation strategies were applied.

Energy performance: In general, the skycourt as an unheated and uncooled space achieved an almost 50% reduction in the annual total energy demand for heating and cooling in comparison with the reference case. In the case of strategy two, the total demand was reduced from 220 kWh/m^2.yr to 91.9 kWh/m^2.yr.

The proposed strategies showed an enormous impact on the skycourt's loads and the internal environment, which in turn influenced the total heating and cooling demand for the building. The significant reason that heating and cooling loads equal zero is that the skycourt does not consume energy for heating or cooling.

It is apparent from the chart in Figure 5-9 that the power and solar gains have the same values due to the similar simulation settings. On the other hand, there were variations in ventilation and fabric loads.

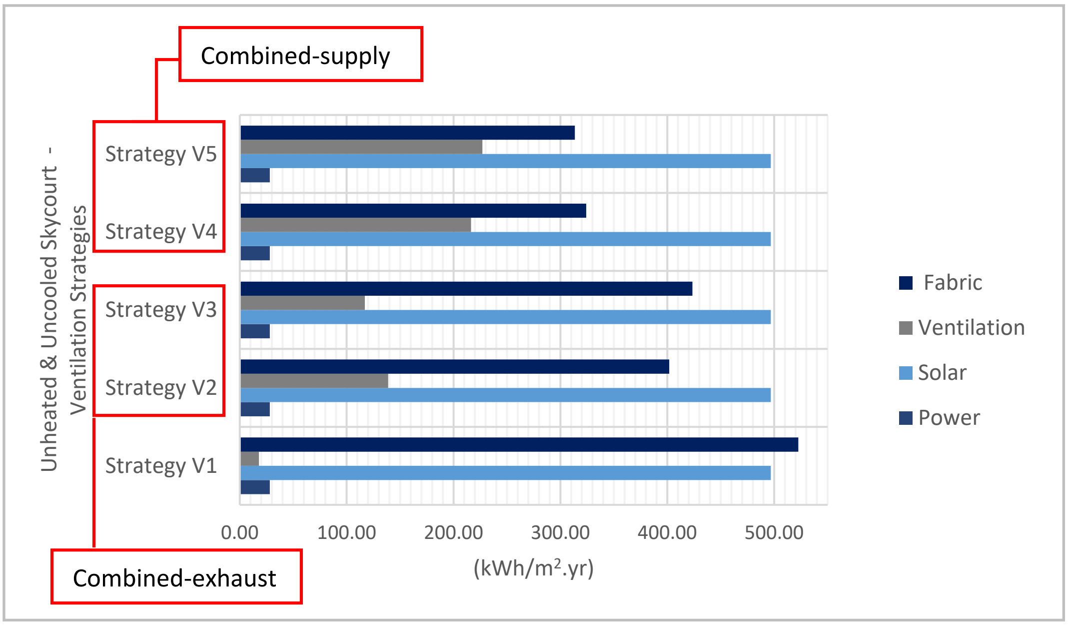


Figure 5-9. Annual solar, fabric and ventilation and power loads comparison for skycourt (A) under the proposed ventilation strategies in stage two

Strategy one records the least ventilation load, i.e. 18 kWh/m^2.yr and the highest fabric loss, i.e. 522.6 kWh/m^2.yr compared to the other strategies. The skycourt in this strategy is assumed a sealed space and depends on infiltration rate only. Strategies two and three accounted for lower ventilation loads, i.e. 138.8 kWh/m^2.yr and 117 kWh/m^2.yr respectively, correlated to strategies four and five, i.e. 216.4 kWh/m^2.yr and 227 kWh/m^2.yr respectively. A possible explanation for this could be the temperature difference between the supply air to the skycourt and the skycourt space. It was higher in the last two cases. Supply air for the skycourt in the combined-exhaust strategies depends on air exhaust from the offices, which is warmer than the supply air in the combined-supply strategies in winter and transitional seasons and colder in summer.

On the other hand, the chart shows that there is a negative correlation between the ventilation and the fabric loads. When the ventilation load decreased, the fabric load increased to achieve energy balance with heat gain inside the skycourt space. Fabric loss is influenced by the difference in temperatures between the inside and the outside of the skycourt. This difference in temperature was higher in the case of the combined-exhaust strategies.

It seems that a greater inlet airflow rate inside the skycourt in the cases of the combined-exhaust strategies causes a greater ventilation load for the skycourt. However, it has the opposite relation in the case of the combined-supplied ventilations. The ventilation rate for strategies two and four was 5.76 ac/h (5.58 m^3/s air volume rate), while it was 2.87 ac/h (2.79 m^3/s air volume rate) in strategies three and five.

Energy loads in the skycourt affect the total heating and cooling demand for the building and cause the following energy savings under the five ventilation strategies:

(i) strategy (V1): 57%, (ii) strategy (V2): 58%, (iii) strategy (V3): 57.7%, (iv) strategy (V4): 50%, and (v) strategy (V5): 55.4%. It seems that the combined-exhaust ventilation strategies (two and three) show greater potentials for energy saving than the combined-supply ventilation strategies (four and five).

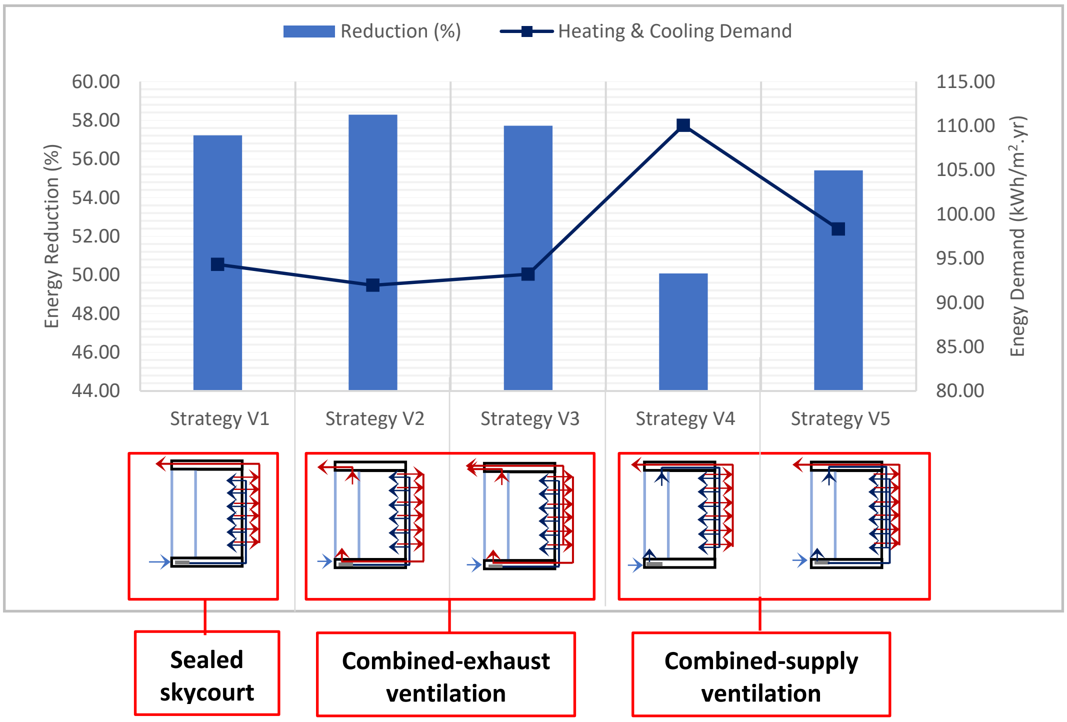


Figure 5-10. Annual total heating and cooling comparison under the proposed ventilation strategies in stage two

The overall results indicate the efficiency of the combined ventilation strategies to reduce the annual energy demand of heating and cooling for the building, significantly; these strategies are based on exhaust air from the offices. Strategy two, the combined-exhaust ventilation strategy, which depends on the maximum airflow rate exhaust from the adjacent offices to the skycourt, records the most energy savings.

One notable result concerning adjacent offices of the skycourt shows that the ventilation strategies have a positive impact on upper offices. It causes a reduction in the total heating and cooling requirements for this floor of about 1% compared to the other ventilation strategies. This is related to the influence of the ventilation strategies on thermal conditions inside the skycourt, which in turn affect the temperatures of the offices.

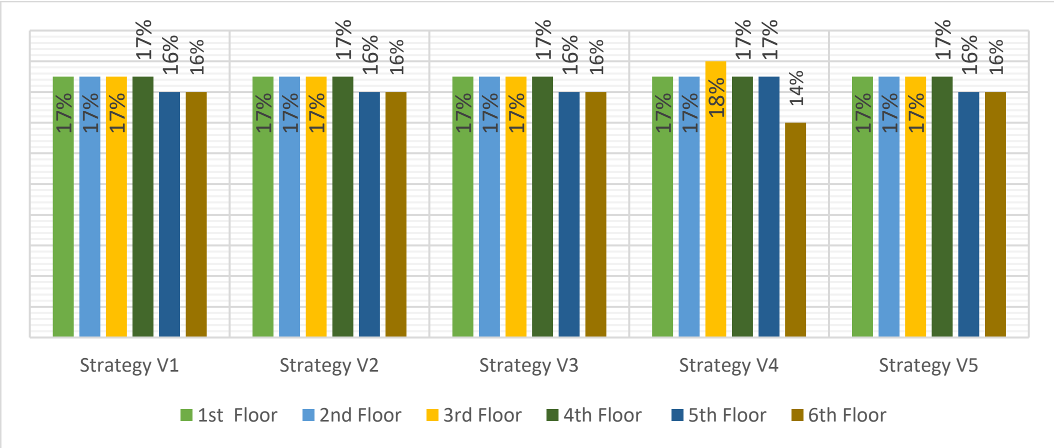


Figure 5-11. Total percentage of heating and cooling demand comparison for the six adjacent offices under the proposed ventilation strategies in stage two

Thermal performance: It is evident that the skycourt cannot be considered a thermal comfort space without an inlet airflow (Figure 5-12). The indoor air temperature using ventilation strategy one was very high, about 50°C at the hottest hour of summer. On the other hand, it was cold in winter, approximately 8°C at the coldest hour. Although the results show that the skycourt is thermally comfortable in transitional seasons, the indoor environment is insufficient for producing good air quality, as this strategy considered infiltration only.

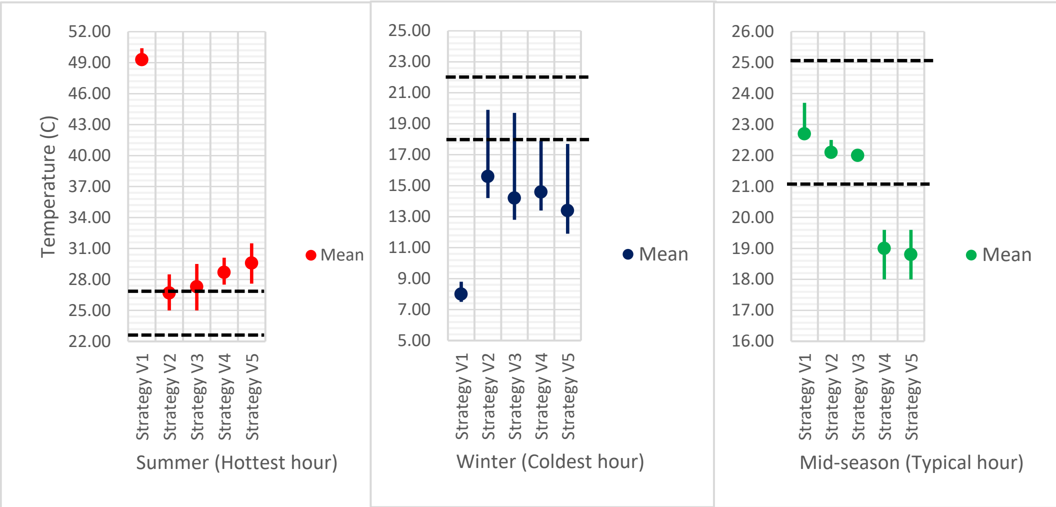


Figure 5-12. Air temperature comparison at the occupancy level in skycourt (A) (dashed lines show comfort air temperature ranges) under the proposed ventilation strategies in stage two

After the application of strategy two, the air temperature in the skycourt in summer was about 26.5°C, with 0.2 m/s average airspeed at the occupancy level. This temperature could be accepted to provide comfort in summer in an office environment as found in a previous study (Serghides *et al*. 2017). However, taking into consideration that the skycourt is a transitional space, a wider limit of temperature is allowed. At the coldest hour, the temperature graduated from 14.2°C to 19.9°C with 0.3 m/s. This range may not provide the required comfort degree in winter. However, it was the best temperature recorded between the proposed ventilation strategies in winter.

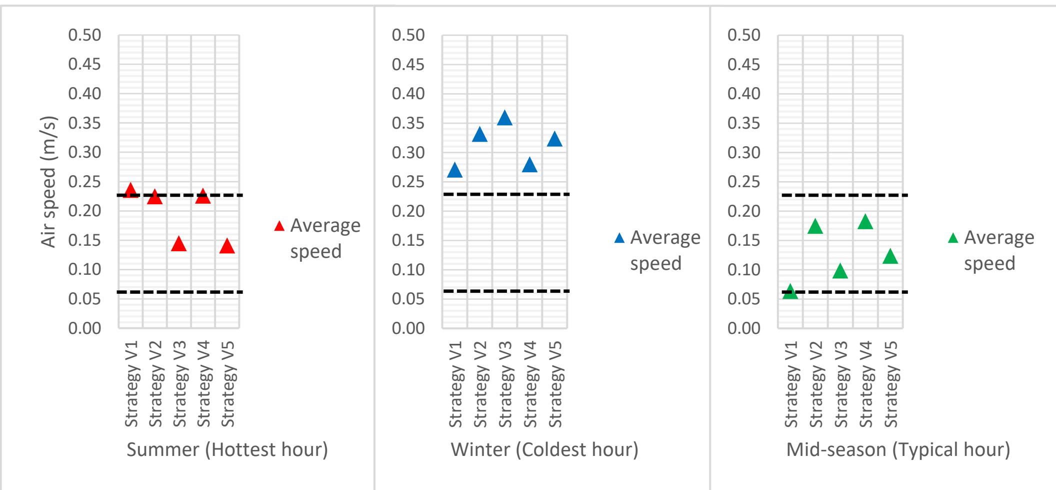


Figure 5-13. Airspeed comparison at the occupancy level in skycourt (A) (dashed lines show comfort airspeed ranges) under the proposed ventilation strategies in stage two

On the other hand, reducing the airflow volume rate inside the skycourt, as suggested in strategy three, caused a rise of air temperature in summer and a decline of air temperature in winter. In summer, the temperature recorded 27.3°C of 0.14 m/s, whereas in winter it ranged between 12.8°C and 19.7°C of 0.36 m/s airspeed.

The skycourt in strategy four performs as a space for mediating the air temperature before entering the office zones. This case provided in summer peak time, air temperature of 28.7°C, and recorded airspeed of 0.22 m/s. In winter, the temperature ranged from 13.4°C to 18°C with 0.28 m/s. Strategy five obtained about 29.6°C with 0.14 m/s at the summer peak hour, and 11.9°C to 17.7°C with 0.32 m/s at the winter peak hour.

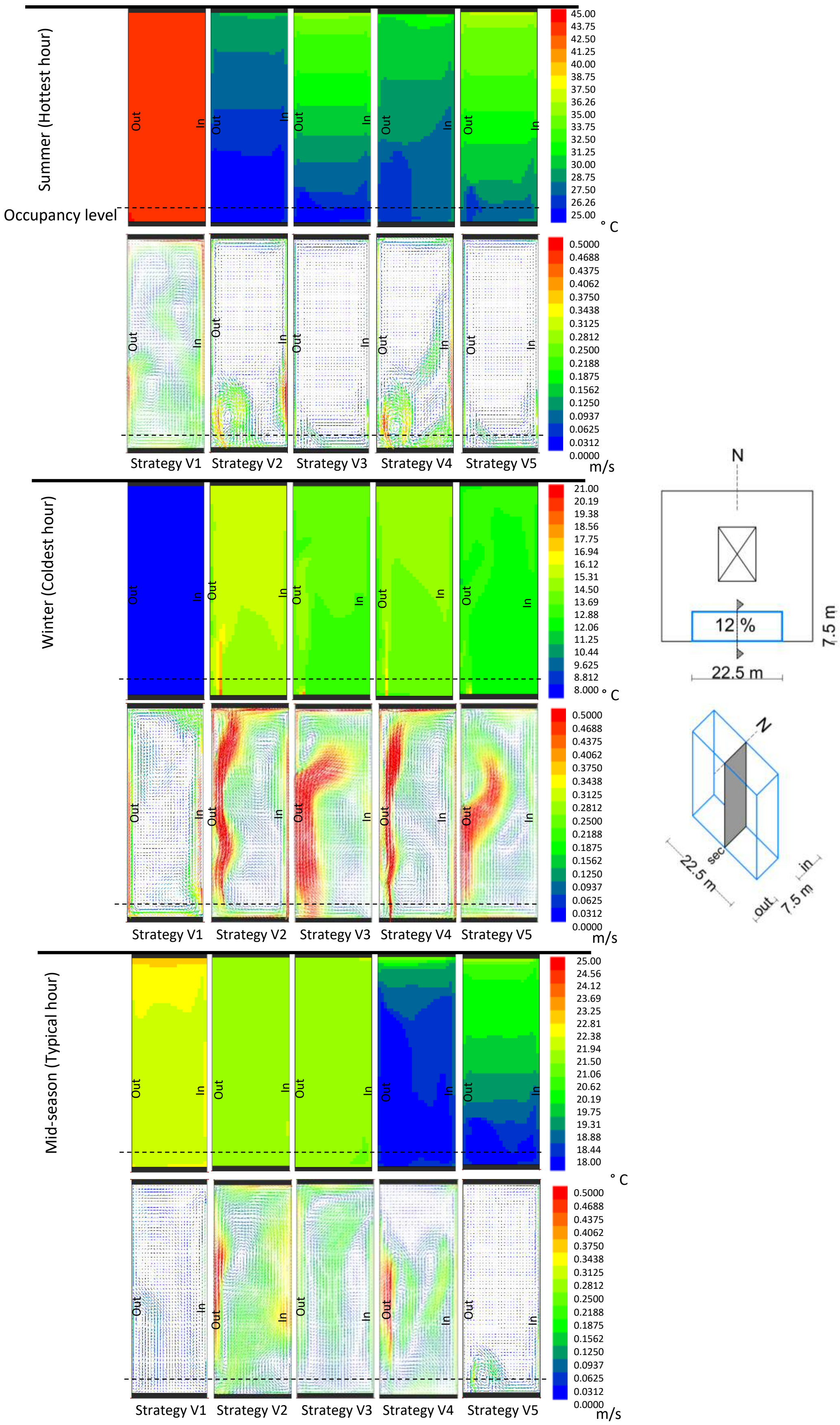


Figure 5-14. Thermal conditions comparison in skycourt (A) at the hottest hour in summer, the coldest hour in winter and typical hour in mid-season under the proposed ventilation strategies in stage two

The simulation at a typical hour in spring showed that strategies one, two and three produced air temperature and airspeed within the level of comfort. However, strategies four and five produced a lower range of air temperature below the comfort level. The five strategies provided the following results: for strategy one, i.e. 22.7°C and 0.06 m/s; for strategy two, i.e. 22.1°C and 0.17 m/s; for strategy three, i.e. 22.0°C and 0.1 m/s; for strategy four, i.e. 19.0°C and 0.18 m/s; and finally about 18.8°C and 0.12 m/s for strategy five.

The results showed that temperatures obtained from ventilation strategy two are almost within the comfort temperature range in different times. Significantly, for cooling the skycourt in summer.

Considering the potential of using a combined-exhaust ventilation strategy (V2) in summer and transitional periods, and a combined-supply strategy (V4) in winter, a favourable temperatures can be confirmed. However, an energy consumption for heating and cooling will increase in comparison of using strategy two (V2) all over the year.

In conclusion, the simulation results highlighted that the combined ventilation strategies for the skycourt have potentials for saving energy and achieving thermal comfort, nevertheless, differently. The different findings of this stage of the research indicated that strategy two is the optimum ventilation strategy to minimise requirements for energy, besides ensuring thermal comfort at the skycourt. Therefore, it is applied as a ventilation strategy in the next stage of the research, stage three. Identification and use of the appropriate strategy will simplify further investigation of the key parameters that influence the energy demands and thermal performance of the skycourt in the next step.

Table 5-1. Ventilation settings identified from stage two: unheated and uncooled skycourt

Ventilation Settings	Details
Ventilation strategies	Ventilation strategy two (V2): depends on the maximum airflow volume rate exhausted from the adjacent offices to the skycourt
Airflow pattern/direction	All supply air enters through the offices. All air exhausts through the skycourt
Inlet air volume rate to the skycourt	5.58 m^3/s
Outlet air volume rate to the skycourt	5.58 m^3/s

5.2.3 The Sensitivity Analysis Results

This stage includes studying relationships between the different parameters of skycourts, and their influence on the performance of ventilation strategy two (V2). These parameters are orientation, height, area percentage to GIA, length to depth, locations of air inlet and outlet openings in relation to floor and ceiling levels of the skycourt, and finally, horizontal positions of air inlet and outlet openings.

The base model with the optimum ventilation strategy (strategy two) was used as a reference when comparing the impact of each parameter. A single parameter was changed, whereas the other parameters were kept identical to those in the reference case. Then, the results were compared to the base model to evaluate the effect of the change made on the simulation results. The results are presented for each parameter separately.

5.2.3.1 Impact of Orientation

The following section presents the simulation results for four comparative models of the skycourt prototype (A), according to its orientation: south, north, east and west. It should be noted that the positive values of energy reduction (%) in the charts indicate a decrease in the energy demand, while the negative values indicate the reverse.

Energy performance: The simulation results indicated a rise in the energy demand for heating and cooling in all orientations when compared to the base case (the south orientation of the skycourt).The average increase was small, i.e. 0.1% to 0.14%. The simulation reported the following annual heating and cooling demands for south, north, west and east cases, respectively: 91.9 kWh/m^2.yr; 92.1 kWh/m^2.yr; 92.03 kWh/m^2.yr; and 92.09 kWh/m^2.yr (Figure 5-15).

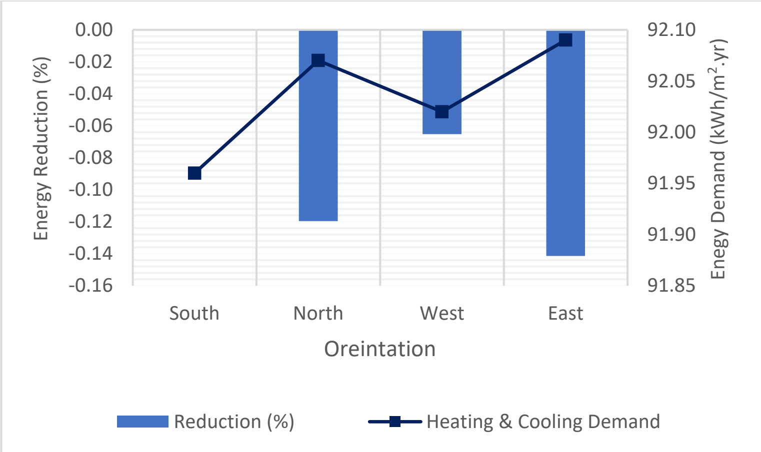


Figure 5-15. Annual total heating and cooling comparison for the building integrated skycourt (A): orientation

The results obtained from the breakdown of the energy loads for the skycourt showed that the solar heat gain varies with the orientation of the skycourt (Figure 5-16). The south orientation recorded the highest solar loads for the skycourt, i.e. 497 kWh/m^2.yr; the west is next, i.e. 432 kWh/m^2.yr; then the east orientation, i.e. 418 kWh/m^2.yr. The north orientation recorded the lowest solar gains, i.e. 352 kWh/m^2.yr. These results could be explained by the fact that the south and the west facades obtain the maximum solar intensity radiation.

The skycourt performs as a thermal buffer zone for the adjacent offices. Therefore, this can reduce heat gains in these areas, which in turn reduces cooling demands for these offices. Takening into consideration that the skycourt does not consume energy for heating and cooling, and considering the air exhausts from the offices, the energy demand for heating and cooling for the building is the least for the southern facades. This is followed by west, east and lastly north directions.

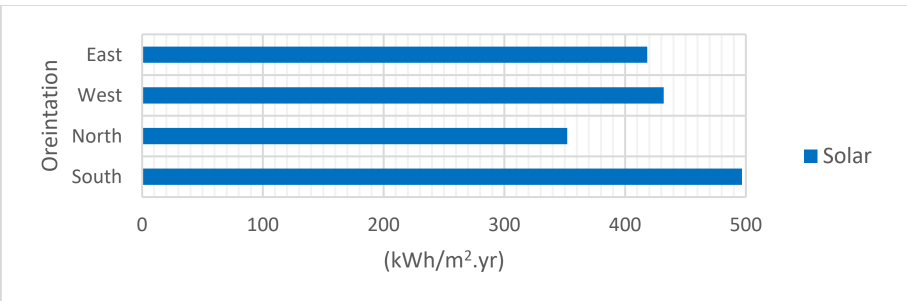


Figure 5-16. Annual solar loads comparison for skycourt (A): orientation

According to these results, skycourt (A) oriented to the south can ensure the minimum energy demands for heating and cooling for the building.

Thermal performance: The air temperature in the whole skycourt volume in summer was the highest when the skycourt is located in the south. It slightly increased from 25°C at the floor level to 32°C at the upper part of the skycourt. Air temperature decreases in skycourts in west, then east and finally north orientation. In these three cases, the air temperature ranged between 25°C and 29°C in the skycourt (Figure 5-17). The observed increase in the south case temperatures could be due to the intensity of solar radiations as mentioned previously.

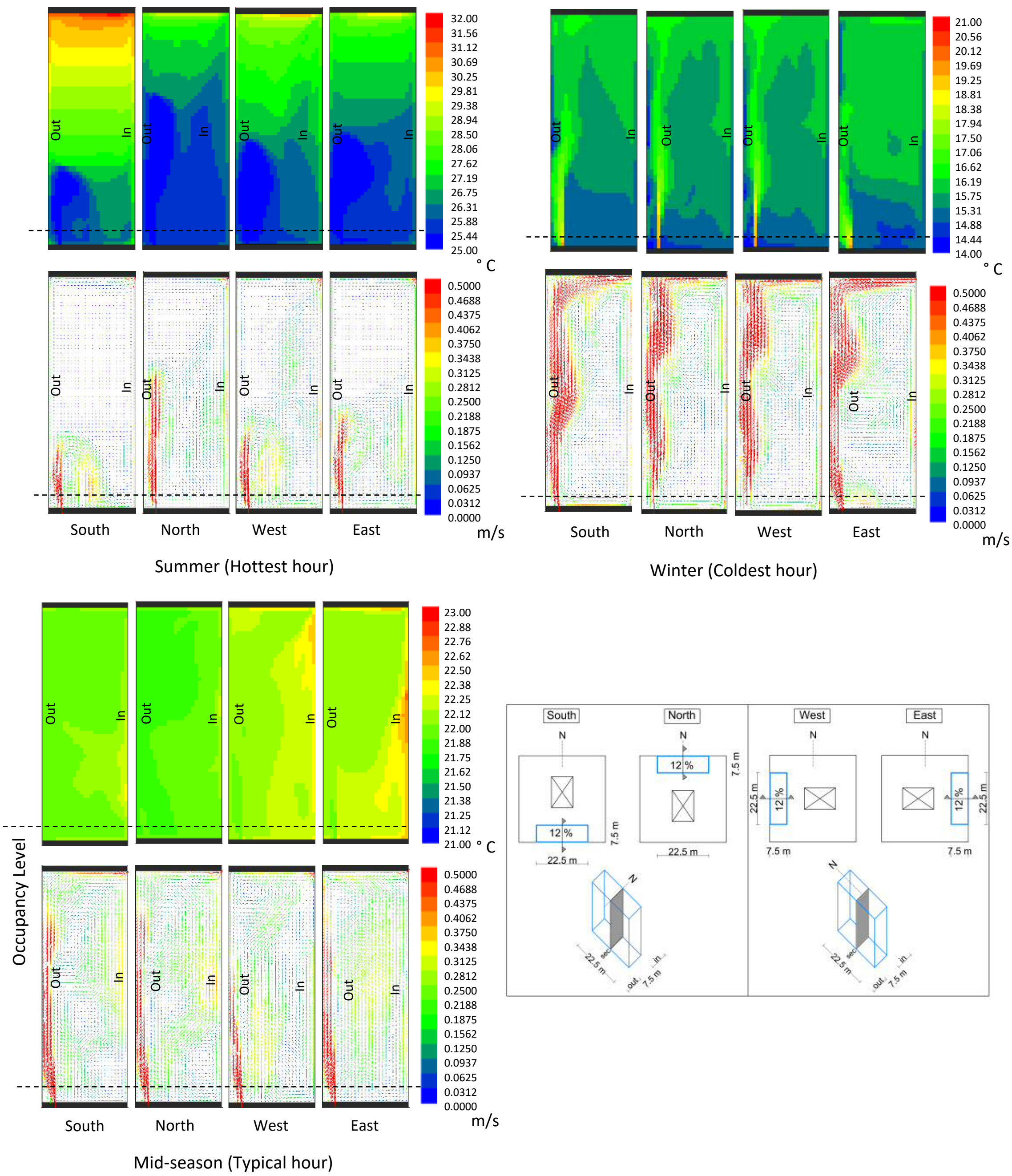


Figure 5-17. Thermal conditions comparison in skycourt (A) at the hottest hour in summer, the coldest hour in winter and typical hour in mid-season: orientation

However, the different orientations of skycourts recorded similar temperatures at the occupied area of the skycourt.

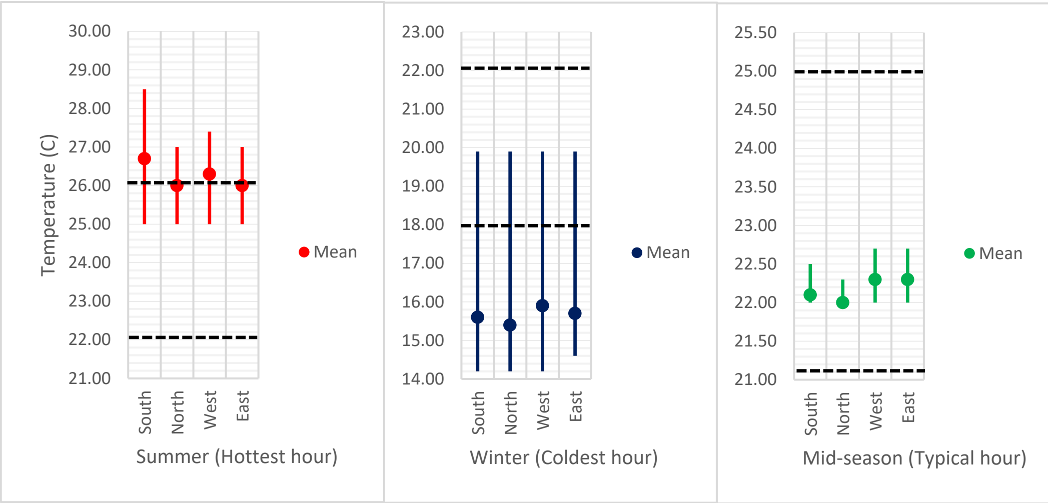


Figure 5-18. Air temperature comparison at the occupancy level in skycourt (A) (dashed lines show comfort air temperature ranges): orientation

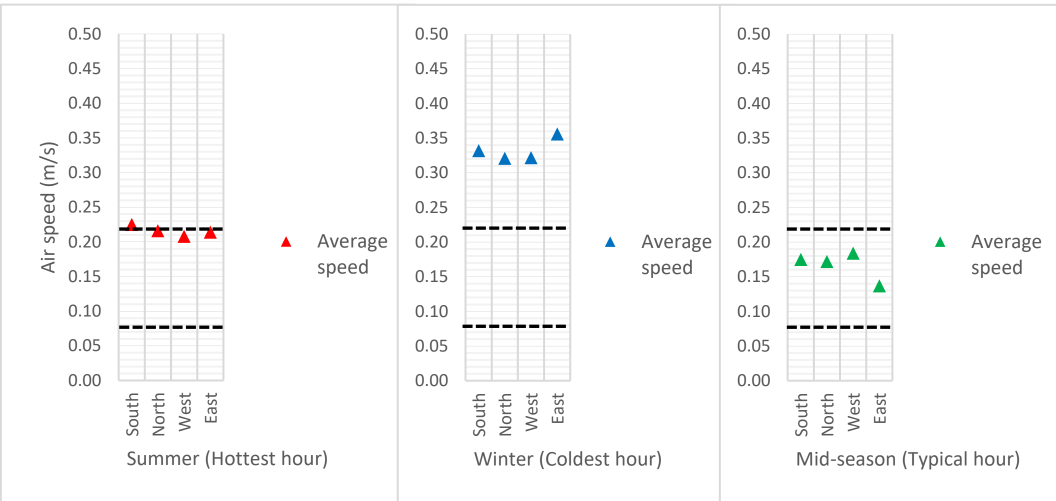


Figure 5-19. Airspeed comparison at the occupancy level in skycourt (A) (dashed lines show comfort airspeed ranges): orientation

The cases recorded an accepted comfort level of air temperature in summer. Temperature ranged between 25°C and 26.5°C, and the average airspeed was found to be similar, i.e. 0.2 m/s. The cases recorded air temperature ranging between 14.2°C and 20°C of 0.3 m/s in winter. In addition, the skycourt has potentials of thermal comfort in the transitional seasons for all cases; it recorded a mean air temperature of 22.1°C with 0.17 m/s (Figure 5-18 and Figure 5-19).

However, the north and east orientations of the skycourt provided favourable conditions in the summer. On the other hand, south is the preferred orientation in winter.

According to the findings of this step, a south orientation for skycourt (A) is suggested to ensure maximum energy savings, and the north orientation is proposed to support thermal comfort cooling conditions. Therefore, south and north orientations were selected for more investigation in stage four.

5.2.3.2 Impact of Height

The influence of height on the skycourt was investigated. Three different heights of skycourt were examined; these were skycourts of six-floor height, three-floor height and nine-floor height.

Energy performance: The results presented a positive relation between the height of the skycourt and the energy saving. Heating and cooling demands decreased when the skycourt became taller (Figure 5-20).

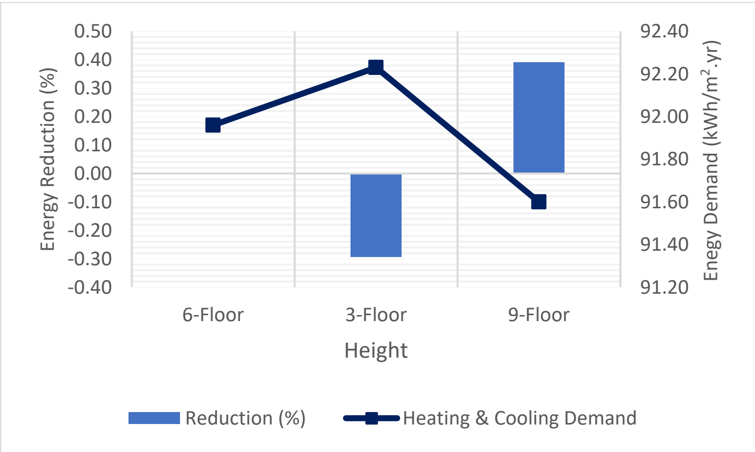


Figure 5-20. Annual total heating and cooling comparison: height

The nine-floor skycourt recorded an average decrease of less than 1% for each office per year compared to the three-floor skycourt. This can be related to the fact that the skycourt provides a shading façade to the adjacent offices. Therefore, more floors of offices can benefit from this in the case of taller skycourts.

Thermal performance: Air temperature results showed that the increase of the skycourt height causes lower temperature ranges in summer and higher temperature in winter (Figure 5-21). However, this factor affected the airspeed negatively at the occupied level of the skycourt and caused uncomfortable conditions in all seasons (Figure 5-22).

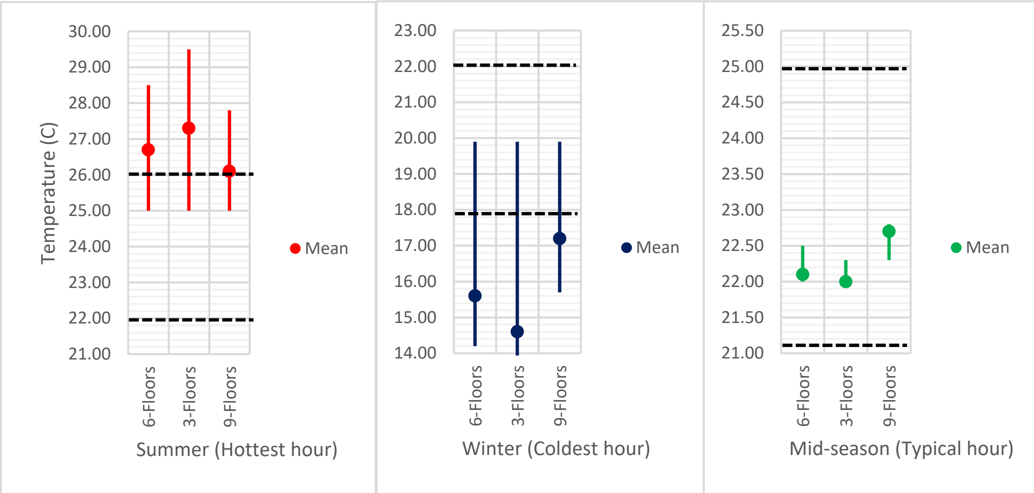


Figure 5-21. Air temperature comparison at the occupancy level in skycourt (A) (dashed lines show comfort air temperature ranges): height

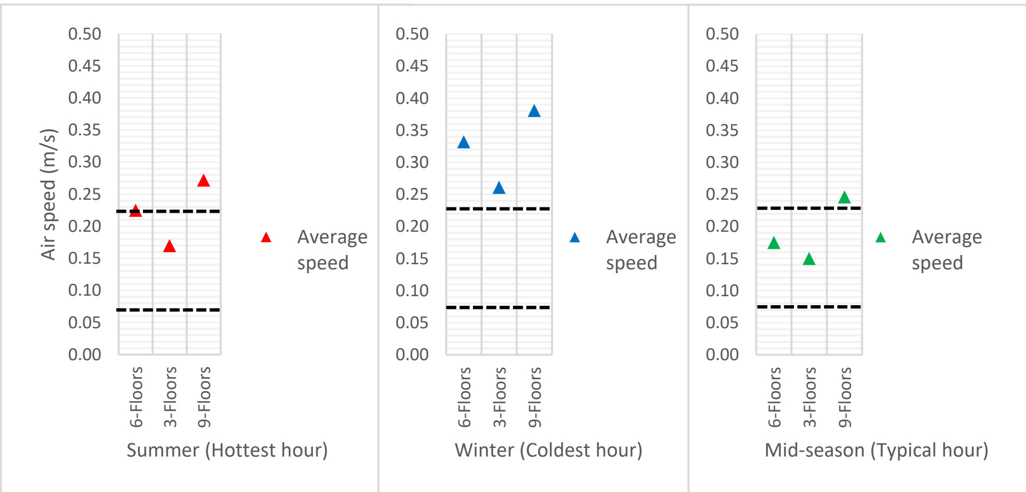


Figure 5-22. Airspeed comparison at the occupancy level in skycourt (A) (dashed lines show comfort airspeed ranges): height

This can be explained due to the mechanism of the ventilation strategy, which supplies air to the skycourt from adjacent offices; a taller skycourt means more air volume rate enters this space. The air volume rate that entered the skycourt in the nine-floor case was three times the rate of the three-floor case.

Taking into consideration that the skycourt has a fixed area in these cases, the following results were recorded at the occupied level of the skycourt:

(i) 25°C to 28.5°C of 0.23 m/s for the six-floor case; (ii) 25°C to 29.5°C of 0.17 m/s for the three-floor case; and (iii) 25°C to 27.8°C of 0.27 m/s for the nine-floor case in summer. In addition, (i) 14.2°C to 19.9°C of 0.33 m/s for the six-floor case; (ii) 13.5°C to 19.9°C of 0.26 m/s for the three-floor case; and (iii) 15.7°C to 19.9°C of 0.38 m/s for the nine-floor case in winter. The cases reported comfortable temperatures in transitional seasons, yet the nine-floor case recorded higher airspeeds than the comfort limit.

Although the nine-floor skycourt can provide the highest energy saving compared to the other cases, it reduces the total floor area of the offices in the building. This may not be an efficient proposal for investment. In addition, it is apparent that the six-floor case is favourable in terms of both air temperature and airspeed together. Therefore, this height was selected for the next stage in this study.

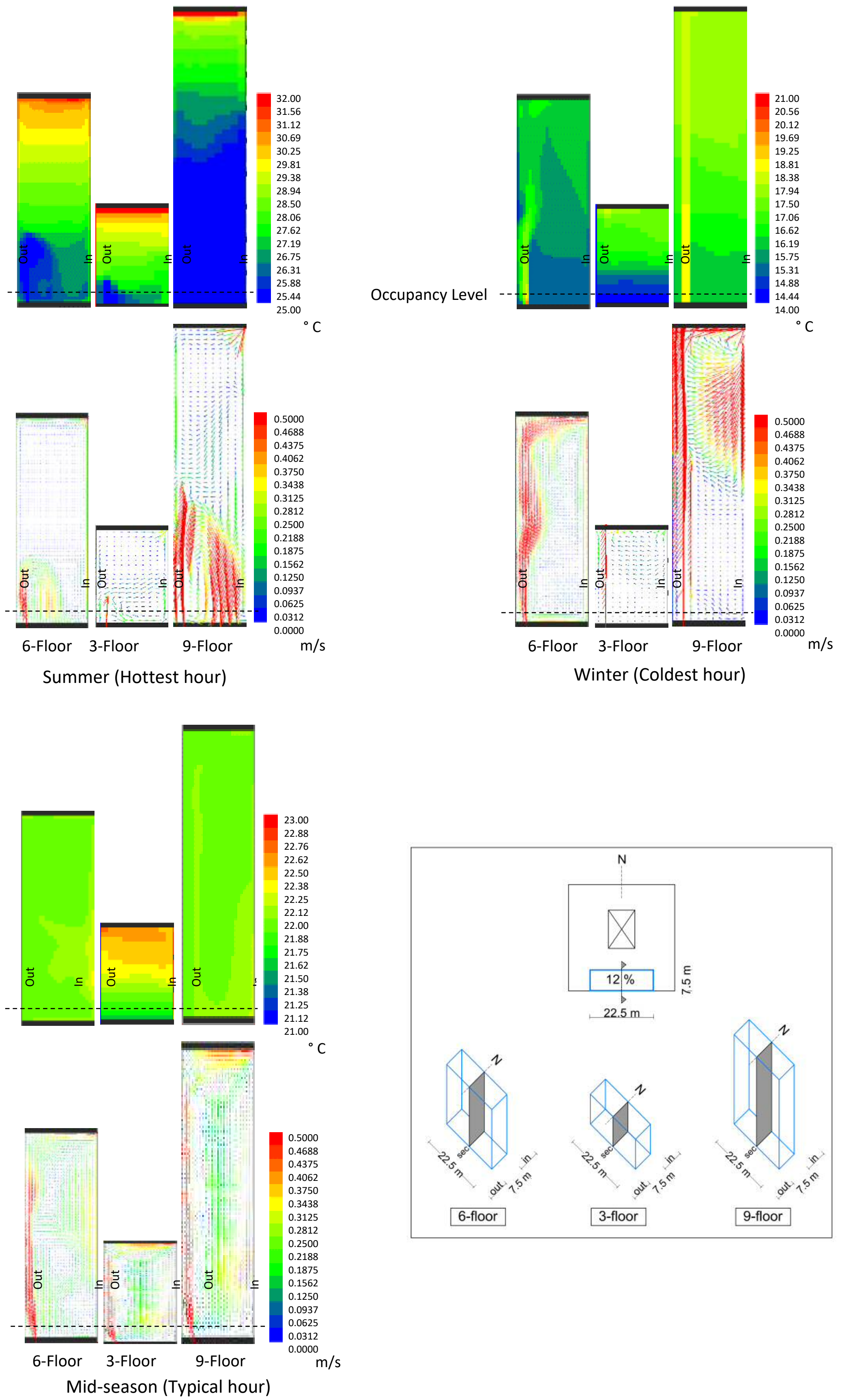


Figure 5-23. Thermal conditions comparison in skycourt (A) at the hottest hour in summer, the coldest hour in winter and typical hour in mid-season: height

5.2.3.3 *Impact of Area*

The influence of the skycourt area in relation to the gross internal floor area in the building was examined. Skycourts of three different areas were investigated; these are 12%, 8% and 4% of the gross internal area (GIA) of the office floor plan.

Energy performance: The results obtained a high correlation between the skycourt floor area and the annual heating and cooling demands for the building. It is obvious that these energy demands decrease when the skycourt area becomes smaller (Figure 5-24).

The 8% GIA case provided an energy saving of about 1% compared to the base case (the 12% GIA), while for the 4% GIA case, the total heating and cooling demands decreased by approximately 1.6%. This result corresponds with the findings of Liu *et al*. (2017) who found that when the floor area of offices increased, heating and cooling demand per area decreased due to the reduced exposed surface area per unit floor area.

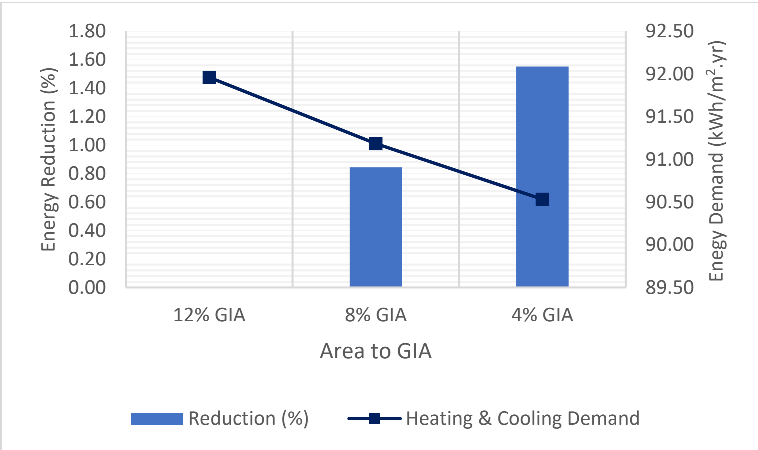


Figure 5-24. Annual total heating and cooling comparison: area

The energy loads comparison of the skycourt for the three cases supported the previous results. The highest ventilation load was found when the area was 4% GIA. It seems possible that this result occurs due to the high airflow volume rate inside the skycourt in this case. The airflow volume rate was the highest for this case, i.e. 6.12 m^3/s. For the other cases, it was 5.82 m^3/s for the 8% GIA and 5.58 m^3/s for the 12% GIA case. This is due to the assumption that the extracted air from offices is considered a supply air to the skycourt. Therefore, the air volume rate to the skycourt increases when the skycourt area decreases. A positive correlation was found between the fabric loads and the skycourt floor area. The greatest skycourt area indicates the largest area of outside façade, which causes a high fabric loss through the façade

Thermal performance: It is apparent that the smaller floor area of the skycourt is associated with more comfortable air temperature at the occupied area of the skycourt in the different seasons (Figure 5-25), yet it is far removed from comfortable airspeed conditions (Figure 5-26).

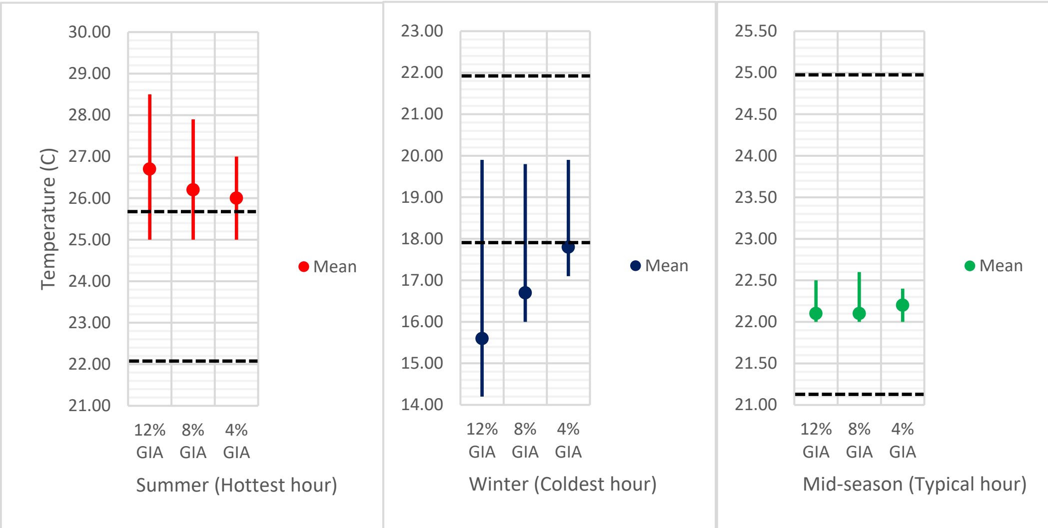


Figure 5-25. Air temperature comparison at the occupancy level in skycourt (A) (dashed lines show comfort air temperature ranges): area to GIA

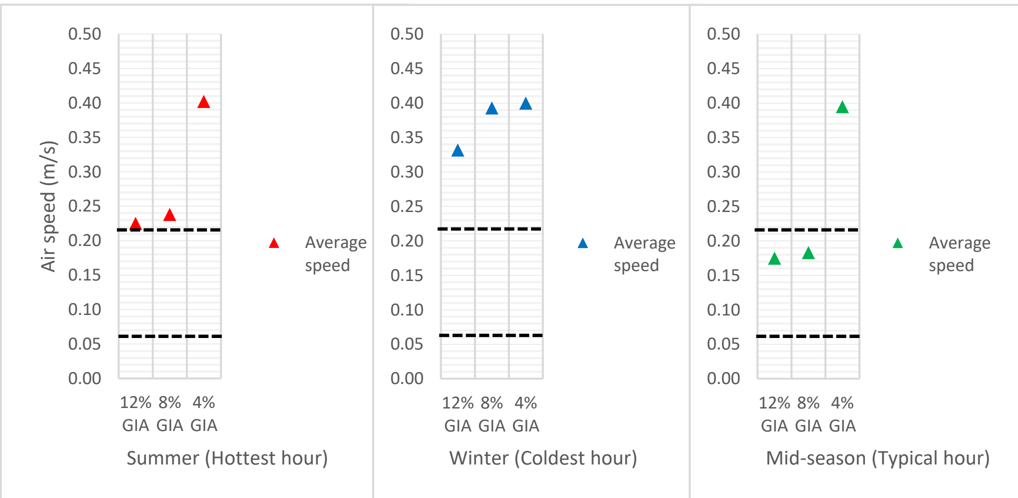


Figure 5-26. Airspeed comparison at the occupancy level in skycourt (A) (dashed lines show comfort airspeed ranges): area to GIA

In summer, the skycourt models recorded the following results at the occupied area:

(i) 25°C to 28.5°C of 0.23 m/s for the 12% GIA area;

(ii) 25°C to 27.9°C of 0.24 m/s for the 8% GIA area; and

(iii) 25°C to 27.6°C of 0.4 m/s for the 4% GIA area.

In winter, the mean air temperature increased from 15.6°C of 0.3 m/s to 18°C of 0.4 m/s for the 4% GIA case, compared to the base case (12% GIA).

The different cases have similar average air temperature in the typical temperature hour, i.e. about 22.1°C. However, the air average speed in the 4% GIA case was uncomfortable, at more than 0.4 m/s, (Figure 5-27).

According to these results, the mean air temperature dropped by 1°C in summer and increased by 2°C in winter, when the skycourt area decreased by 4%.

The ventilation strategy obtained in the skycourt depends on the adjacent offices. When the floor area of the integrated skycourt decreases, the airflow volume rate from the offices increases. Also, the heat gain is influenced by the external façade area. Less solar radiation can enter into the skycourt when the façade is smaller in size.

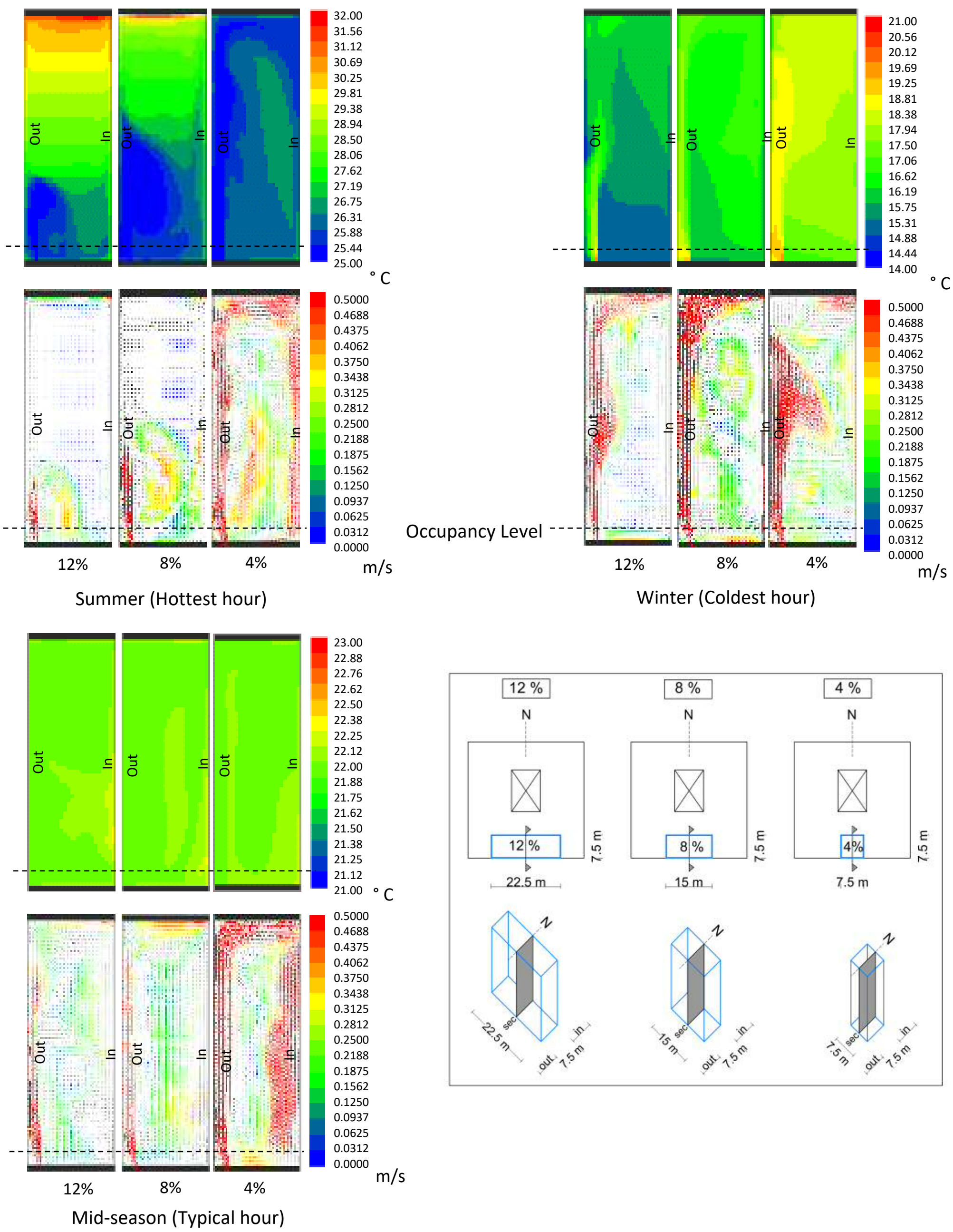


Figure 5-27. Thermal conditions comparison in skycourt (A) at the hottest hour in summer, the coldest hour in winter and typical hour in mid-season: area to GIA

As a summary, the results indicated that there is a significant positive correlation between the floor area of the skycourt and the energy saving of the building, and air temperature. When the floor area is small, the energy demands for heating and cooling will drop, as well as the air temperature being closer to the comfort range. However, the airspeed will increase.

The existence of a skycourt with 4% GIA is unlikely to happen, and this area is minimal compared to the proportion of the building. Therefore, the 8% GIA will be adopted for the next stage.

5.2.3.4 Impact of Length and Depth

Changes in energy and thermal performance as a result of the modifications of length and depth of the skycourt were examined. Four cases with various combinations of length and depths were simulated. These are the following: (i) 22.5 m × 7.5 m; (ii) 15 m × 7.5 m; (iii) 7.5 m × 15 m; and (iv) 7.5 m × 7.5 m.

Energy performance: The energy results revealed a decrease in heating and cooling demands for the building when the length of the skycourt increased. Increasing the length of the skycourt involves a higher exposure to the external climate of the skycourt. This affects the skycourt loads, and generates a rise in the solar gain (Figure 5-28). However, this influenced the offices, and provided less exposed surfaces to the external and more thermal protection, which indicates a decrease in the heating and cooling demand for the offices.

The impact of length when the area of the skycourt was fixed showed that cooling and heating reduction for the building increased about 0.84% for the 15 m length compared to the 7.5 m case (Figure 5-29).

On the other hand, when the depth of the skycourt increases, the solar gain drops for the skycourt and rises for the adjacent offices. This causes an expansion of the cooling demand to achieve thermally comfort offices.

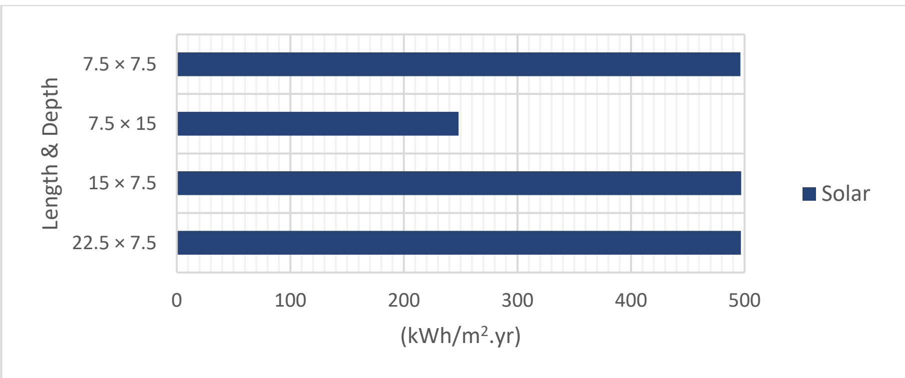


Figure 5-28. Annual solar loads comparison for skycourt (A): length and depth

There was a growth in the energy demand when the skycourt depth was altered from 7.5 m to 15 m, while the length was constant. The energy demand was raised by approximately 1 kWh/m^2.yr when the depth of the skycourt was doubled.

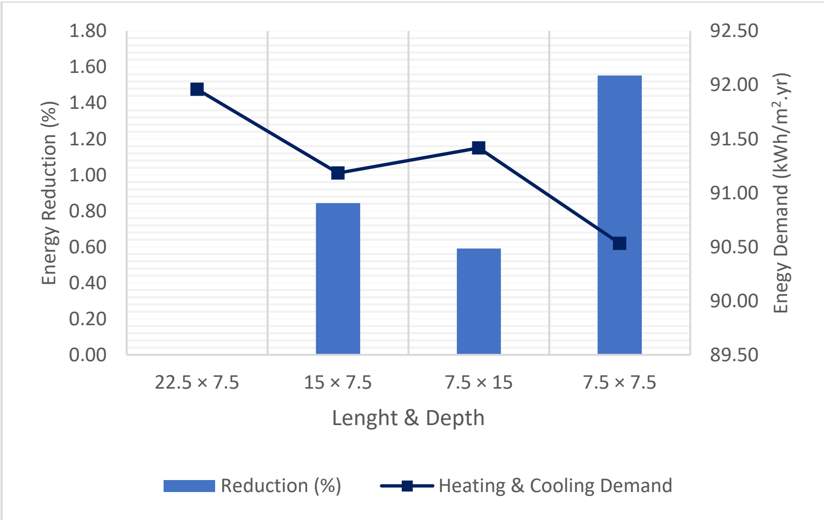


Figure 5-29. Annual total heating and cooling comparison: length and depth

Other comparisons of the influence of length were obtained when the depth is constant (7.5 m). Results of the energy demand are the following: (i) 91.96 kWh/m^2.yr for the 22.5 m case; (ii) 91.18 kWh/m^2.yr for the 15 m case; and (iii) 90.53 kWh/m^2.yr for the 7.5 m case. These results were affected by the change in the area. When the skycourt length or depth changed, the office floor area is altered consequently as the building floor area is fixed (37.5 m × 37.5 m). Therefore, the rise in the area of the office indicates a decrease in the heating and cooling demands.

According to these findings, the case of 15 m × 7.5 m length and depth is suggested for ensuring more considerable energy savings.

Thermal performance: It was found that the larger length of the skycourt revealed higher air temperature in summer and lower air temperature in winter, while airspeed decreases when the length increases at the various seasons. For instance, the air temperature at the occupied area decreased by about 1°C in summer when the length changed from 22.5 m to 7.5 m. The 7.5 m length case recorded a temperature of 26^{o}C, while the average airspeed increased from 0.2 m/s to 0.4 m/s. In winter, the temperature increased by about 2°C for the smaller length case. This recorded about 18^{o}C.

On the other hand, the larger depth of the skycourt produced lower air temperatures in summer and higher air temperatures in winter. The skycourt thermal performance greatly depends on the solar gain, and other ventilation and fabric loss through its external skin. The greater solar gain in summer provides higher air temperatures.

The comparison with the impact of depth, as seen in the charts (Figure 5-31 and Figure 5-32) displayed that air temperature differences between the cases are small at the occupancy level in summer, yet airspeed varies significantly in winter. For the 7.5 m depth, the temperature was about 26.2°C of 0.23 m/s in summer, and about 17°C of 0.4 m/s in winter. Whereas, the 15 m depth case recorded 25.9°C with 0.23 m/s in summer, and about 18°C with 0.3 m/s in winter.

In a typical hour during the transitional seasons, the simulated cases reported similar air temperature, i.e. about 22.1°C; yet, the airspeed was beyond the comfort level in the 7.5 m depth case. From these results, the skycourt case with a 7.5 m x 15 m length and depth is suggested to provide thermal comfort at the occupied area of the skycourt, as well as a positive influence on the adjacent offices.

In conclusion, positive correlations were found between the skycourt length and energy savings in buildings. However, in order to ensure a good result of air temperature and airspeed at the occupant level inside the skycourt, it is suggested to have a skycourt with a small length and a considerable depth. Therefore, the 15 m × 7.5 m and 7.5 m × 15 m length and depth models were further investigated in the correlated optimised parameters stage.

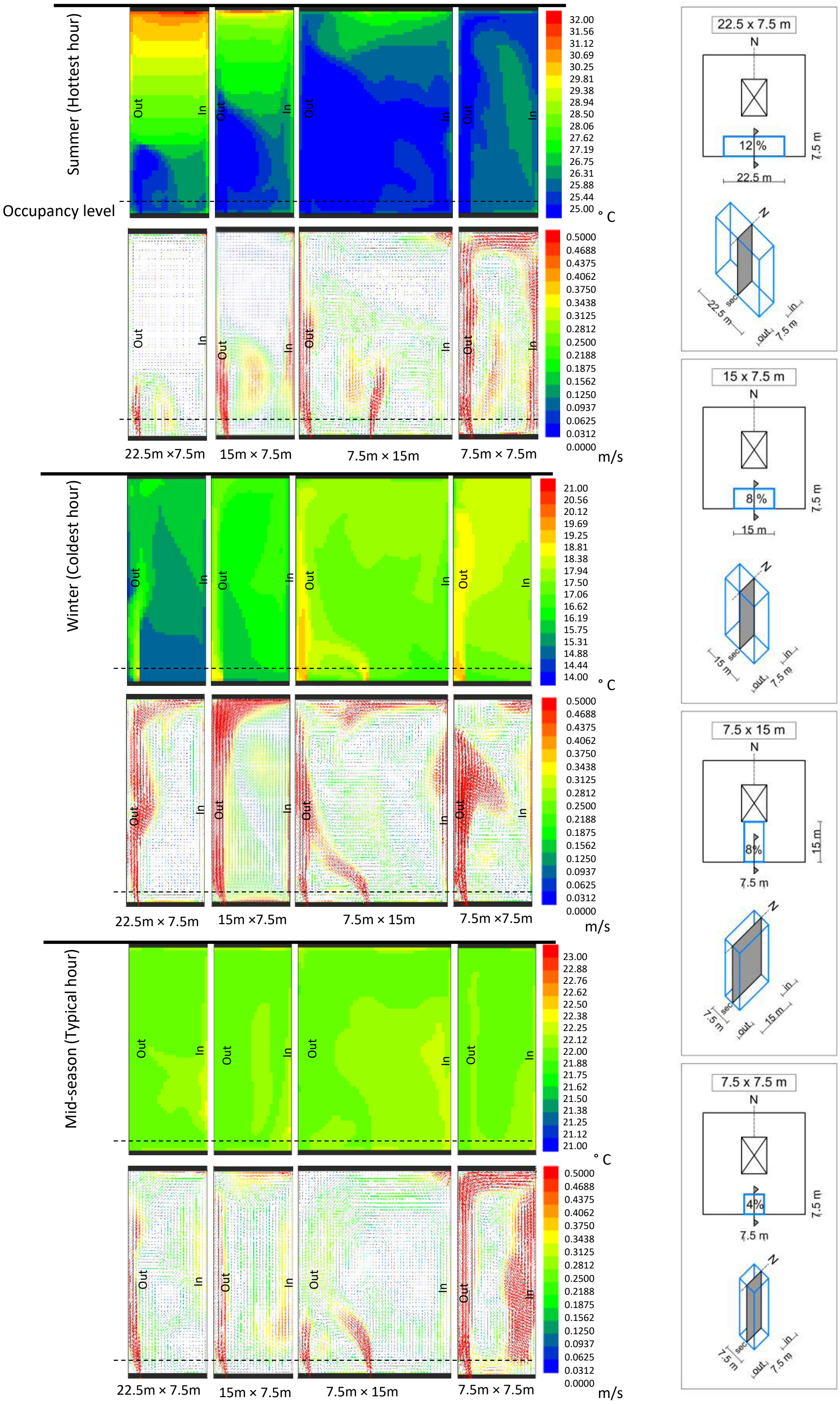


Figure 5-30. Thermal conditions comparison in skycourt (A) at the hottest hour in summer, the coldest hour in winter and typical hour in mid-season: length and depth

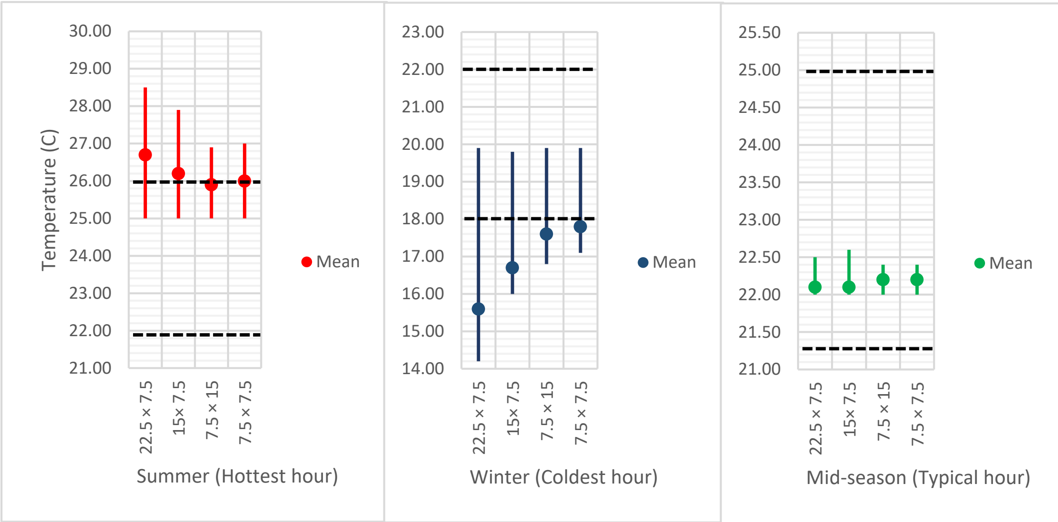


Figure 5-31. Air temperature comparison at the occupancy level in skycourt (A) (dashed lines show comfort air temperature ranges): length and depth

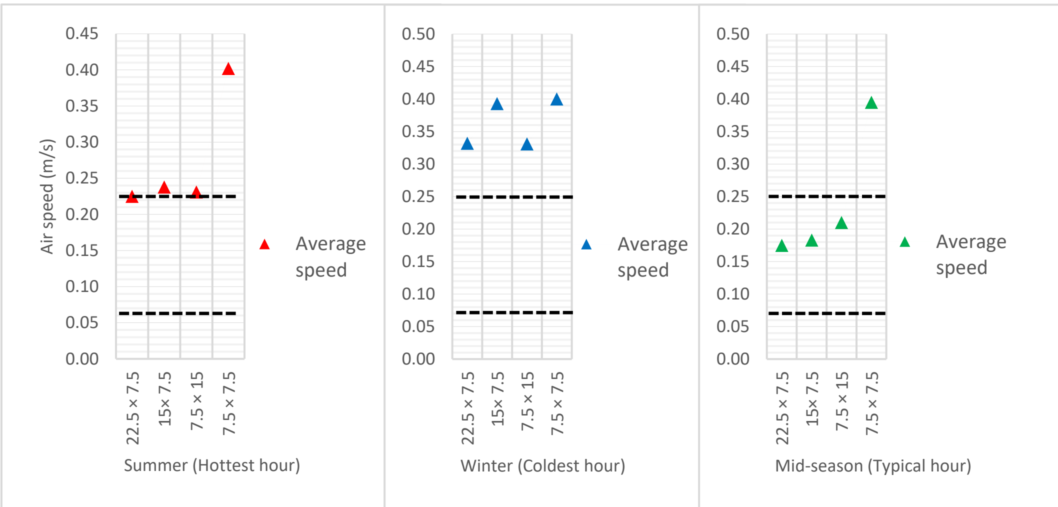


Figure 5-32. Airspeed comparison at occupancy level in skycourt (A) (dashed lines show comfort airspeed ranges): length and depth

The next two divisions present results of the influence of air inlet and outlet openings' vertical locations and horizontal positions on the effectiveness of the ventilation strategy.

5.2.3.5 Impact of Air Inlet and Air Outlet Vertical Distribution

The research study investigated the influence of the location of air inlet and outlet openings on airflow performance. Five proposed alternatives for their distribution between the floor and the ceiling of the skycourt were examined. These are the following: (a) all air inlet openings are located at the floor level of the skycourt, while all air outlet openings are located at the ceiling level of the skycourt. (b) Air inlet and outlet openings are distributed between the floor and the ceiling levels of the skycourt. (c) Air inlet and outlet openings are located at the floor level of the skycourt. (d) Air inlet and outlet openings are located at the ceiling level of the skycourt. Finally, (e) air inlet openings are located at the floor and ceiling levels of the skycourt, while air outlet openings are located on the floor level of the skycourt.

Energy performance: The main concern of this stage is identification of the thermal performance of these alternatives inside the skycourt. Therefore, the energy simulation settings were fixed in all cases according to the base case. Respectively, the annual heating and cooling demand for the building was the same value in the five alternatives. These demands recorded 91.96 kWh/m^2.yr for the buildings.

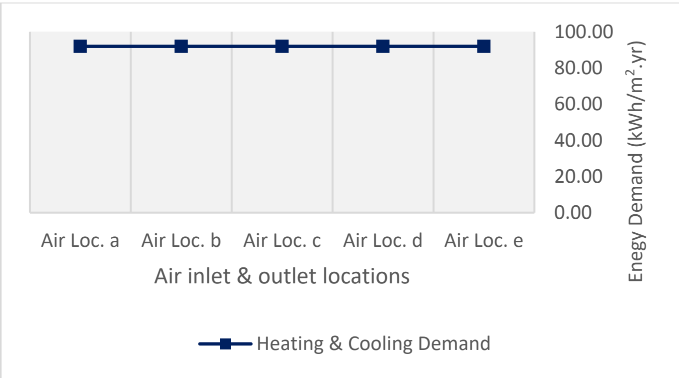


Figure 5-33. Annual total heating and cooling comparison: air inlet and air outlet vertical distribution

Thermal performance: The air temperature at the occupied area of the skycourt in alternative (a) and alternative (c) was 1°C lower in summer, and higher by about 0.5°C in winter than the other three alternatives (b), (d) and (e) (Figure 5-34).

This result can be explained due to the location of air inlet openings. All inlet openings are located at the floor level of the skycourt in alternative (a) and alternative (c), while in the other alternatives, air inlet openings are distributed between the skycourt's floor and ceiling. Therefore, the air volume rate that entered through the skycourt floor level was double the rate of the other alternatives. The height of the skycourt reduces the positive impact of the inlet air supplied from the ceiling openings to cool or heat the occupied area of the skycourt.

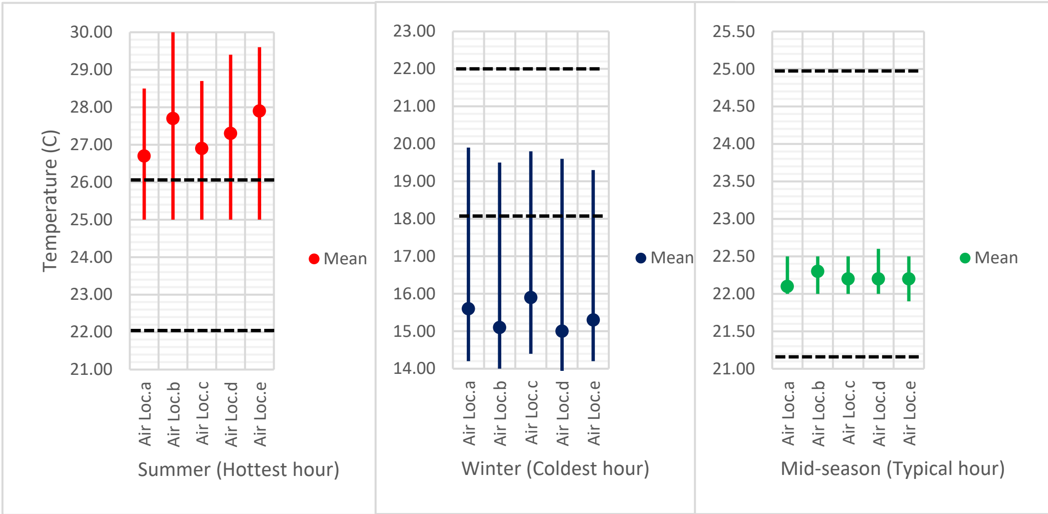


Figure 5-34. Air temperature comparison at the occupancy level in skycourt (A) (dashed lines show comfort air temperature ranges): air inlet and air outlet vertical distribution

However, the average airspeed reported various values. The lowest value of average airspeed was observed under the cases where inlet openings were distributed between the floor and the ceiling levels of the skycourt; such as alternatives (b), (d) and (e). These cases recorded about 0.09 m/s to 0.05 m/s less than other alternatives, (a) and (c) (Figure 5-35).

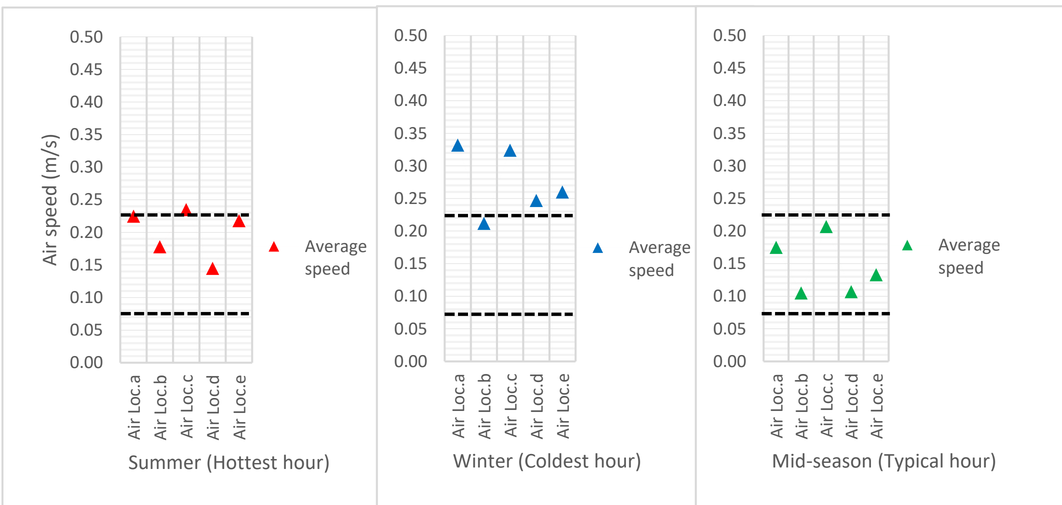


Figure 5-35. Airspeed comparison at the occupancy level in skycourt (A) (dashed lines show comfort airspeed ranges): air inlet and air outlet vertical distribution

Overall, what is interesting in this data is that the proposed alternatives for air inlet and outlet openings have an impact on the adjacent offices (Figure 5-36). The air temperature distribution inside the volume of the skycourt varied across the different locations of inlet and outlet openings.

For instance, alternative (c) recorded a higher air temperature in summer by 1°C to 2°C, and a lower air temperature in winter by 0.5°C for the whole volume of the skycourt, compared to the base case (alternative (a)). The other cases recorded similar ranges of temperature gradient between 25°C and 32°C of 0.12 m/s in summer, 14.2°C and 20°C of 0.28 m/s in winter. Temperature increased in the transitional seasons from 22°C to 22.6°C of 0.21 m/s in the mid-season case.

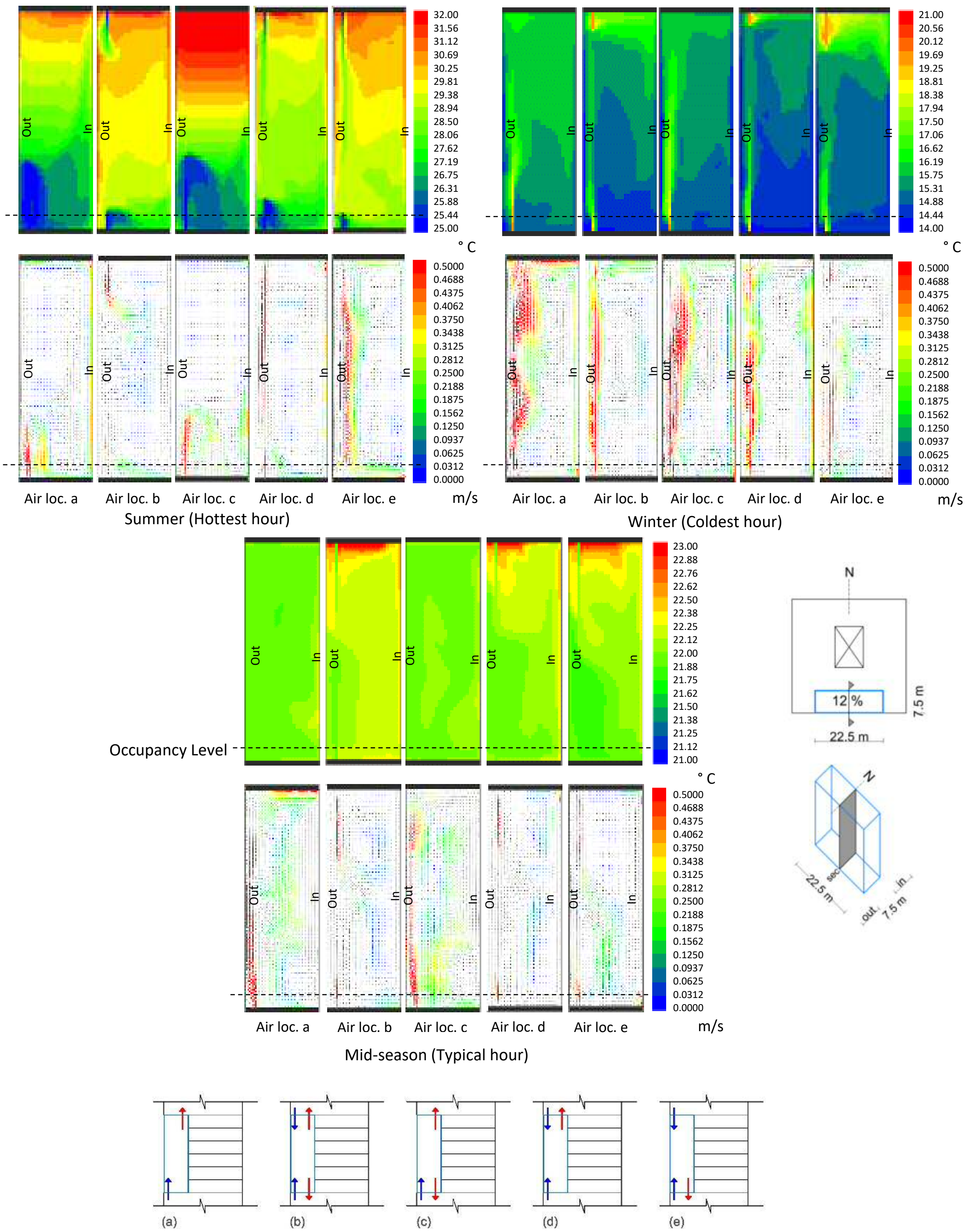


Figure 5-36. Thermal conditions comparison in skycourt (A) at the hottest hour in summer, the coldest hour in winter and typical hour in mid-season: air inlet and air outlet vertical distribution

The above results indicated that alternative (a) ensures comfort air temperature and average airspeed at the occupied area of the skycourt. In addition, this strategy positively enhances the thermal conditions in the adjacent offices. Therefore, alternative (a) in which all air inlet openings are located at the floor level of the skycourt and the all air outlet openings are located at the ceiling of the skycourt is suggested in order to induce efficient airflow strategy.

5.2.3.6 Impact of Air Inlet and Air Outlet Horizontal Position

The study investigated the influence of the horizontal position of air inlet and outlet openings on thermal conditions. Four alternatives were considered for their positions to the external façade and internal wall of the skycourt. These are (a) inlet openings are closer to the external wall, and outlet openings are closer to the internal wall of the skycourt. (b) Inlet openings are closer to the inner wall, and outlet openings are closer to the external wall of the skycourt. (c) Both inlet and outlet openings are closer to the external wall of the skycourt. Finally, (d) both inlet and outlet openings are closer to the internal wall of the skycourt.

Energy performance: As mentioned previously, the main concern of this simulation stage is investigating the thermal performance of airflow inside the skycourt. Therefore, the energy performance of the building and the breakdown of the energy loads of the skycourt were considered regarding the base model.

Thermal performance: It is apparent from the results obtained that the air temperatures at the occupied area of the skycourt were slightly similar; there was no significant air temperature differences across the different horizontal positions of inlet and outlet openings (Figure 5-37).

The mean air temperature in the hottest hour in summer was about 27°C, and ranged between 25°C and 29°C. In the coldest hour in winter it was 16°C, distributed between 14°C and 20°C. In mid-seasons, it was 22.2°C. This is due to the same amount of airflow volume rate, and the same temperature enters through the floor level of the skycourt regardless of the varying positions of the air openings.

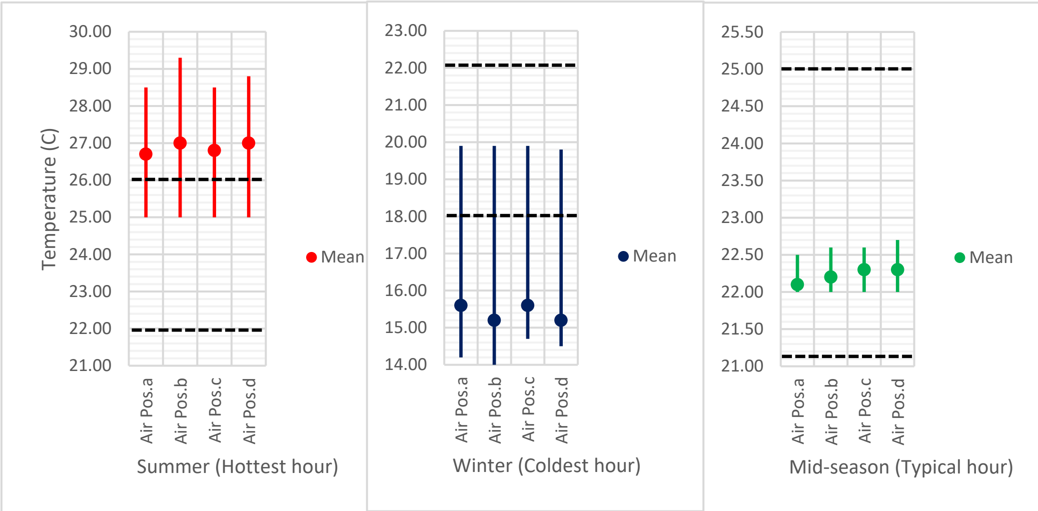


Figure 5-37. Air temperature comparison at the occupancy level in skycourt (A) (dashed lines show comfort air temperature ranges): air inlet and air outlet horizontal position

However, differences in the horizontal positions of air inlets and outlets have an effect on the average airspeed at the occupied area, particularly across the winter cases. Inlet openings positioned closer to the external façade, provide readings closer to the comfort ranges in winter. Other inlet positions yield more average airspeed. For instance, in alternative (a), the lowest average was recorded for airspeed, i.e. 0.3 m/s at the occupancy level, and 0.2 m/s in the whole skycourt. However, across the other alternatives, airspeed was more than 0.42 m/s in the occupied area and an average of 0.23 m/s across the entire skycourt (Figure 5-38). This is due to the conduction effect of the external environment. As the temperature of the external air is low, airspeed will be reduced near the external façade, and therefore, it acts as an insulation to the internal environment.

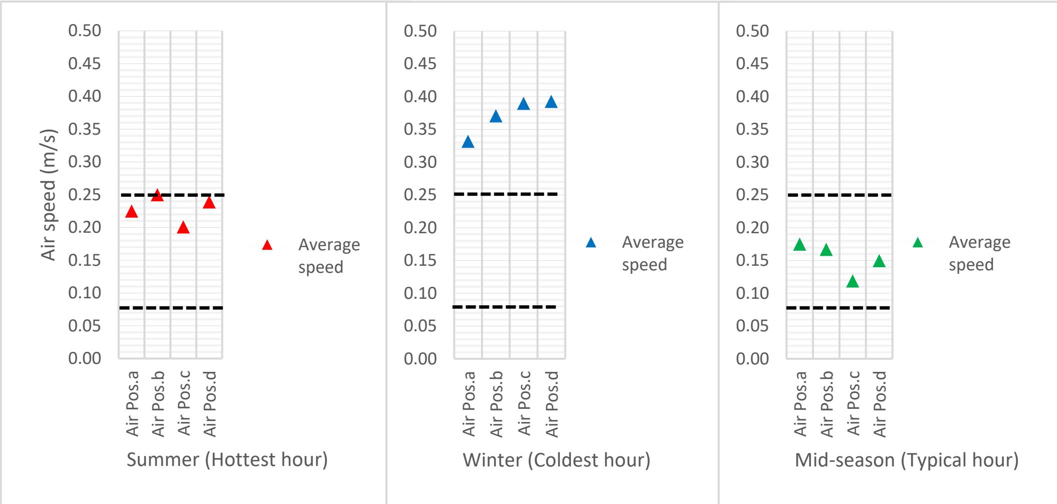


Figure 5-38. Airspeed comparison at the occupancy level in skycourt (A) (dashed lines show comfort airspeed ranges): air inlet and air outlet horizontal position

There was no significant difference across the alternative locations in terms of the air temperature inside the skycourt volume. Air temperature ranged between 25°C and 32°C in summer, 14°C and 20°C in winter, and 22°C and 23°C in mid-season (Figure 5-39).

However, it was found that the opposite positions of air inlet and outlet openings, such as alternative (a) and alternative (b), have a better influence on air temperatures inside the volume of the skycourt. This yields a positive impact on the adjacent offices, compared to air inlet and outlet openings positioned in a linear position, such as alternative (c) and alternative (d).

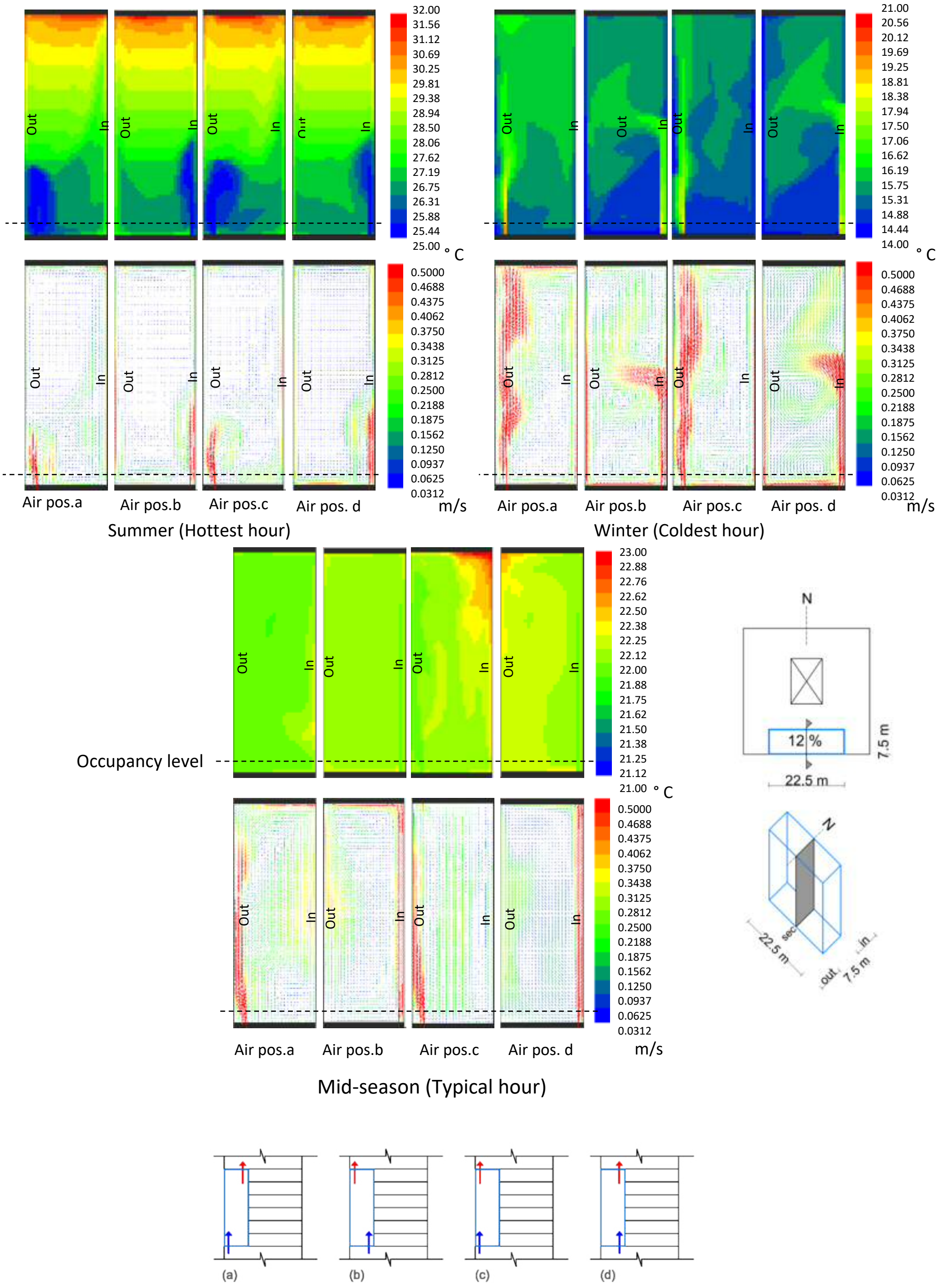


Figure 5-39. Thermal conditions comparison in skycourt (A) at the hottest hour in summer, the coldest hour in winter and typical hour in mid-season: air inlet and air outlet horizontal position

In conclusion, differences in air inlet and outlet positions closer to internal or external walls were found to have no crucial effect on the temperature of the occupied area. However, the horizontal position has an impact on the average airspeed, particularly in winter.

Therefore, it is suggested that the inlet openings should be positioned closer to the external facade of the skycourt and the outlet openings closer to the internal wall of the skycourt to ensure the occupants' thermal comfort at the occupied level in the different seasons. Therefore, alternative (a) is favourable.

5.2.3.7 Summary of Sensitivity Analysis Results

Results of the sensitivity analysis showed that the investigated factors have a slight effect on the thermal conditions of the skycourt, which in turn affect heating and cooling demand for the building. These results are important to simplify further investigation for the optimum configuration of the skycourt in the next stage.

Table 5-2. Summary of key factors concluded from sensitivity analysis of the hollowed-out skycourt (A) geometry and ventilation strategy

	Parameters	Details
Prototype (A): hollowed-out space	**Geometry:**	
	. Orientation	2 cases: South North
	. Height	6-floor height
	. Percentage of area to GIA	8% to GIA
	. Length & Depth	2 cases: 15 m x 7.5 m 7.5 m x 15 m
	Ventilation strategy:	
	. strategy	Strategy two (V2) .
	. Air inlet & outlet location	Air-openings vertical location (a): All air inlet are located at the floor level of the skycourt, while all air outlet openings are located at the ceiling of the skycourt
	. Air inlet air inlet position	Air-openings horizontal position (a): inlet openings are closer to the external facade (that is connected to the outside climate) of the skycourt , while air outlet openings are closer to the internal wall of the skycourt

The optimised parameters for prototype (A) skycourt (the hollowed-out form) in terms of energy efficiency are the south orientation, and a length equal to double the depth, e.g. 15 m × 7.5 m. In terms of thermal comfort inside the skycourt, the optimised configurations are the north orientation, and the shorter length compared to the depth (7.5 m × 15 m). However, various factors were found to afford both energy savings for the building and provide an accepted level of thermal conditions inside the skycourt. These are the six-floor height, area percentage to GIA of 8%, air inlet openings located at the floor level closer to the external facade; and the air outlet openings located at the ceiling closer to the internal wall of the skycourt.

5.2.4 The Improved Configurations Results

The correlated optimised parameters of the skycourt were investigated to define the optimal geometry for skycourt (A) (Figure 5-40).

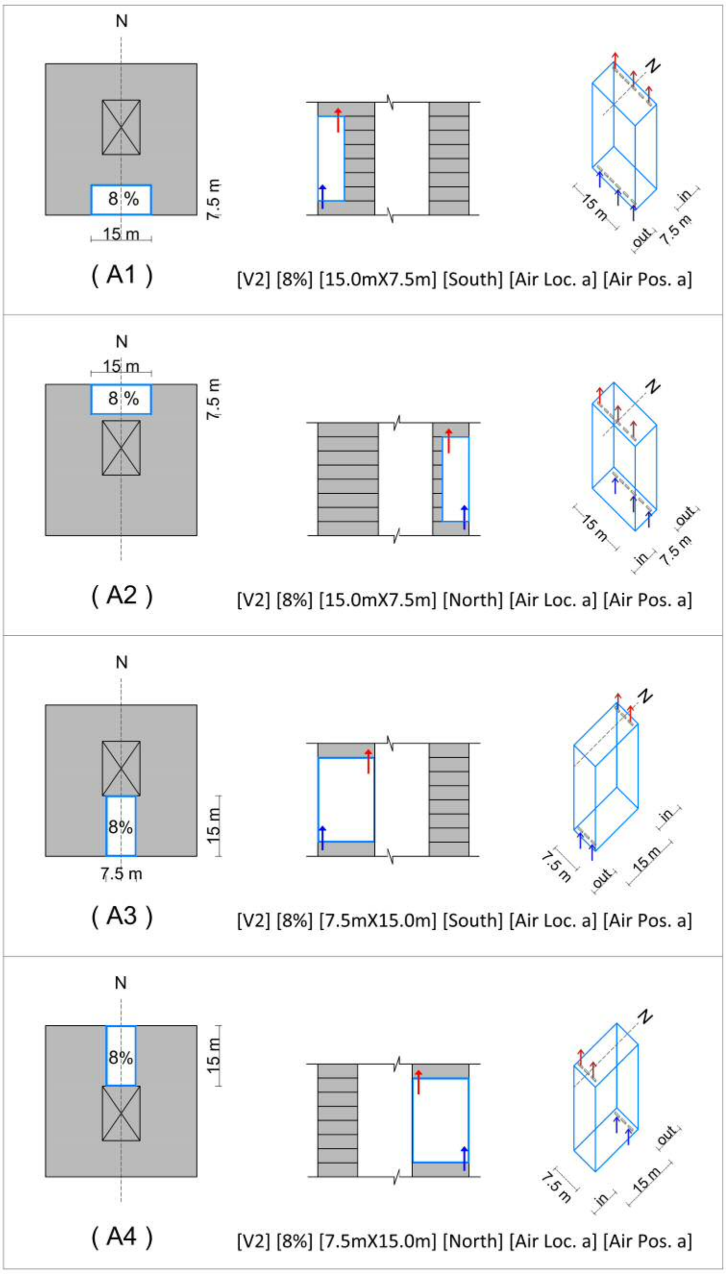


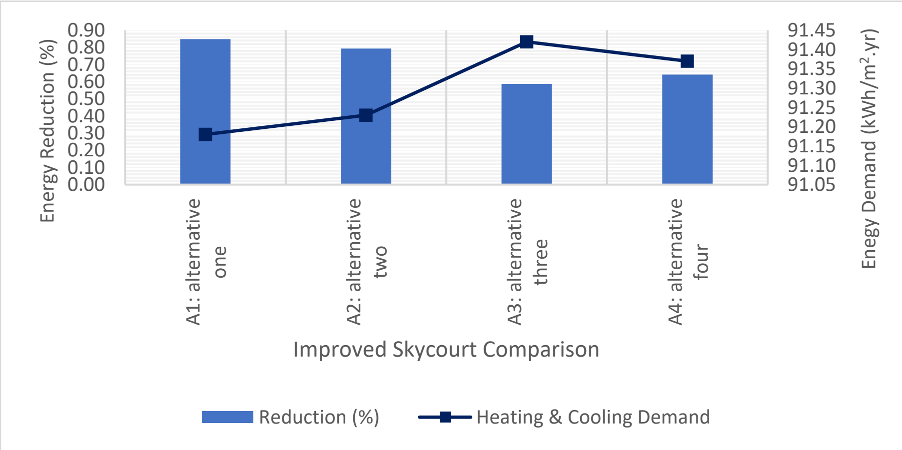
Figure 5-40. Schematic diagrams of models concluded from stage three for skycourt (A) geometry design: alternative one (A1), alternative two (A2), alternative three (A3) and alternative four (A4)

These alternatives obtained ventilation strategy two (V2). Skycourts are six-floor high and occupy 8% of the GIA of building floor. The locations of air inlet and outlet openings are fixed in all buildings. The differences between cases are due to the orientation, length, and depth of the skycourt. Therefore, four models were simulated: alternative one (A1), alternative two (A2), alternative three (A3) and alternative four (A4).

The energy performance of each building was compared with the performance of the base model (Figure 5-41). The heating and cooling demand decreased with the increase of the skycourt length when the area is constant. However, this effect is not significant.

The building that integrates a 15 m × 7.5 m (length and depth) skycourt achieved higher percentages of energy savings than the building that integrated a 7.5 m × 15 m skycourt. This was about 0.2%. In addition, different energy consumptions were found across the models on the south and north orientations of the skycourt. It is obvious that the building with the south skycourt consumes less energy for heating and cooling. These findings are also reinforced with the sensitivity analysis results.

According to the study, the best configuration of the skycourt yields the highest heating and cooling demand reduction for the building. Therefore, alternative one (A1) of the skycourt that has a 15 m façade length, and oriented to the south, was the efficient model to produce the lowest energy consumption.



A1: Skycourt (A) alternative one: [V2] [South] [8%] [15 m × 7.5 m] [Air Loc. a] [Air Pos. a]
A2: Skycourt (A) alternative two: [V2] [North] [8%] [15 m × 7.5 m] [Air Loc. a] [Air Pos. a]
A3: Skycourt (A) alternative three: [V2]][South] [8%] [7.5 m × 15 m] [Air Loc. a] [Air Pos. a]
A4: Skycourt (A) alternative four: [V2] [North] [8%] [7.5 m × 15 m] [Air Loc. a] [Air Pos. a]

Figure 5-41. Annual total heating and cooling comparison: improved configurations

The thermal comparison showed a potential of the skycourt alternatives towards a thermal comfort range (Figure 5-42 and Figure 5-43). It is obvious that air temperatures are within the comfort range in the occupied area of the skycourt across the various models in the different seasons. Overall, the air temperature ranged between 25°C and 27°C in the hottest hour in summer; 16°C and 20°C in the coldest hour in winter; and 22°C of 0.2 m/s in a typical hour in the transitional seasons. However, temperatures are slightly higher under the cases of the south orientation. The average airspeed is higher in winter under the 15 m × 7.5 m (length and depth) models.

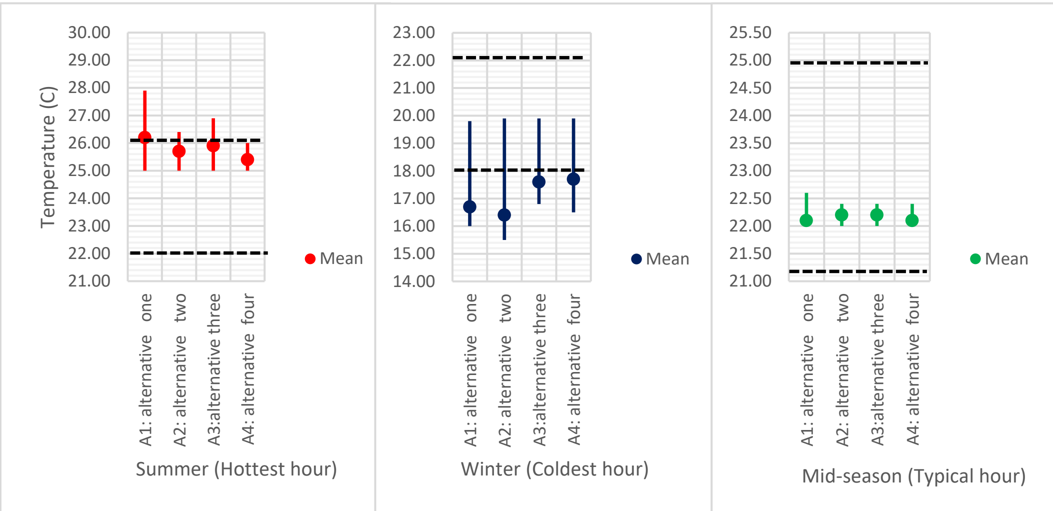


Figure 5-42. Air temperature comparison at the occupancy level in skycourt (A) (dashed lines show comfort air temperature ranges): improved configurations

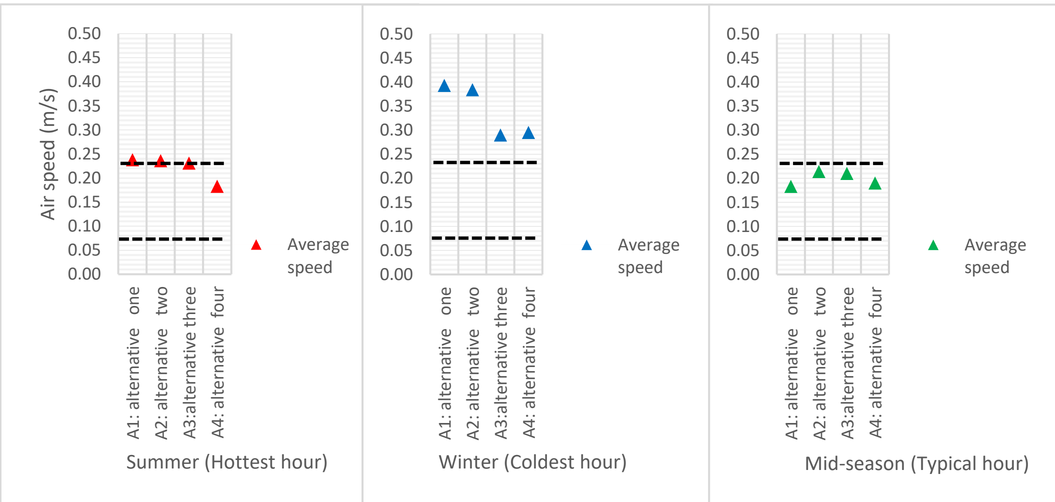


Figure 5-43. Airspeed comparison at the occupancy level in skycourt (A) (dashed lines show comfort airspeed ranges): improved configurations

These findings are consistent with those of the sensitivity analysis, which showed similar results for the correlations between the skycourt's orientation, length and depth, and thermal conditions inside the skycourt.

According to the study, the best configuration of the six parameters of the skycourt provides the maximum energy saving for the building, and ensures the best comfort range of air temperature and average airspeed at the occupied area of the skycourt in the different seasons. Another consideration is the positive effect on the adjacent offices (Figure 5-44). For example, the south-oriented skycourt provided more shading to the offices, when the length was increased. Therefore, the south orientation, and a 15 m × 7.5 m length and depth, are preferred across other alternatives.

Overall, the alternatives showed small differences in temperature ranges across the occupied area of the skycourt. Therefore, the best configuration of the skycourt will be considered based on energy savings for the building. A six-floor high skycourt that has a 15 m façade length oriented to the south is the useful model to produce the highest heating and cooling savings for the building. This affects the adjacent offices positively in terms of providing shading.

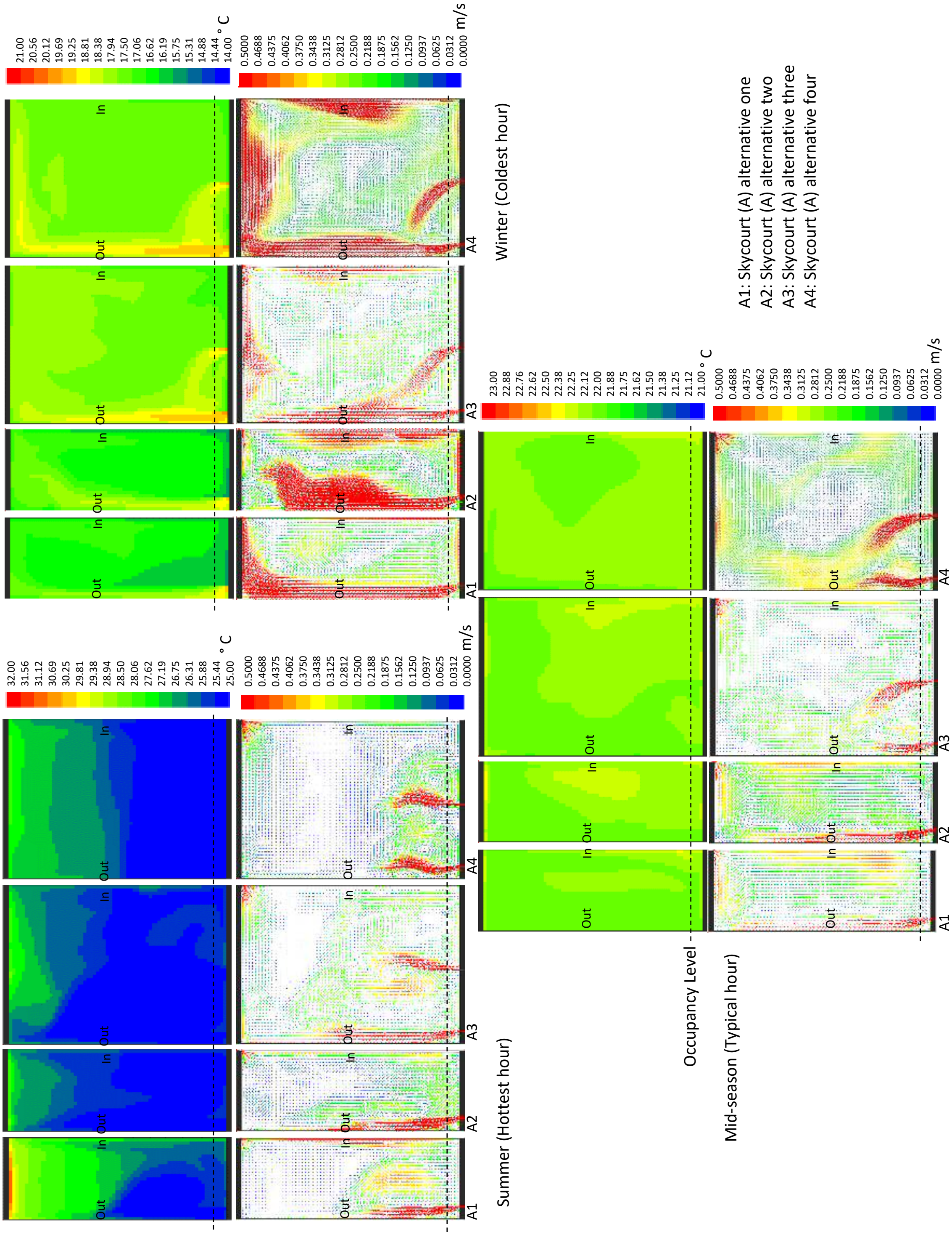


Figure 5-44. Thermal conditions comparison in skycourt (A) at the hottest hour in summer, the coldest hour in winter and typical hour in mid-season: improved configurations

5.2.5 The Optimal Hollowed-out Skycourt

This stage aims to compare the optimal configuration of the skycourt to the reference model (Stage 1) and the base model (Stage 2) (Table 5-3).

Table 5-3. Summary of design parameters, energy demand and thermal conditions for the reference model, base case and optimal case among simulation cases for the hollowed-out skycourt

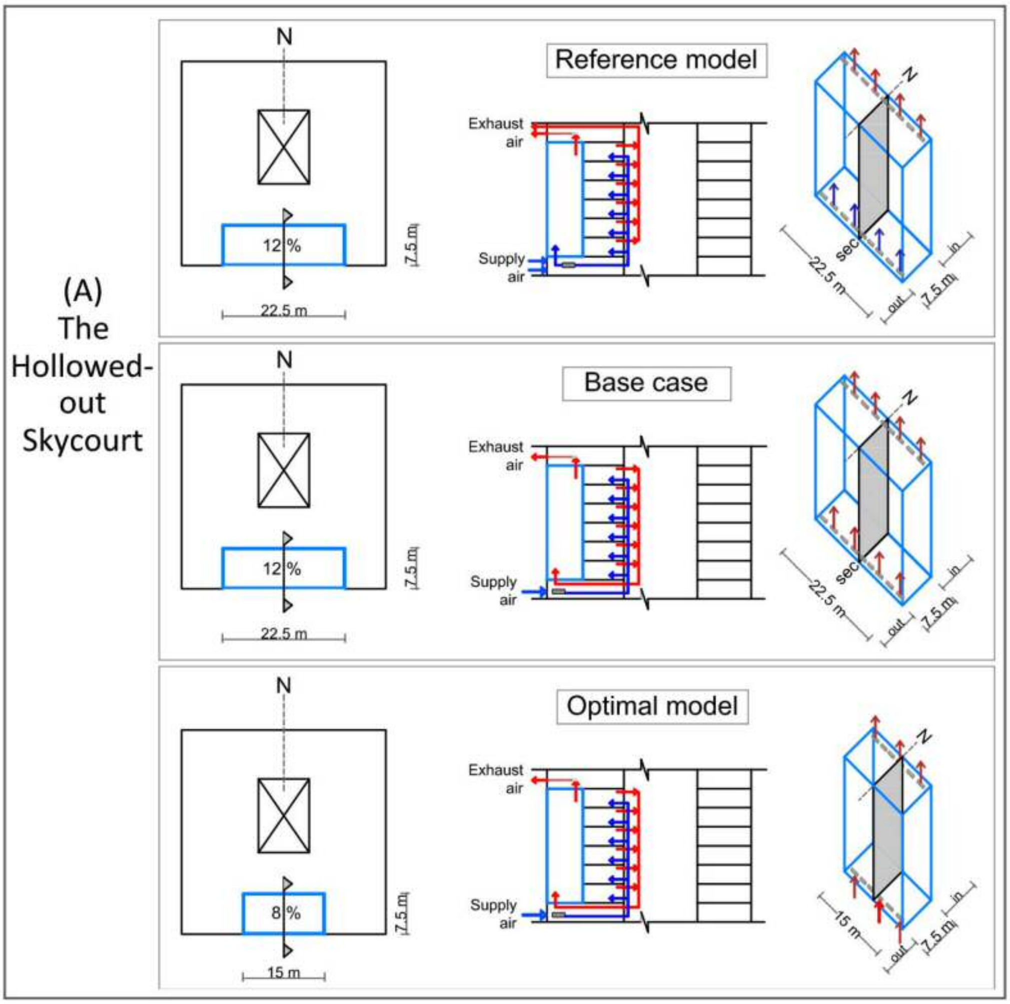
	Reference (A) Model Heated and Cooled Skycourt (stage 1)	**Base (A) Model Unheated and Uncooled Skycourt (stage 2)**	**Optimal (A) Model Unheated and Uncooled Skycourt**
Ventilation strategy for the skycourt	Isolated ventilation: air-conditioned skycourt	Strategy two (V2): combined-exhaust	Strategy two (V2): combined-exhaust
Geometric attributes of the skycourt			
Orientation	South	South	South
Height	Six-floor height	Six-floor height	Six-floor height
Area (%) to GIA	12% GIA	12% GIA	8% GIA
Length and depth	22.5 m × 7.5 m	22.5 m × 7.5 m	15 m × 7.5 m
Air inlet and outlet vertical locations inside the skycourt	Alternative (a): air inlet openings located at the floor level, and air outlet openings are located at the ceiling level of the skycourt	Alternative (a): air inlet openings located at the floor level, and air outlet openings are located at the ceiling level of the skycourt	Alternative (a): air inlet openings located at the floor level, and air outlet openings are located at the ceiling level of the skycourt
Air inlet and outlet horizontal positions inside the skycourt	Alternative (a): air inlet openings positioned closer to the external façade, and air outlet openings are closer to the internal wall of the skycourt	Alternative (a): air inlet openings positioned closer to the external façade, and air outlet openings are closer to the internal wall of the skycourt	Alternative (a): air inlet openings positioned closer to the external façade, and air outlet openings are closer to the internal wall of the skycourt
Energy demand of the building			
Annual heating and cooling demand for adjacent offices	220.5 $kWh/m^2.yr$	92.0 $kWh/m^2.yr$	91.2 $kWh/m^2.yr$
Thermal condition at the occupied area of the skycourt			
Summer, at external temperature 28°C	25°C of 0.08 m/s	26.5°C of 0.2 m/s	26°C of 0.2 m/s
Winter, at external temperature -5°C	19.1°C of 0.3 m/s	16°C of 0.3 m/s	17°C of 0.4 m/s
Mid-seasons, at external temperature 13°C	21.1°C of 0.06 m/s	22.1°C of 0.2 m/s	22.1°C of 0.2 m/s

The table displays the comparison between the three models in terms of: (i) Design configuration of the skycourt (ventilation strategy, geometric parameters, vertical location and horizontal position of air inlet and outlet openings), (ii) energy performance of the building, and (iii) thermal performance of the skycourt. Geometric differences between the three models of skycourts are due to the area percentage to GIA, and length and depth of the skycourt.

It is obvious that differences in energy consumption for the building, and thermal performance of the skycourt, were correlated with the variation of the ventilation strategy applied in the building.

The optimal hollowed-out skycourt under the combined-exhaust ventilation strategy accomplished significant improvement in terms of energy performance for the building.

An energy saving for heating and cooling of up to 59% per year was found for the optimal skycourt building compared to the building with an air-conditioned skycourt. The base skycourt building achieved 58% energy savings. This provides a clear picture about the efficiency of the unheated and uncooled skycourt to reduce the high heating and cooling demand for the air-conditioned skycourt, which is the first goal of this study.



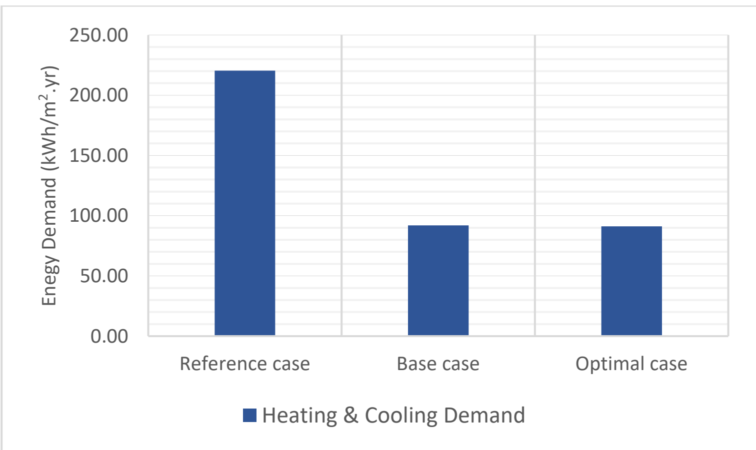


Figure 5-45. Annual total heating and cooling comparison between reference model, base case and optimal model for the hollowed-out skycourt building

The thermal results for the occupied area of the skycourt showed the following:

(i) It was obvious that the accepted level of comfortable temperatures and airspeed were achieved in the base and the optimal models of the skycourt when the combined-exhaust strategy has been employed under the different seasons. This causes a 2°C to 3°C increase in air temperature ranges in summer; and a 2°C to 3°C decrease in winter temperatures compared to the reference case. The airspeed is relatively comfortable in summer and mid-season cases, i.e. 0.2m/s. However, it was above the comfort level in winter as the reference case.

(ii) The results showed that the increase in the airflow volume rate that occurred in the optimal case has positive influences on thermal comfort conditions at the skycourt (Figure 5-46). This creates about a 1°C difference between the base skycourt and the optimal skycourt in summer and winter.

(A) The Hollowed-out Skycourt

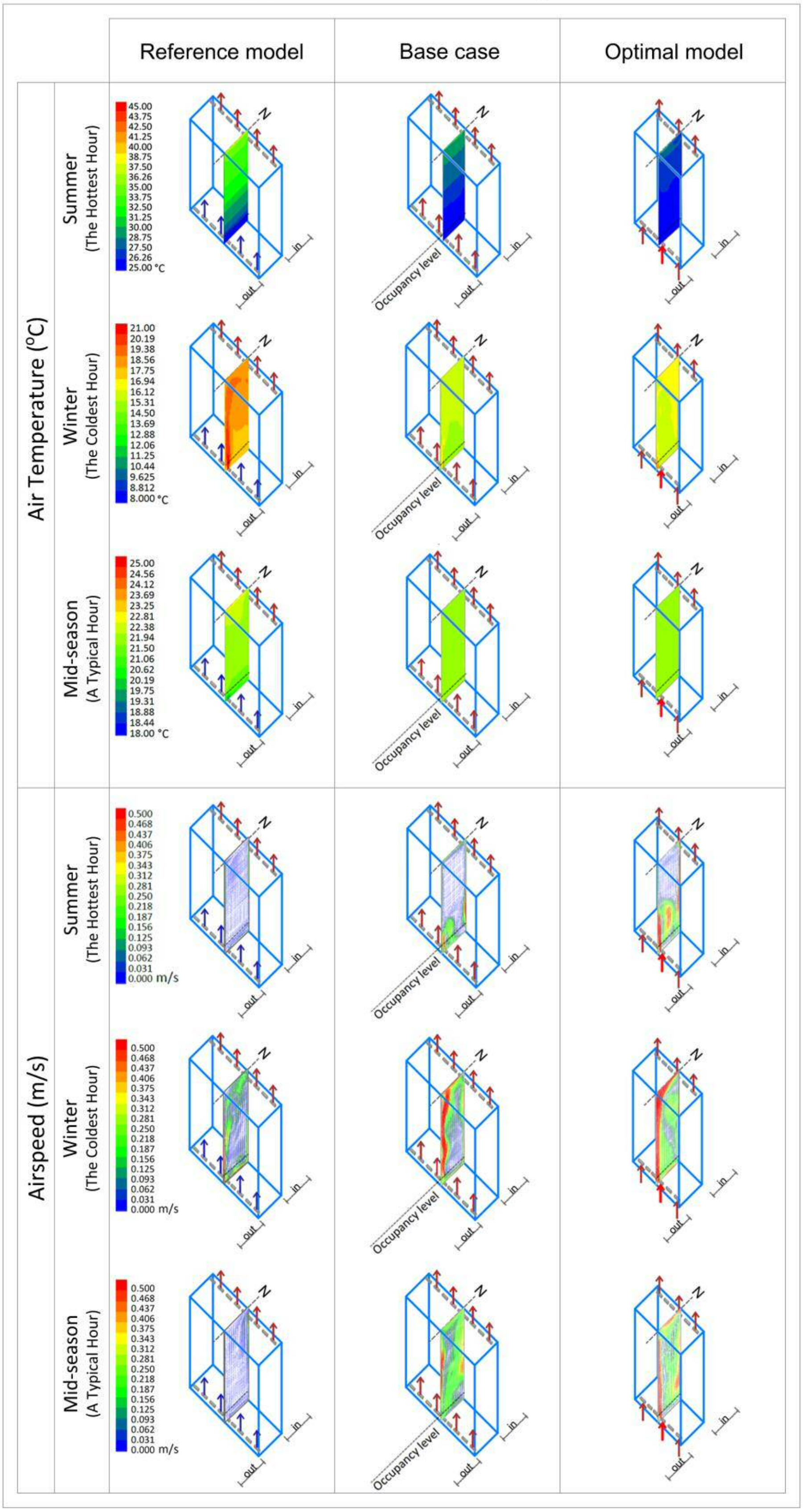


Figure 5-46. Thermal conditions comparison in the hollowed-out skycourt at the hottest hour in summer, the coldest hour in winter and typical hour in mid-season: reference model, base case and optimal model

5.2.6 Summary_ Hollowed out Skycourt

The results of investigating the hollowed-out skycourt (prototype (A)) in terms of heating and cooling energy consumption for the building, air temperature, and airspeed at the occupied area of the skycourt are now presented. The following summaries the main findings of the main stages:

For the first stage, the impact of integrating a skycourt in the design of office buildings was investigated under the assumption that the skycourt is an air-conditioned space, heated and ventilated separately from the adjacent offices. The total heating and cooling demand of the building, and significantly, the cooling load was found to be high.

For the second stage, the potential of the skycourt to perform as an unheated and uncooled zone was investigated. Five ventilation strategies were examined to mediate the thermal conditions in the skycourt. The hollowed-out skycourt was found to perform efficiently as a thermal comfort space under the combined-exhaust strategy two (V2).

This strategy provides air to the skycourt depending on the maximum airflow volume rate that exhausts from the adjacent offices. The air temperature increased by 2°C in the hottest hour in summer and decreased by 3°C in the coldest hour in winter, compared to the conditions in the air-conditioned skycourt. In addition, the average airspeed was 0.2 m/s in the hottest hour in summer and in a typical hour in transitional seasons. The ventilation strategy presents a high potential for energy saving. About 58% energy savings for heating and cooling can be achieved by adopting this strategy in office buildings.

The effects of the geometric parameters of skycourts on thermal performance in skycourts and energy performance of buildings were studied in the third stage. Orientation, height, area percentage to GIA, length and depth, vertical locations and horizontal positions of air inlet and outlet openings inside the skycourt were optimised.

In the fourth stage, the optimum parameters of the sensitivity analysis were correlated, and then investigated to define the best configuration of the six parameters. The results showed that the main design elements for the optimal hollowed-out skycourt were a six-floor height, which covered 40% of the south façade, and occupied 8% of the floor area of the adjacent offices.

In addition, air inlet openings located at the floor level of the skycourt closer to its external facade; and air outlet openings located at the ceiling level of the skycourt closer to the internal walls of it, are important to produce the best results of the thermal comfort.

The optimal hollowed-out skycourt under the combined-exhaust ventilation strategy accomplished a significant improvement. Annual heating and cooling demand was reduced to 91.2 kWh/m^2 compared to 220.5 kWh/m^2 for an air-conditioned, heated and cooled skycourt. In addition, occupied comfort temperature ranges were achieved during the different seasons at the skycourt.

Temperatures for the optimal model achieved: (i) 25°C to 28°C of 0.24 m/s in the summer case, (ii) 16°C to 20°C of 0.4 m/s in the winter case, and (iii) 22°C to 23°C of 0.2 m/s in the transitional season case. Whereas, the heated and cooled skycourt recorded: (i) 22°C to 27.5°C of 0.08 m/s in summer, (ii) 17°C to 22.6°C of 0.3 m/s in winter, and (iii) 19.6°C to 22°C of 0.06 m/s in mid-seasons.

However, it should be noted that the above estimations were calculated based on the simulation results under the particular conditions and the assumptions made for this study. Figure 5-47 to Figure 5-50 display results for all cases.

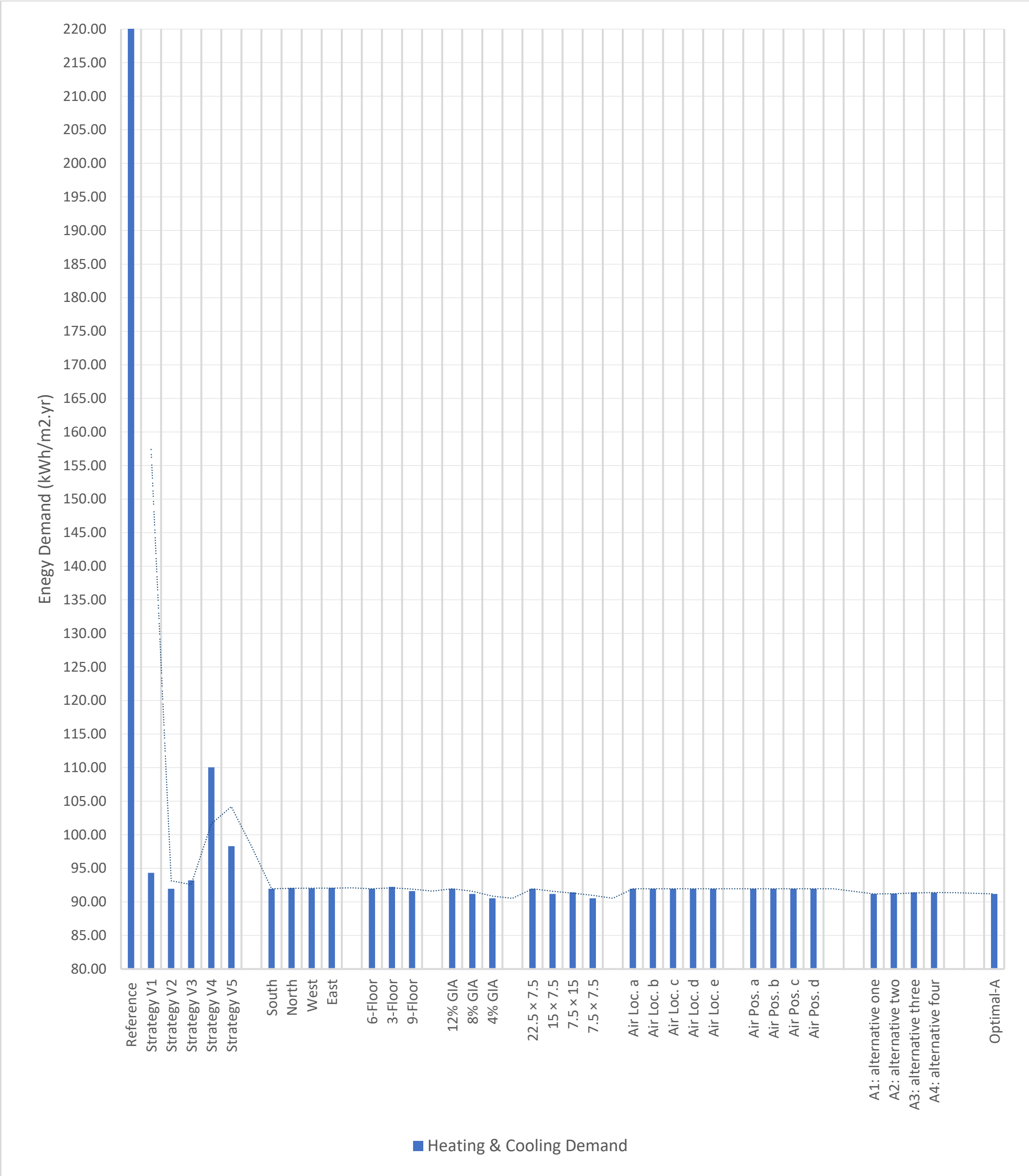
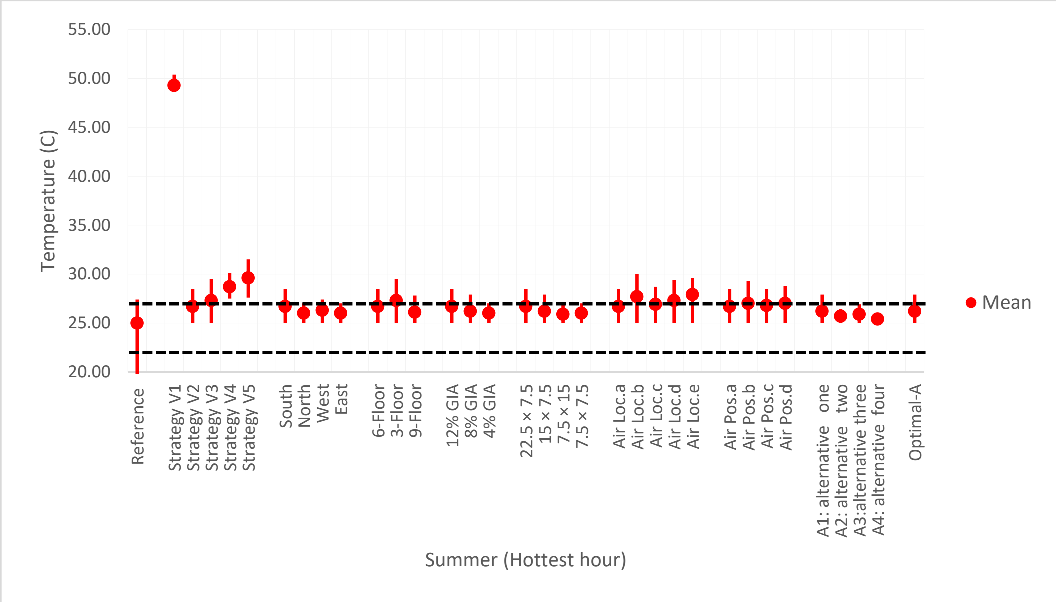


Figure 5-47. Annual total heating and cooling of buildings that integrate hollowed-out skycourts: comparison for all cases



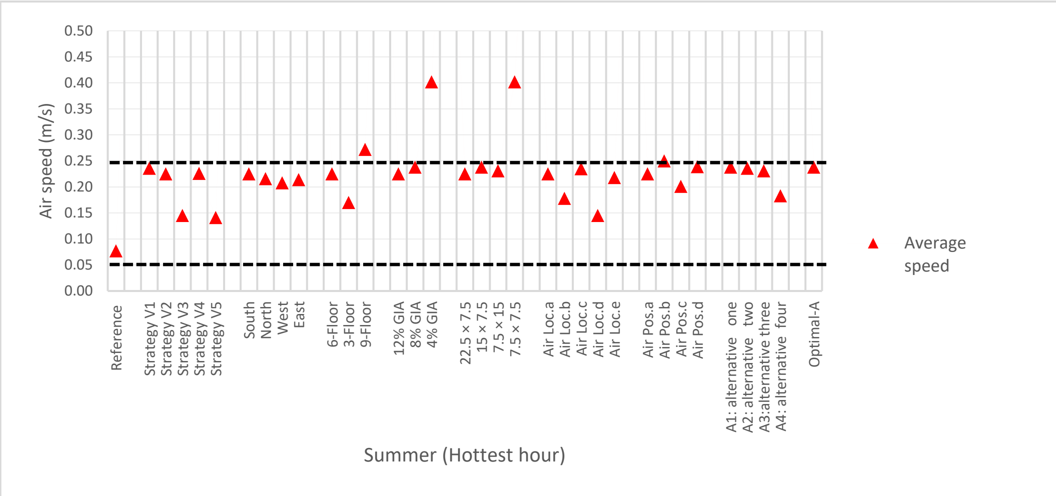


Figure 5-48. Air temperature and airspeed comparison at the occupancy level of the hollowed-out skycourt (A) at the hottest hour of summer (dashed lines show comfort ranges) for all cases

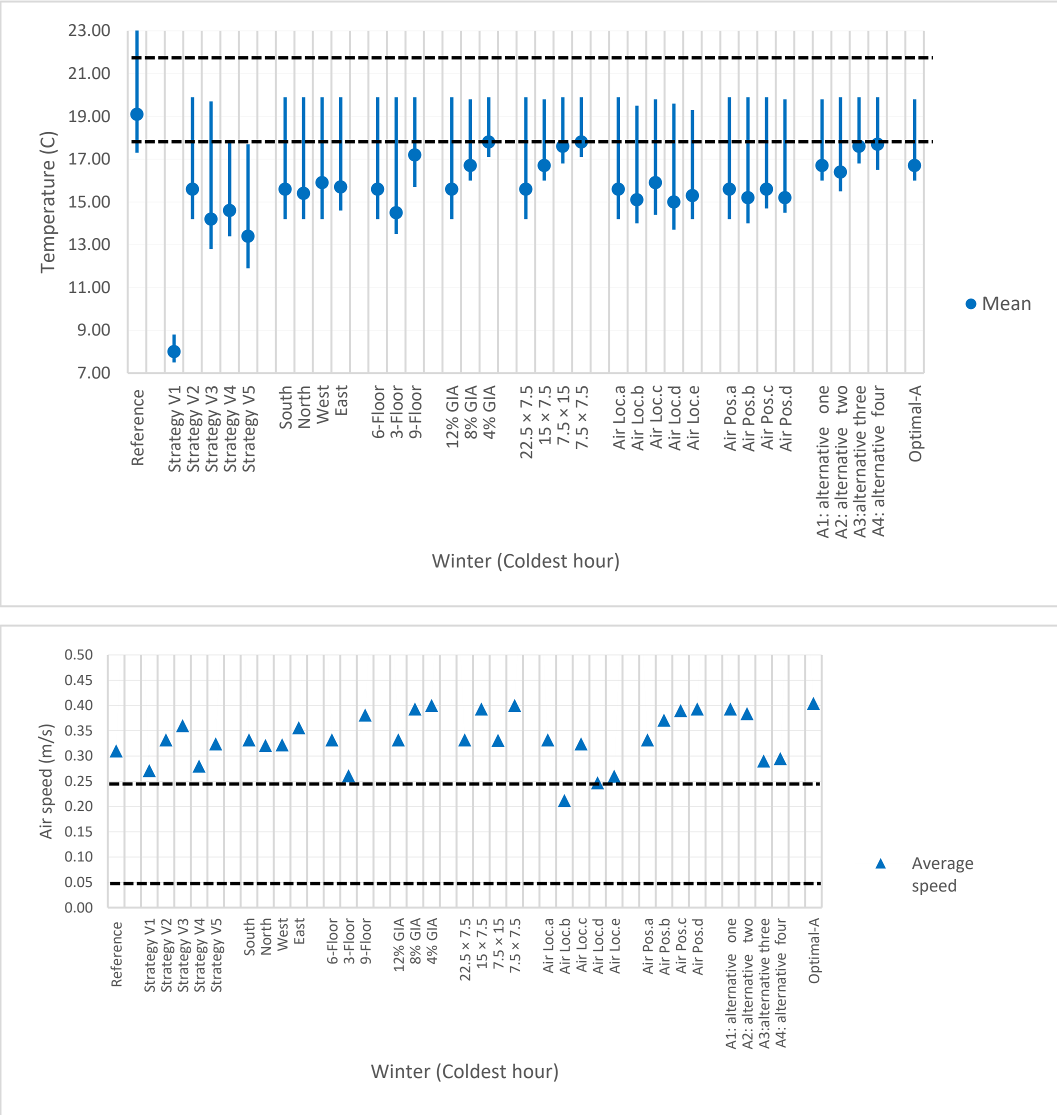


Figure 5-49. Air temperature and airspeed comparison at the occupancy level of the hollowed-out skycourt (A) at the coldest hour of winter (dashed lines show comfort ranges) for all cases

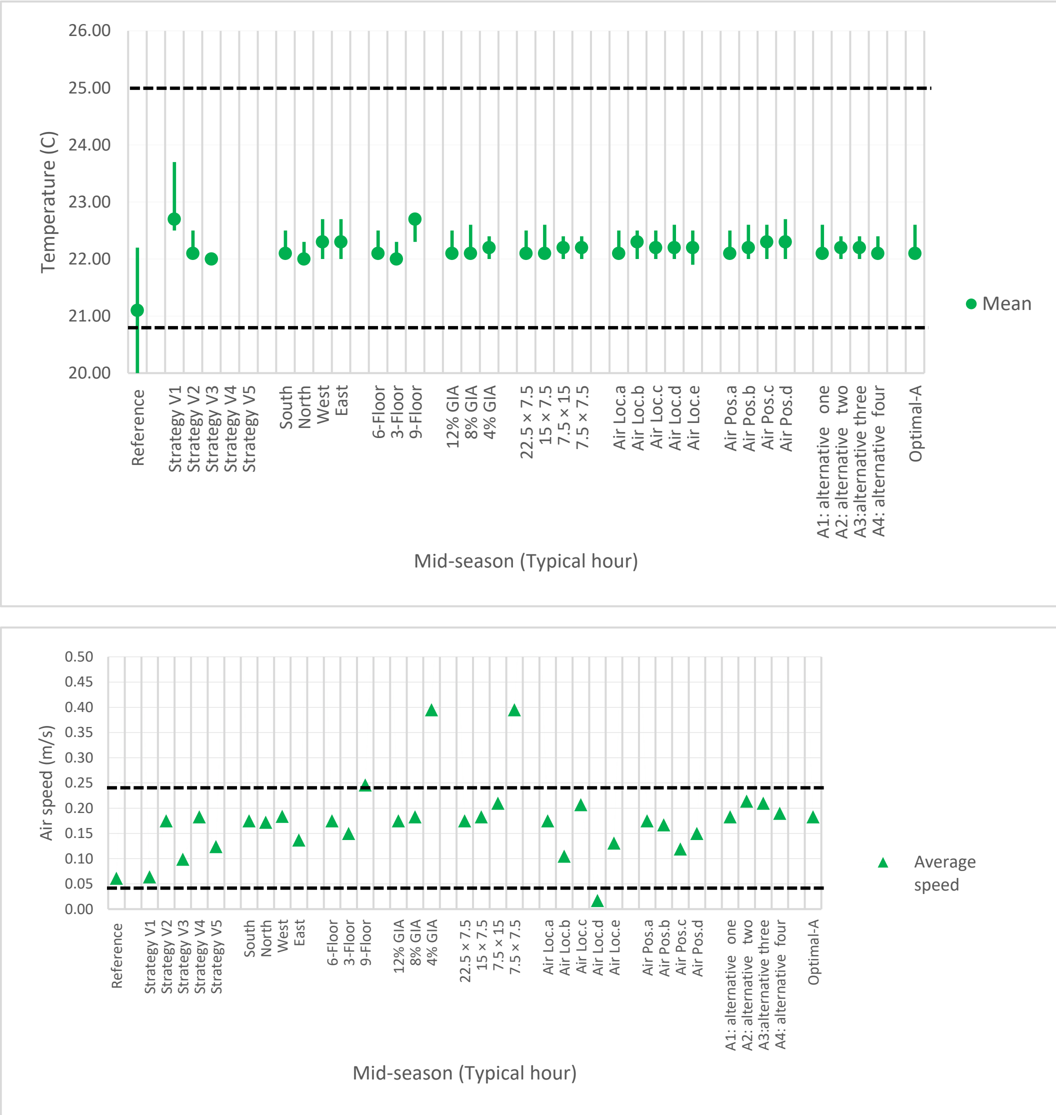


Figure 5-50. Air temperature and airspeed comparison at the occupancy level of the hollowed-out skycourt (A) at the typical hour of mid-season (dashed lines show comfort ranges) for all cases

5.3 SKYCOURT PROTOTYPE (B): THE CORNER SKYCOURT

This section presents an overview of the main simulation results for the skycourt prototype (B), the corner skycourt. This skycourt has two extended facades. Results of the simulations are organised in four parts representing the main stages. First, the optimum ventilation strategy for the unheated and uncooled skycourt is defined. This includes comparing the performance of this ventilation strategy to the heated and cooled skycourt. Second, the results of the sensitivity analysis are considered. Third, the results of correlating the optimised geometric parameters of the skycourt and air inlet and outlet openings inside the skycourt are considered. Finally, the optimal configurations of the skycourt are defined.

5.3.1 Results of the Ventilation Strategies

This section shows the simulation results for investigating six ventilation strategies. These consider: (i) the air-conditioned, heated and ventilated skycourt (reference case), (ii) the proposed ventilation strategies for the ventilated, unheated and uncooled skycourt.

Simulation results for the six ventilation strategies adopted were considered in this comparison. These strategies are the isolated ventilation strategy for the air-conditioned skycourt and adjacent offices in the reference model, and the five proposed ventilation strategies for the unheated and uncooled skycourt. These include ventilation strategy one (V1), ventilation strategy two (V2), ventilation strategy three (V3), ventilation strategy four (V4), and ventilation strategy five (V5).

The annual heating and cooling demands for the building indicated the ineffectiveness of the air-conditioned skycourt. This strategy requires a high energy demand for cooling the skycourt (Figure 5-51). The total demand for annual heating and cooling of the building under this strategy was very high, i.e. 245 kWh/m^2.yr. Results of the simulation reported a temperature of 25°C in summer and 19°C in winter at the occupied area of the skycourt during the target times (Figure 5-52 and Figure 5-53).

On the other hand, the five proposed ventilation strategies, which are based on the concept of ventilating the skycourt without consuming energy for heating and/or cooling, provided an almost 60% reduction in the total heating and cooling demand for the building per year in comparison with the reference case.

The five strategies reported sequentially the following demand: (i) 93.8 kWh/m^2.yr, (ii) 91.5 kWh/m^2.yr, (iii) 92.7 kWh/m^2.yr, (iv) 99 kWh/m^2.yr, and (v) 98 kWh/m^2.yr. The results show that the combined-exhaust ventilation strategies (strategy two and strategy three) can remarkably reduce the annual total heating and cooling demand by 63% and 62%, respectively. Whereas in the combined-supply ventilation strategies (strategy four and strategy five), percentages of energy reduction are less, i.e. 59.5% and 60%, respectively.

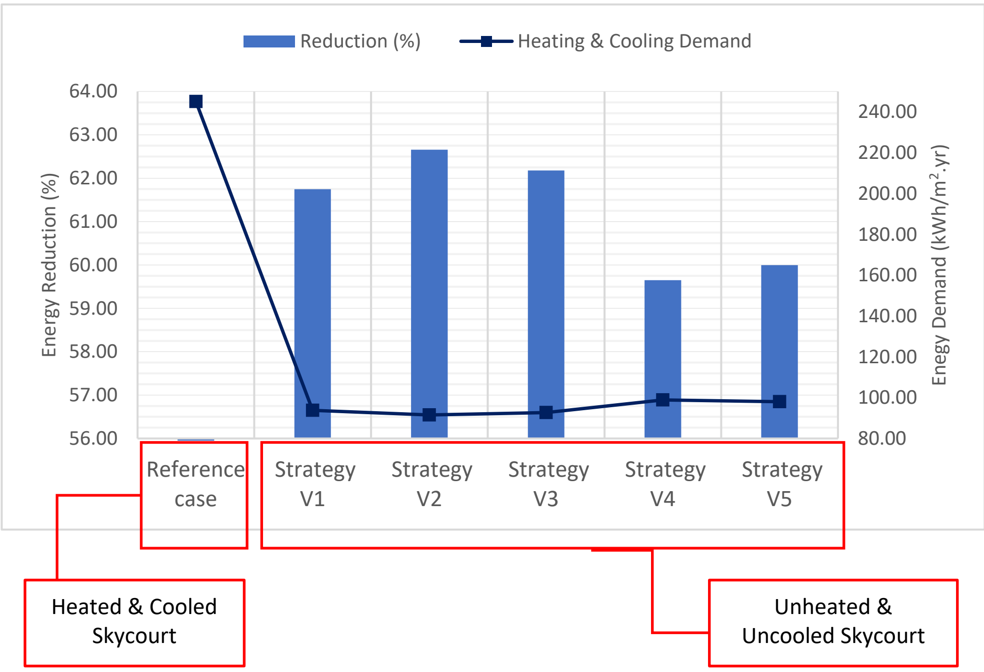


Figure 5-51. Annual total heating and cooling demand comparison in the corner skycourt (B) building: ventilation strategies

CFD results showed that temperatures for strategy one, which considers the infiltration only, reported unacceptable thermal conditions in summer and winter in the skycourt.

Thermal conditions at the occupied area of the skycourt were almost within the accepted comfort temperature level in summer and mid-seasons when adopting strategy two. It recorded 26.8°C of 0.2 m/s in summer, and 22.3°C of 0.16 m/s in mid-seasons, whereas it was 14.5°C of 0.3 m/s in winter.

The other combined strategies recorded a difference of 1°C to 3°C compared to strategy two. They provided higher temperatures in summer and lower temperatures in winter.

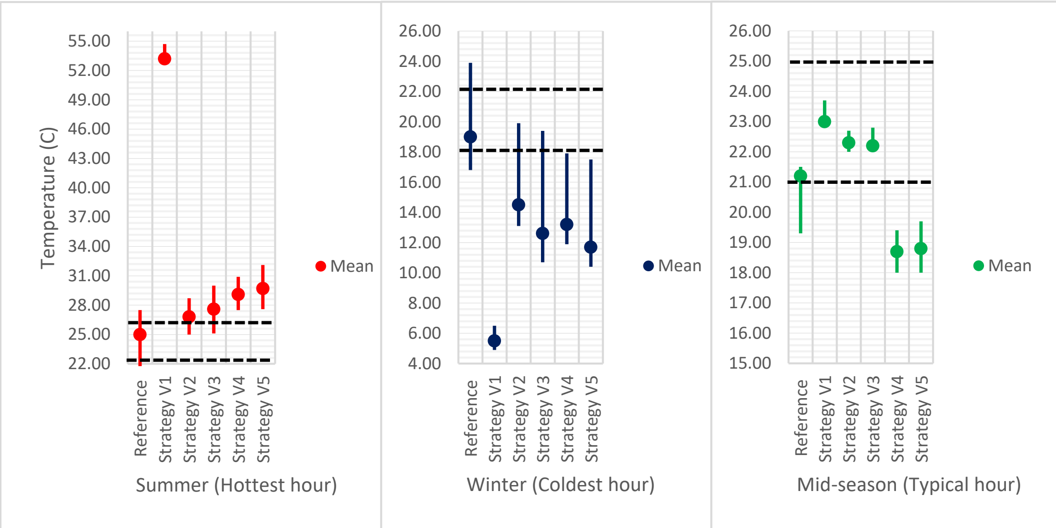


Figure 5-52. Air temperature comparison at the occupancy level in skycourt (B) (dashed lines show comfort air temperature ranges): ventilation strategies

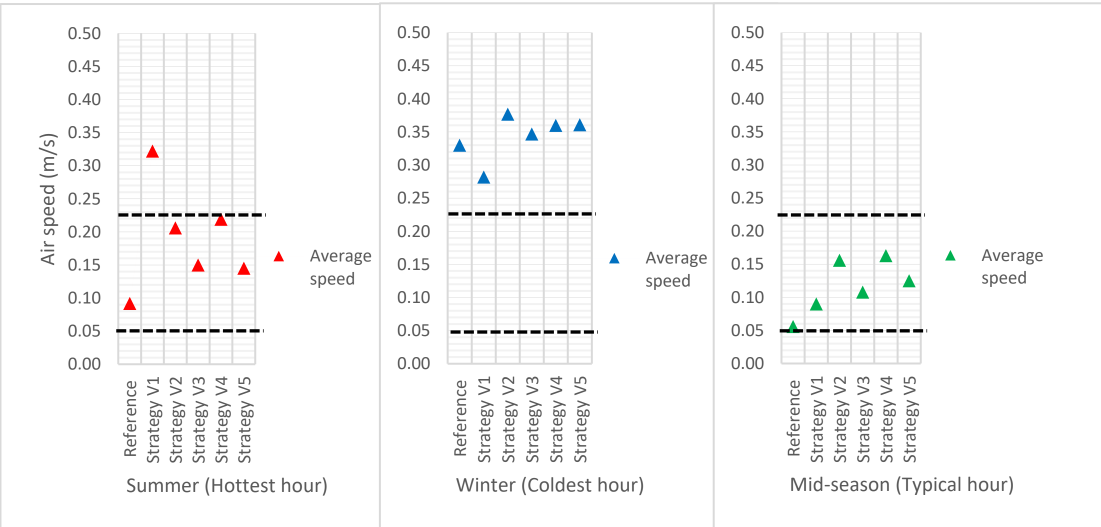


Figure 5-53. Airspeed comparison at the occupancy level in skycourt (B) (dashed lines show comfort airspeed ranges): ventilation strategies

Taken together, the combined ventilation strategies for the skycourt show high potentials for energy saving and thermal comfort.

The findings of this stage indicated that strategy two is the optimum ventilation strategy to minimise the energy consumptions of the building, besides ensuring a comfort level of temperature and airspeed in skycourt (B). The combined-exhaust ventilation strategy two (V2) depends on the maximum rate of airflow volume that exhausts from the adjacent offices as supply air to the skycourt. Therefore, strategy two was applied as a ventilation strategy in the next stage to investigate the influence of key parameters on building energy consumption and skycourt thermal performance.

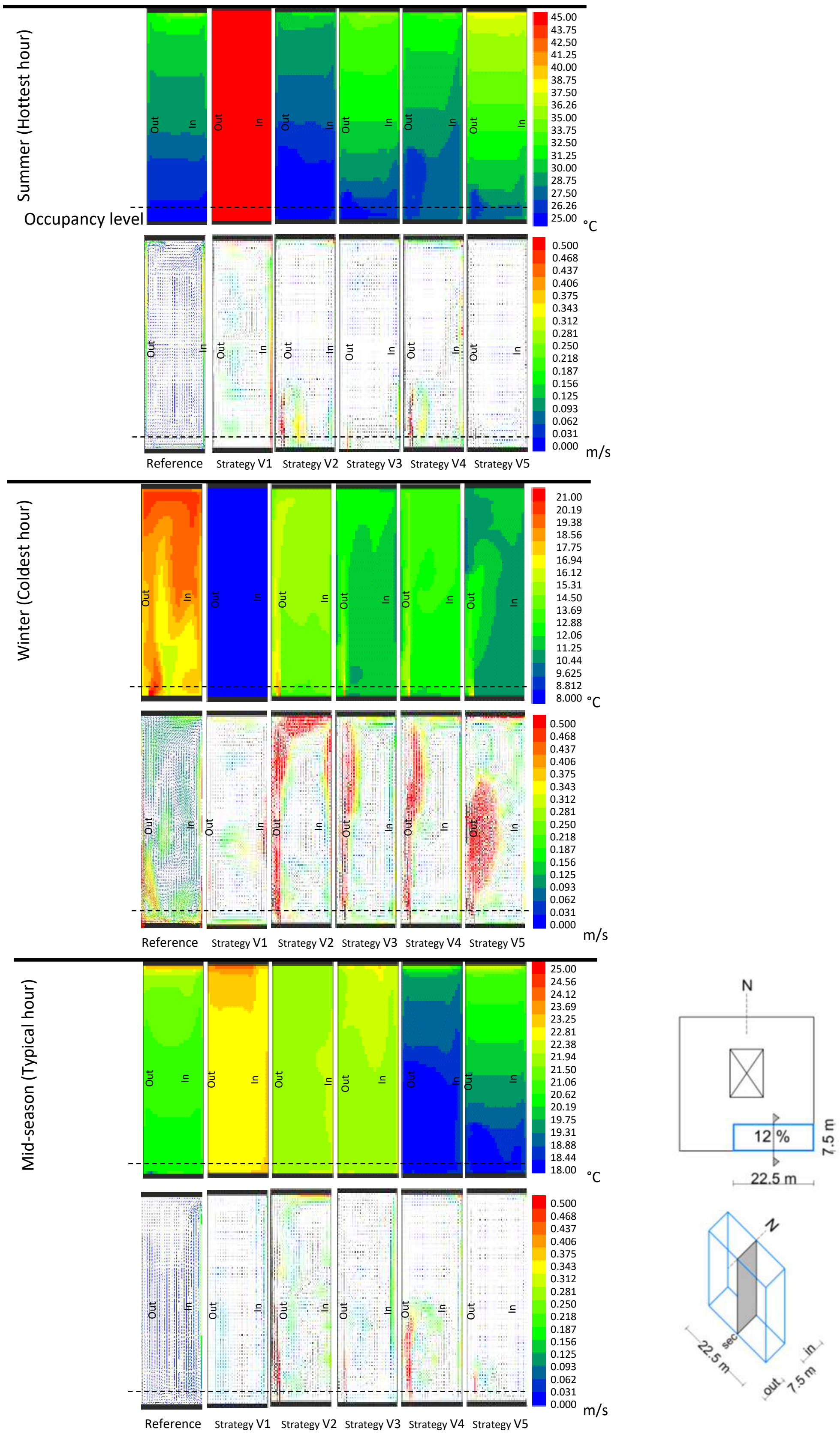


Figure 5-54. Thermal conditions in skycourt (B) at the hottest hour in summer, the coldest hour in winter and typical hour in mid-season: ventilation strategies

5.3.2 The Sensitivity Analysis Results

This section presents the simulation results for investigating the impact of: (i) geometric parameters of the skycourt (orientation, height, area, length and depth), (ii) ventilation vertical locations and horizontal positions of air inlet and outlet openings inside the courtyard. The results showed that there are marginal impacts on the energy performance for the building, as well as on the thermal conditions inside the skycourt. The model integrating the unheated and uncooled skycourt with the optimum ventilation strategy from the previous stage is used as a base case for comparing the impact of each parameter.

Figure 5-55 compares the results of the annual heating and cooling consumption for the building according to the investigated parameters. Figures 5-56 to 5-58 compare results of air temperature and airspeed at the occupied area of the skycourt for these cases. Detailed figures for CFD thermal conditions inside the skycourt in the selected times for each tested parameter are illustrated in Appendix D.

The following summaries the main findings of this stage:

The corner skycourt (B) is attached to the exterior by two edges; the orientation is described firstly by the main façade, then the other edge of the skycourt. Four orientations are considered in this comparison: south-east, north-west, west-south, and east-north.

It is clear that differences in heating and cooling demands between cases are less than 0.1%. The south-east case reported the highest energy saving, as other orientations caused a rise in heating and cooling demand for the building. Results regarding temperature gradients indicated that north-west and east-north orientations of the skycourt provided similar and favourable thermal conditions at the occupied level of the skycourt. It recorded 26.2°C of 0.2 m/s in summer; 14.6°C of 0.35 m/s in winter; and 22.1°C of 0.17 m/s in mid-seasons. However, the north-west skycourt is predicted to provide better effects on the adjacent offices, as temperature ranges through the volume of the skycourt are 0.5°C lower in summer and higher in winter, than the east-north case.

The results of heating and cooling consumptions displayed that increasing the height of the skycourt provides greater reduction in heating and cooling demands. In addition, more accepted levels of temperature could be achieved, yet airspeed levels were less satisfactory.

Considering the three-floor skycourt as a case of comparison, it is apparent that increasing the skycourt height to nine floors causes a reduction in heating and cooling demands by 0.12% per year for each office. In addition, the summer temperature in the skycourt was reduced by about 0.5°C, while temperature increased in winter by about 0.6°C; yet airspeed was increased. The six-floor height of the skycourt provided an accepted level of both temperature and airspeed comfort.

Three areas of skycourt were tested. These were defined according to the skycourt percentage of the gross internal area of the office floor as 12% GIA, 8% GIA, and 4% GIA. The results indicated that a smaller skycourt area achieves less heating and cooling demand for the building per square metre. The 4% GIA case accounted for about a 1.4% reduction compared to the 12% GIA case, while the 8% GIA case reported about half of this percentage.

However, the thermal conditions in the occupied area of the skycourt were favourable under the 8% GIA case. CFD results presented that the temperature of the 4% GIA case was higher than the 8% GIA case by about 0.5°C. This increase in temperature is favourable in winter, but not in summer. This difference could be due to the high solar gain in this space; it collected about 914 kWh/m^2.yr, whereas, the 8% GIA collected about 706 kWh/m^2.yr. The average airspeed in the 4% GIA case was high; i.e. about 0.3 m/s to 0.4 m/s in the different seasons. However, the thermal conditions of the 12% GIA and 8% GIA cases were similar. Therefore, the 8% GIA case was considered for the next stage.

In terms of skycourt dimensions, when taking into consideration its length and depth when the area is fixed, a positive correlation was found between energy savings and the skycourt length. Increasing the depth of the skycourt reduced energy savings. However, the difference was small, i.e. about 0.1% between the two cases. The simulation results show that to ensure a satisfactory air temperature and airspeed at the occupants' level inside the skycourt, a small length and a larger depth of the skycourt should be adopted. Therefore, two models are advised for the optimal configuration stage. These are depth and length of 15 m × 7.5 m and 7.5 m × 15 m.

The results indicated that locating all air inlet openings at the floor level of the skycourt and all air outlet openings at the ceiling of the skycourt, provided favourable ranges of air temperature and average airspeed at the occupied area of the skycourt in the different seasons. It recorded temperatures of 26.8°C of 0.2 m/s in summer; 14.5°C of 0.37 m/s in winter; and 22.3°C of 0.16 m/s in mid-seasons. In other alternatives, where air inlet openings were distributed between the floor and ceiling level of the skycourt, the air temperature was higher in summer by 1°C to 2°C, whereas it was lower in winter by 0.5°C to 1°C. Therefore, the first alternative is suggested to induce an efficient airflow strategy.

The effect of the horizontal positions of air openings on the airflow performance was investigated. Air inlet openings were positioned at the floor level, and air outlet openings at the ceiling level within the skycourt space. There was no major effect on the occupied area temperature, yet there were significant impacts on the average airspeed, and on the adjacent offices of the skycourt.

It is efficient to position air inlet and outlet openings opposite to each other vertically. Moreover, placing the inlet openings closer to the external facade of the skycourt, and the outlet openings closer to the internal wall of the skycourt is favourable to ensure the occupants' thermal comfort at the occupied level in the different seasons. Therefore, this alternative was selected for next stage of the investigation.

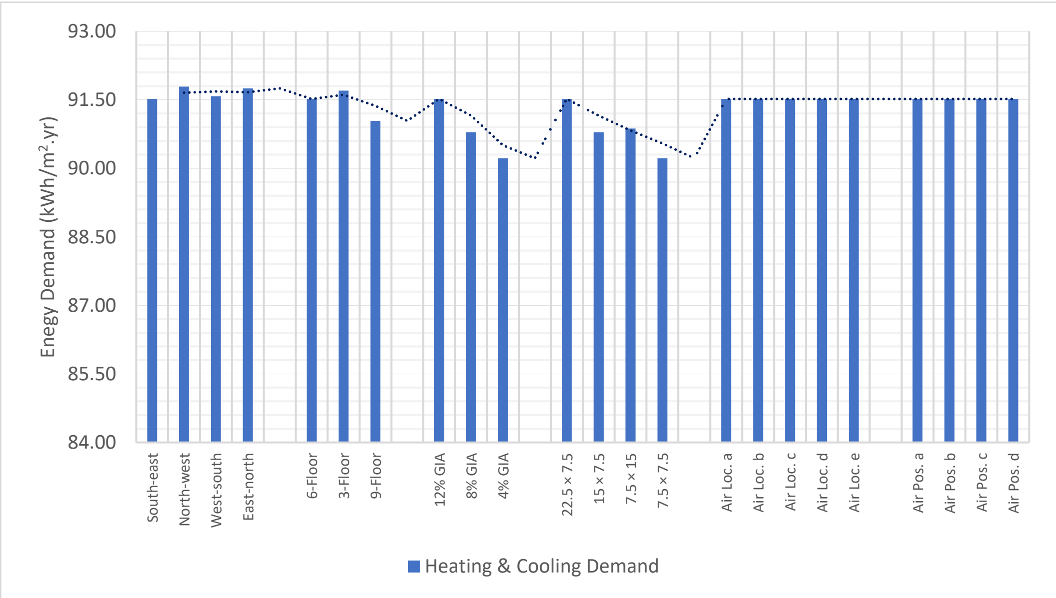


Figure 5-55. Annual total heating and cooling comparison in the corner skycourt (B) building: sensitivity analysis

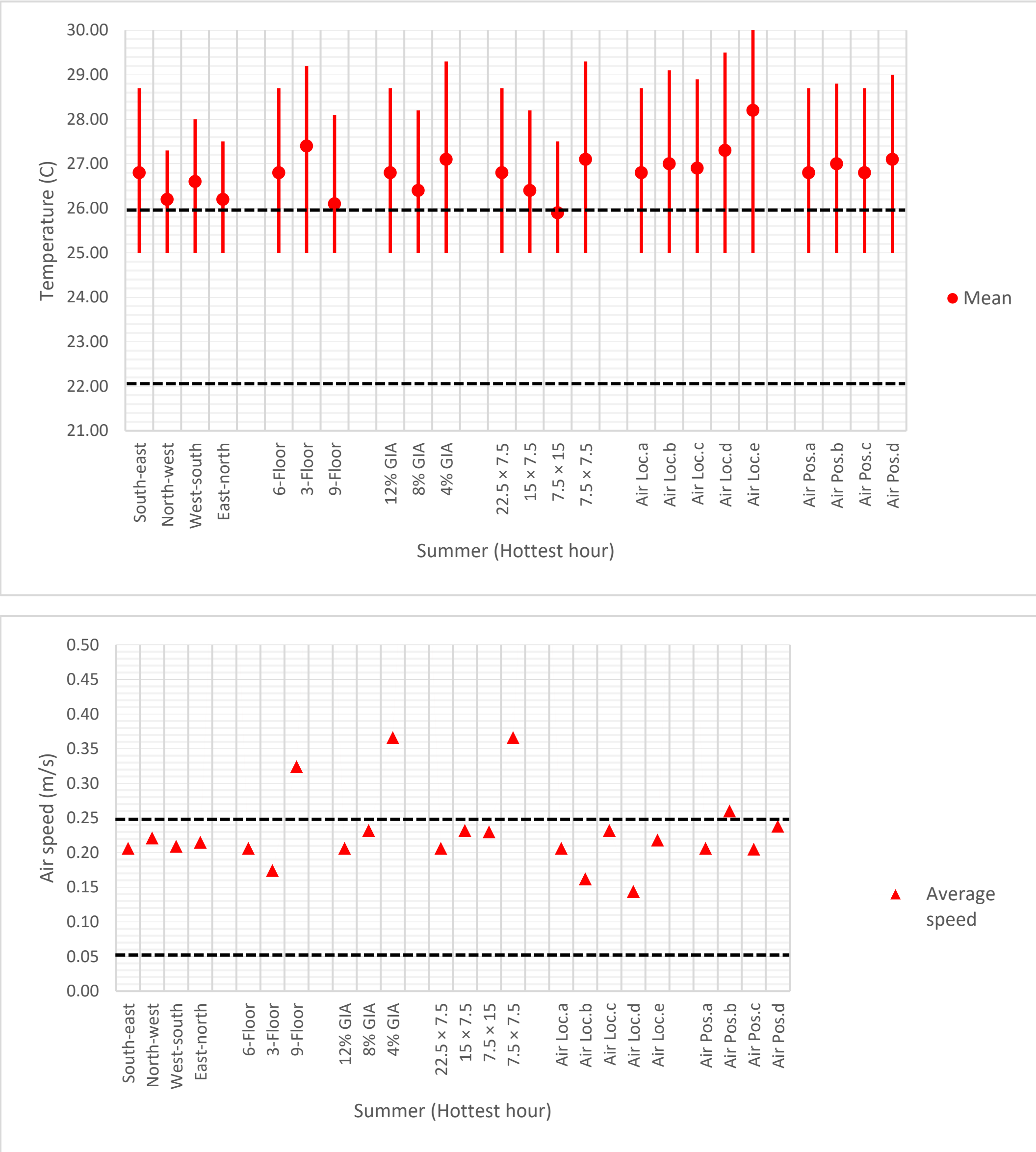


Figure 5-56. Air temperature and airspeed comparison at the occupancy level of corner skycourt (B) in summer case (dashed lines show comfort ranges): sensitivity analysis

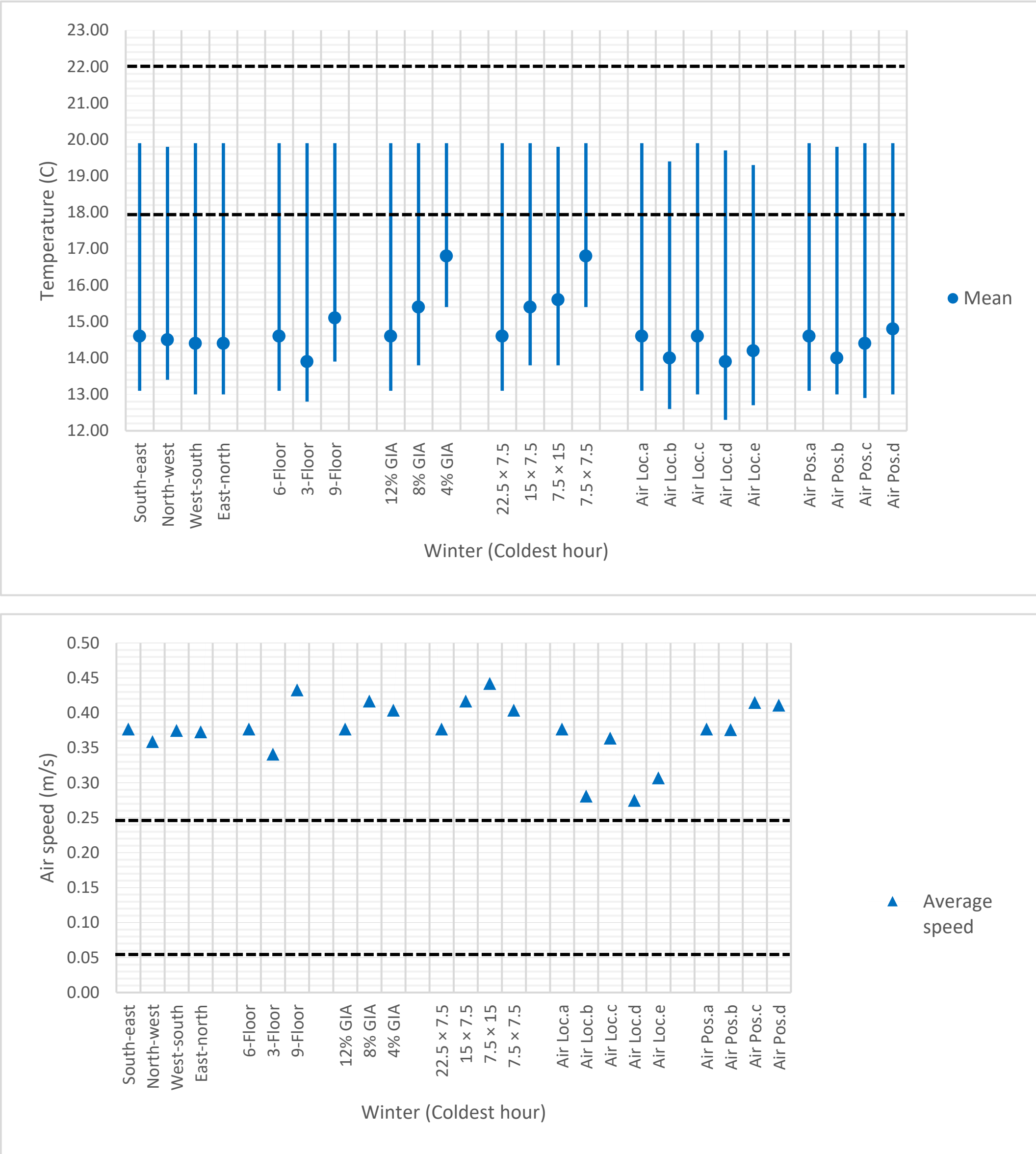
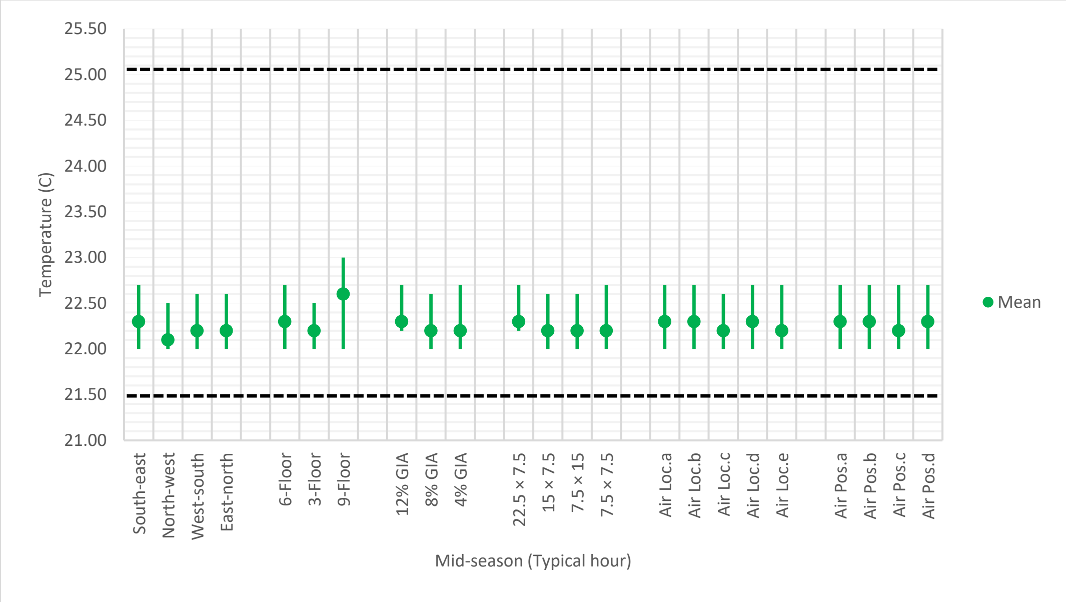


Figure 5-57. Air temperature and airspeed comparison at the occupancy level of the corner skycourt (B) in winter (dashed lines show comfort ranges): sensitivity analysis



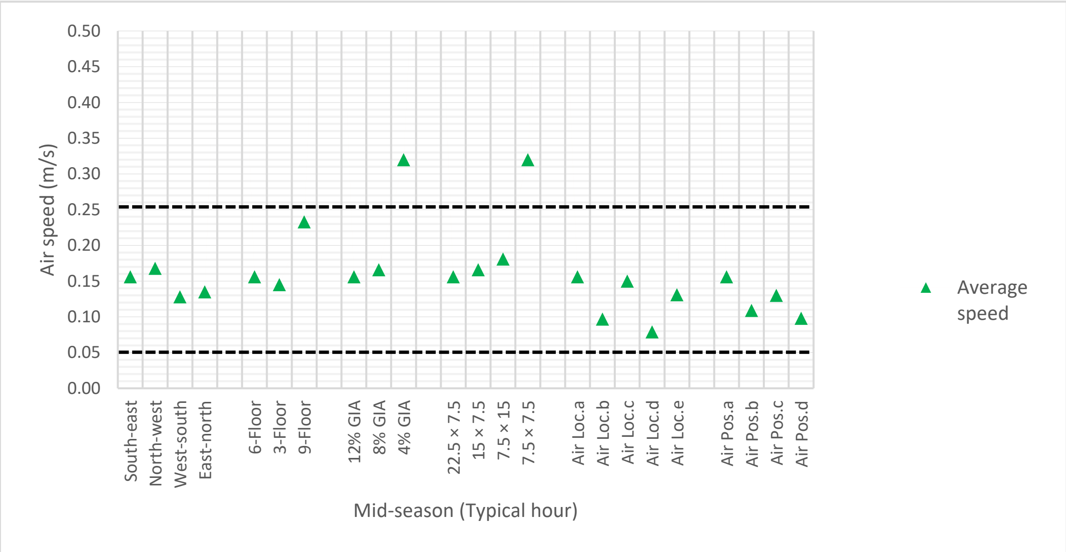


Figure 5-58. Air temperature and airspeed comparison at the occupancy level of the corner skycourt (B) in mid-season case (dashed lines show comfort ranges): sensitivity analysis

5.3.3 The Improved Configurations Results

In this stage, the optimised parameters for the corner skycourt (B) were correlated. Four models were examined to assess the actual improvement on thermal and energy performance. The fixed parameters for the skycourt in the developed alternative models are as follows: six-floor height, 8% area to GIA, and the location of air inlet openings at the floor level closer to the external façade, and the air outlet openings at the ceiling closer to the internal wall of the skycourt (Figure 5-59).

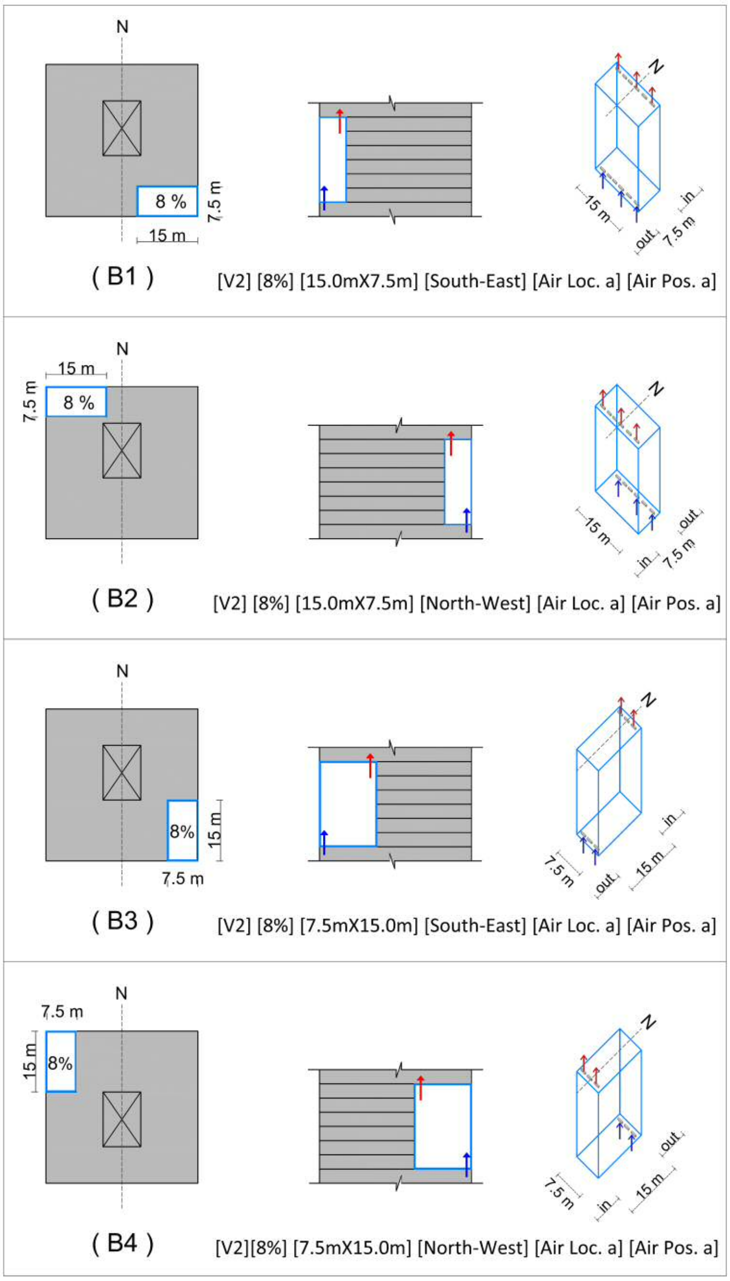


Figure 5-59. Schematic diagrams of models concluded from stage three for skycourt (B) geometry design: alternative one (B1), alternative two (B2), alternative three (B3) and alternative four (B4)

In alternative one (B1), the longer length of the skycourt (15 m × 7.5 m) was oriented to the south direction, while in alternative two (B2), it was oriented to the north. Alternatives three (B3), and four (B4) considered the south and the north orientations, respectively, for the 7.5 m length of the skycourt.

The annual demands for heating and cooling of the buildings were compared with the base building in stage two of the skycourt (B). The base model is 22.5 m × 7.5 m, oriented to the south-east, and occupying 12% of the office floor area. It was apparent that the differences in energy performance occurred with the variation of the orientation (Figure 5-60). The energy demand decreased with the increase of the skycourt's length. The 15 m × 7.5 m model produced a higher percentage of energy savings than the 7.5 m × 15 m model, i.e. about 1%. In addition, differences in energy consumption between the south-east and the north-west models were observed. The south-east model consumed less energy for heating and cooling. These findings were also reinforced with the sensitivity analysis results.

According to the study, the best configuration of the six parameters yields the highest reduction in heating and cooling demand. Therefore, alternative one (B1) has the potential to produce the lowest energy consumption.

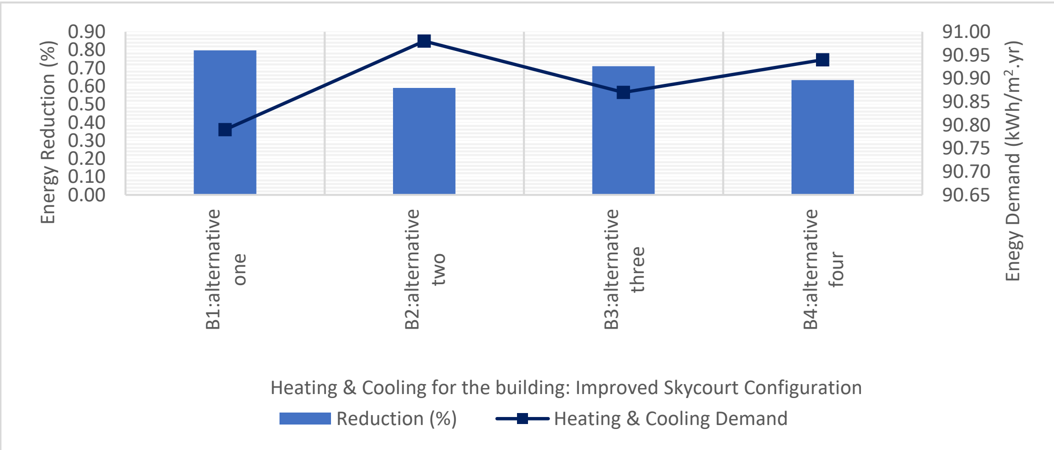


Figure 5-60. Annual energy comparison in the corner skycourt (B) building: improved configurations

Thermal conditions at the occupied area of the different skycourt configurations are presented in Figure 5-61 and Figure 5-62. Overall, the air temperature ranged between

25°C and 28°C of 0.25 m/s in summer; 14°C and 20°C of 0.44 m/s in winter; and 22.2°C of 0.2 m/s in transitional seasons. However, temperatures were slightly higher for the south-east orientation, of less than 0.5°C in different seasons. These findings are consistent with the results of the sensitivity analysis.

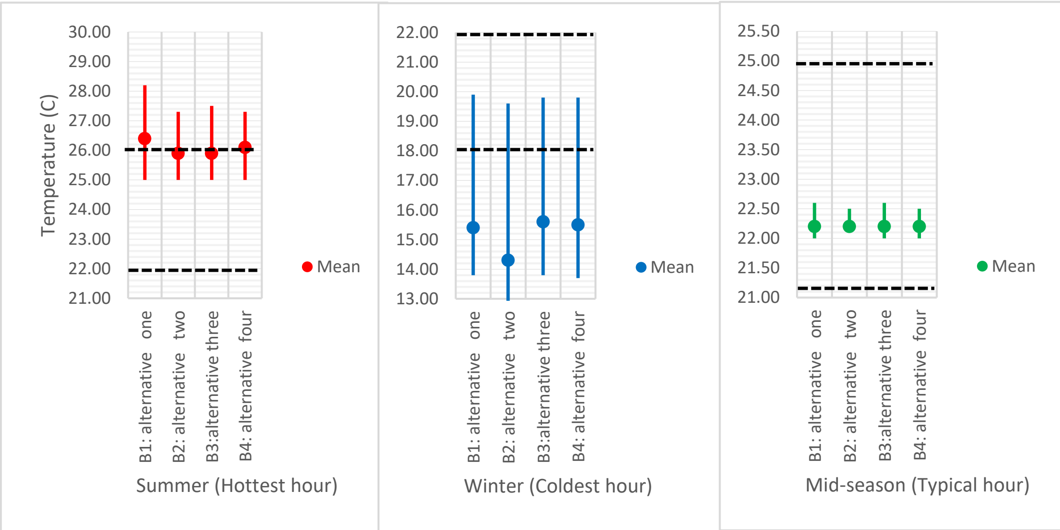


Figure 5-61. Air temperature comparison at the occupancy level in skycourt (B) (dashed lines show comfort air temperature ranges): improved configurations

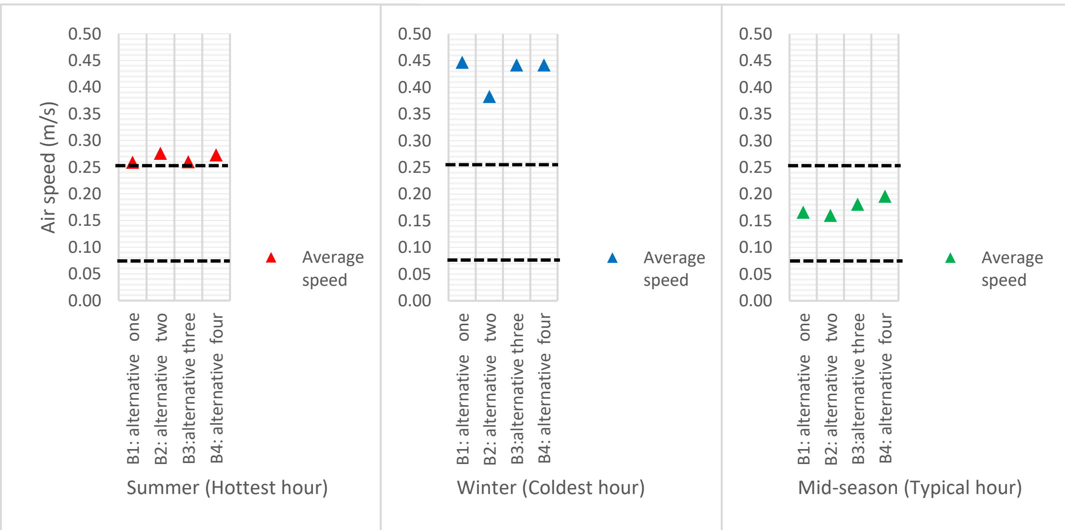
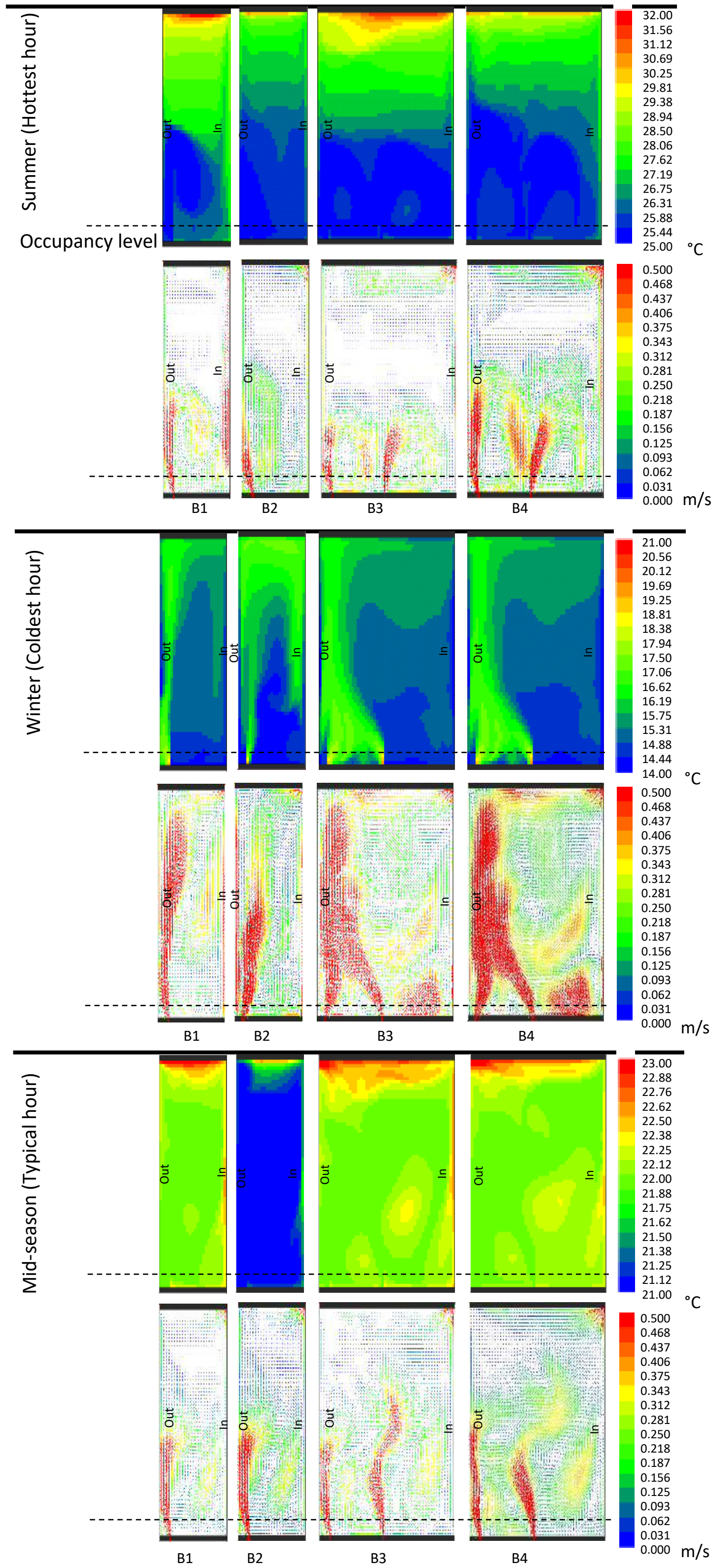


Figure 5-62. Airspeed comparison at the occupancy level in skycourt (B) (dashed lines show comfort airspeed ranges): improved configurations

When taking the energy and thermal performances together, alternative one (B1) ensures thermal comfort at the occupied area of the skycourt. In addition, it affects the adjacent offices positively in terms of reducing heating and cooling demand and providing shading.



B1: Skycourt (B) alternative one: [V2] [South-East] [8%] [15m × 7.5m] [Air Loc. a] [Air Pos. a]
B2: Skycourt (B) alternative two: [V2] [North-West] [8%] [15m × 7.5m] [Air Loc. a] [Air Pos. a]
B3: Skycourt (B) alternative three: [V2] [South-East] [8%] [7.5m × 15m] [Air Loc. a] [Air Pos. a]
B4: Skycourt (B) alternative four: [V2] [North-West] [8%] [7.5m × 15m] [Air Loc. a] [Air Pos. a]

Figure 5-63. Thermal conditions in skycourt (B) at the hottest hour in summer, the coldest hour in winter and typical hour in mid-season: improved configurations

5.3.4 The Optimal Corner Skycourt

The optimal configuration of the unheated and uncooled corner skycourt (prototype (B)) is defined through the following parameters. A space of six-floor height, occupying 8% of the floor space of adjacent offices; its main facade is oriented to the south, and its other facade is oriented to the east. This skycourt is ventilated by the air extracted from the adjacent offices through inlet openings located at the floor level closer to the external façade. The air is extracted through outlet openings located at the ceiling closer to the internal wall of the skycourt.

Table 5-4. Summary of design parameters, energy demand and thermal conditions for the reference model and optimal case among simulation cases for the corner skycourt

	Reference (B) Model Heated and Cooled Skycourt	**Optimal (B) Model Unheated and Uncooled Skycourt**
Ventilation strategy for the skycourt	Isolated ventilation: air-conditioned	Strategy two (V2): combined-exhaust
Geometric attributes of the skycourt		
Height	Six-floor height	Six-floor height
Orientation	South-east	South-east
Area (%) to GIA	12% GIA	8% GIA
Length and depth	22.5 m × 7.5 m	15 m × 7.5 m
Air inlet and outlet vertical locations inside the skycourt	Alternative (a): air inlet openings located at the floor level, and air outlet openings located at the ceiling level of the skycourt	Alternative (a): air inlet openings located at the floor level, and air outlet openings located at the ceiling level of the skycourt
Air inlet and outlet horizontal positions inside the skycourt	Alternative (a): air inlet openings positioned closer to the external façade, and air outlet openings closer to the internal wall of the skycourt	Alternative (a): air inlet openings positioned closer to the external façade, and air outlet openings closer to the internal wall of the skycourt
Energy demand of the building		
Annual heating and cooling demand for adjacent offices	245 kWh/m^2.yr	90.8 kWh/m^2.yr
Thermal conditions at the occupied area of the skycourt		
Summer, at external temperature 28°C	25°C of 0.09 m/s	26.4°C of 0.2 m/s
Winter, at external temperature -5°C	19°C of 0.3 m/s	15.5°C of 0.4 m/s
Mid-seasons, at external temperature 13°C	21.2°C of 0.06 m/s	22.2°C of 0.2 m/s

The optimal corner skycourt building is compared with the reference building of the air-conditioned skycourt. Table 5-4 summaries the comparison between the two models in terms of design configurations (ventilation strategy, geometry, and air inlet and outlet opening distributions), energy performance of the building, and thermal conditions of the skycourt. Geometric differences between the two models are related to the area percentage to GIA, and dimensions of the skycourt. It is obvious that the differences in energy demand and thermal performance were due to the ventilation strategy applied in the building. The optimal unheated and uncooled skycourt model showed potentials in energy saving for heating and cooling, i.e. about 63% per year, compared to the reference model that applied an isolated heating and cooling strategy for both the skycourt and adjacent offices (Figure 5-64).

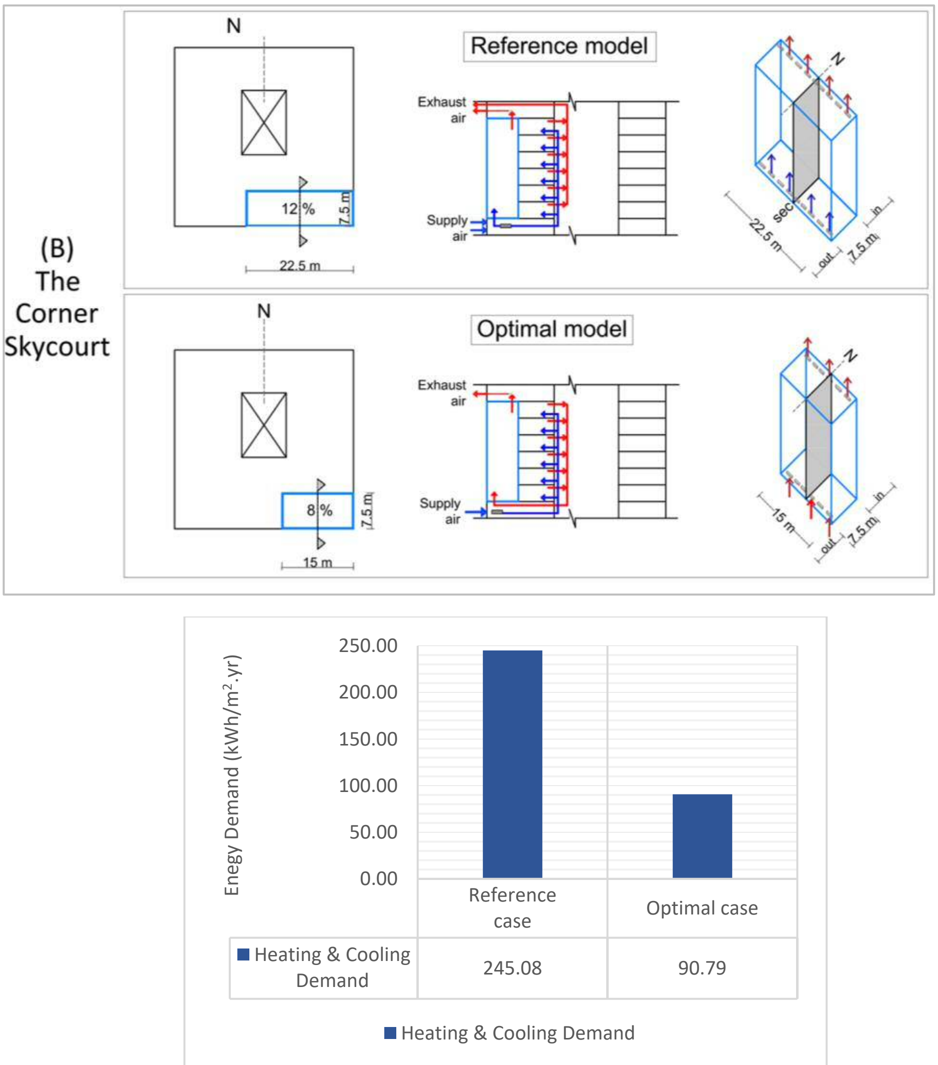


Figure 5-64. Annual energy comparison in the corner skycourt building: reference and optimal models

When comparing thermal conditions of the optimal skycourt to those found in the reference model, it was obvious that comfort level can be accepted in the optimal model. This model adopted the combined-exhaust strategy over the different seasons. Air temperature in summer increased by about 1.5°C at the hottest hour, and decreased in winter by about 3.5°C at the coldest hour, compared to the reference case (Figure 5-65).

The temperature ranges at the occupied area of the optimal skycourt and reference skycourt were the following:

i) At an external temperature of 28^{o}C in summer, the optimal model recorded 25°C to 28°C of 0.2 m/s, while it was 18°C to 27.5°C of 0.09 m/s in the reference model.

ii) At an external temperature of -5^{o}C in winter, temperature in the optimal model ranged between 14°C and 20°C of 0.4 m/s, whereas, it was between 17°C and 24°C of 0.3 m/s in the reference model.

iii) At an external temperature of 13^{o}C in mid-season, the optimal corner skycourt reported 22°C to 23°C of 0.2 m/s, whereas, temperature was between 19°C to 22°C of 0.06 m/s, in the reference model.

In conclusion, the optimal corner skycourt under the combined-exhaust ventilation strategy accomplished a significant improvement in terms of heating and cooling demand reduction for the building, and thermal performance inside the skycourt.

(B) The Corner Skycourt

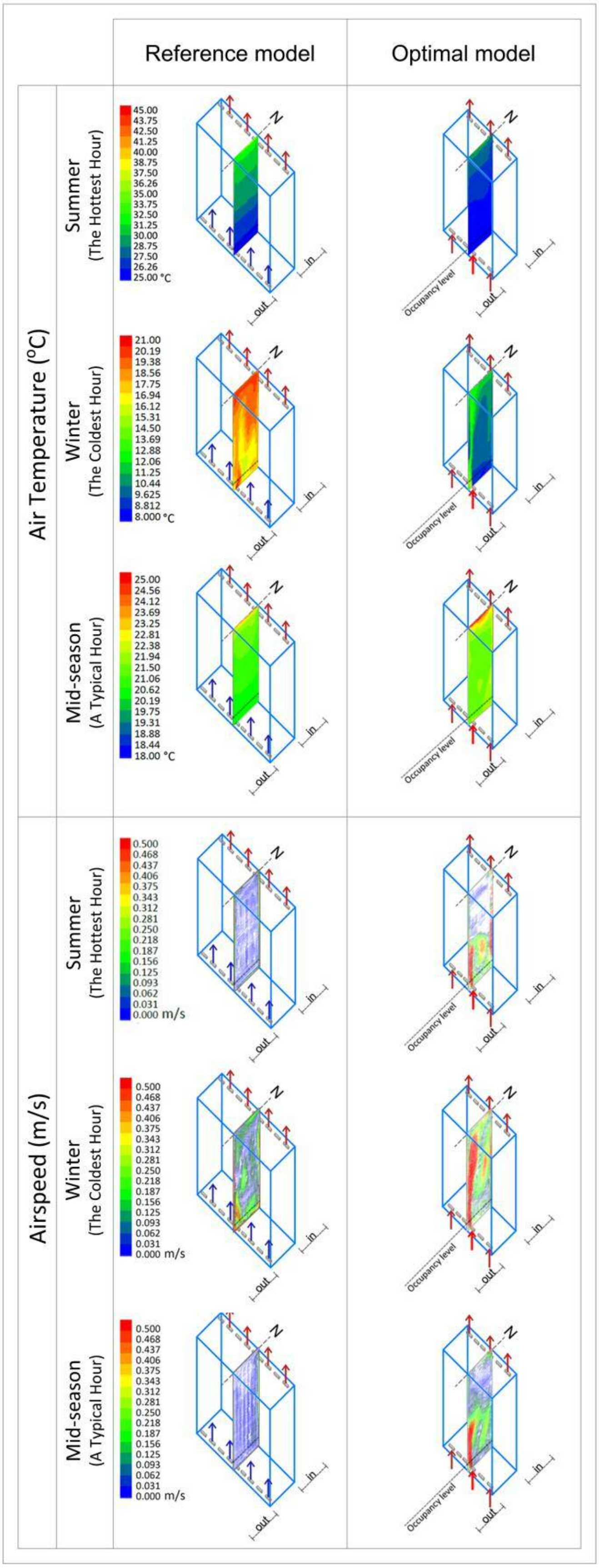


Figure 5-65. Thermal conditions in the corner skycourt at the hottest hour in summer, the coldest hour in winter and typical hour in mid-season: reference and optimal models

5.4 SKYCOURT PROTOTYPE (C): THE SIDED SKYCOURT

This section presents a brief analysis of the main results of energy and CDF simulation for the sided skycourt (Prototype (C)). This prototype is connected to the outside by three external façades. The main façade extends along the whole edge of the building, and the other two occupy the adjacent corners. The summary considers results of investigating the effective ventilation strategy, defining the effect of the skycourt configuration on the ventilation performance, and optimising the key parameters to define the optimal formation of this skycourt.

5.4.1 Results of the Ventilation Strategies

The results showed that considering the skycourt as an unheated and uncooled space, as suggested in the combined ventilation strategies, has a positive impact. These strategies accounted for an almost 70% reduction in the total annual energy demand for heating and cooling in comparison to the reference case. The total heating and cooling demand of the building that integrates an air-conditioned, heated and ventilated sided skycourt was very high, i.e. 330 kWh/m^2.yr (Figure 5-66).

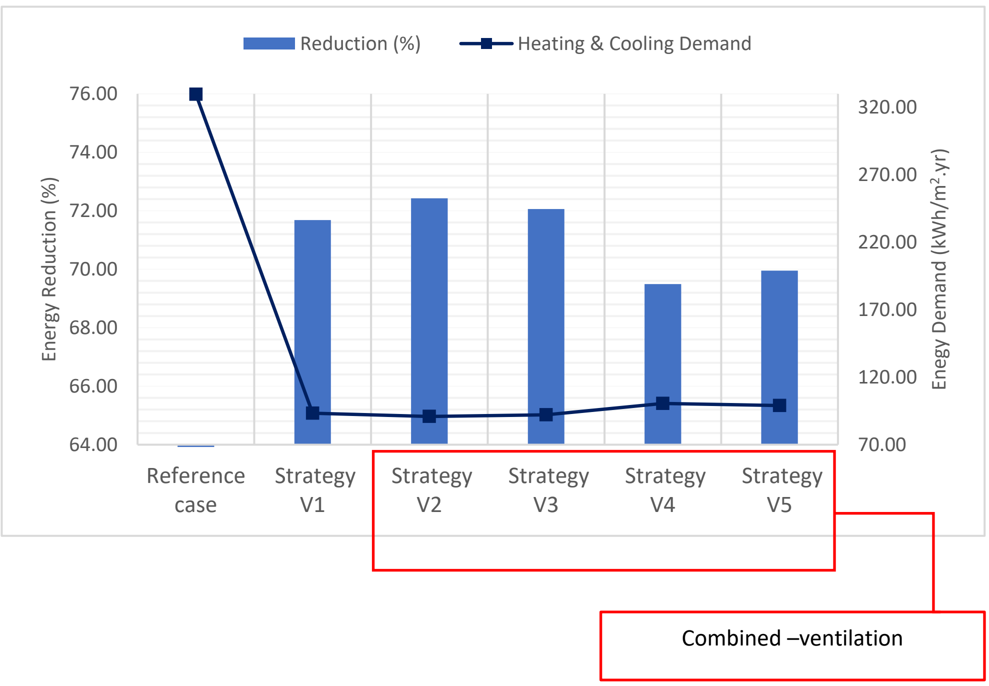


Figure 5-66. Annual total heating and cooling demand comparison in the sided skycourt (C) building: ventilation strategies

Strategies two and three (the combined-exhaust ventilation strategies) were able to reduce the annual total heating and cooling by 72.4% and 72%, respectively. Whereas, the reduction percentage was less when applying strategies four and five (the combined-supply ventilation strategies) by about 2%.

In terms of thermal performance inside the occupied area of skycourt (Figure 5-67, Figure 5-68 and Figure 69), the combined ventilation strategies show an increase between 2°C and 5°C in summer temperature, and a decrease between 6°C and 9°C in winter temperature.

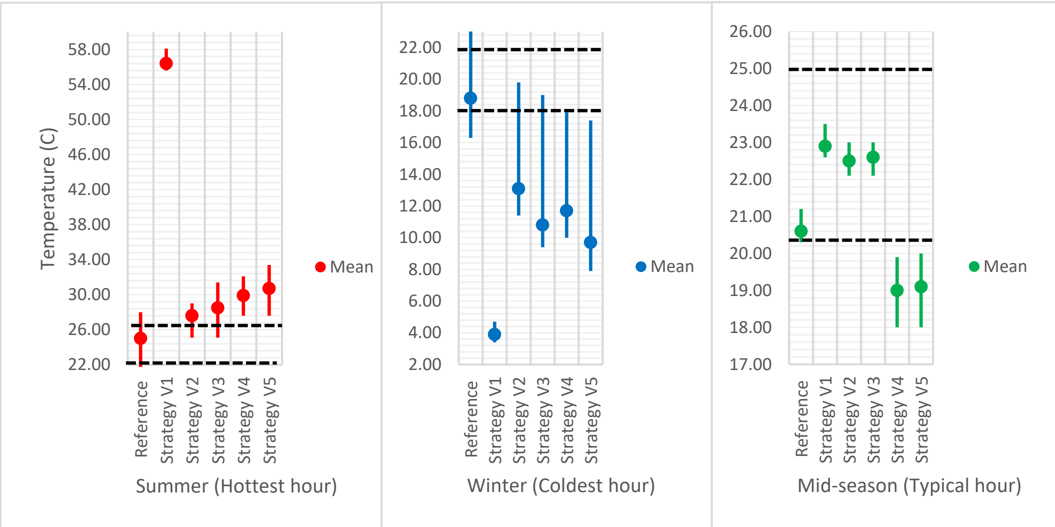


Figure 5-67. Air temperature comparison at the occupancy level in skycourt (C) (dashed lines show comfort air temperature ranges): ventilation strategies

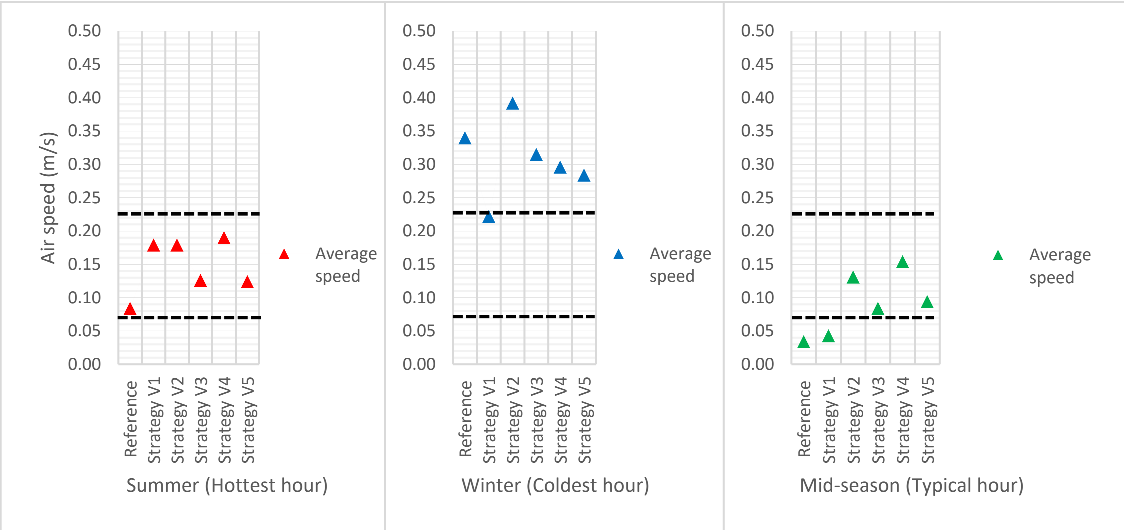


Figure 5-68. Airspeed comparison at the occupancy level in skycourt (C) (dashed lines show comfort airspeed ranges): ventilation strategies

In addition, CFD simulation results showed that the air temperature and airspeed obtained for strategy two were near the comfort level in the different seasons. It accounted for conditions of 27.6°C of 0.2 m/s in summer; up to 20°C of 0.4 m/s in winter; and 22.5°C of 0.13 m/s in mid-seasons. Therefore, strategy two was applied as the ventilation mechanism for the cases in the next stage.

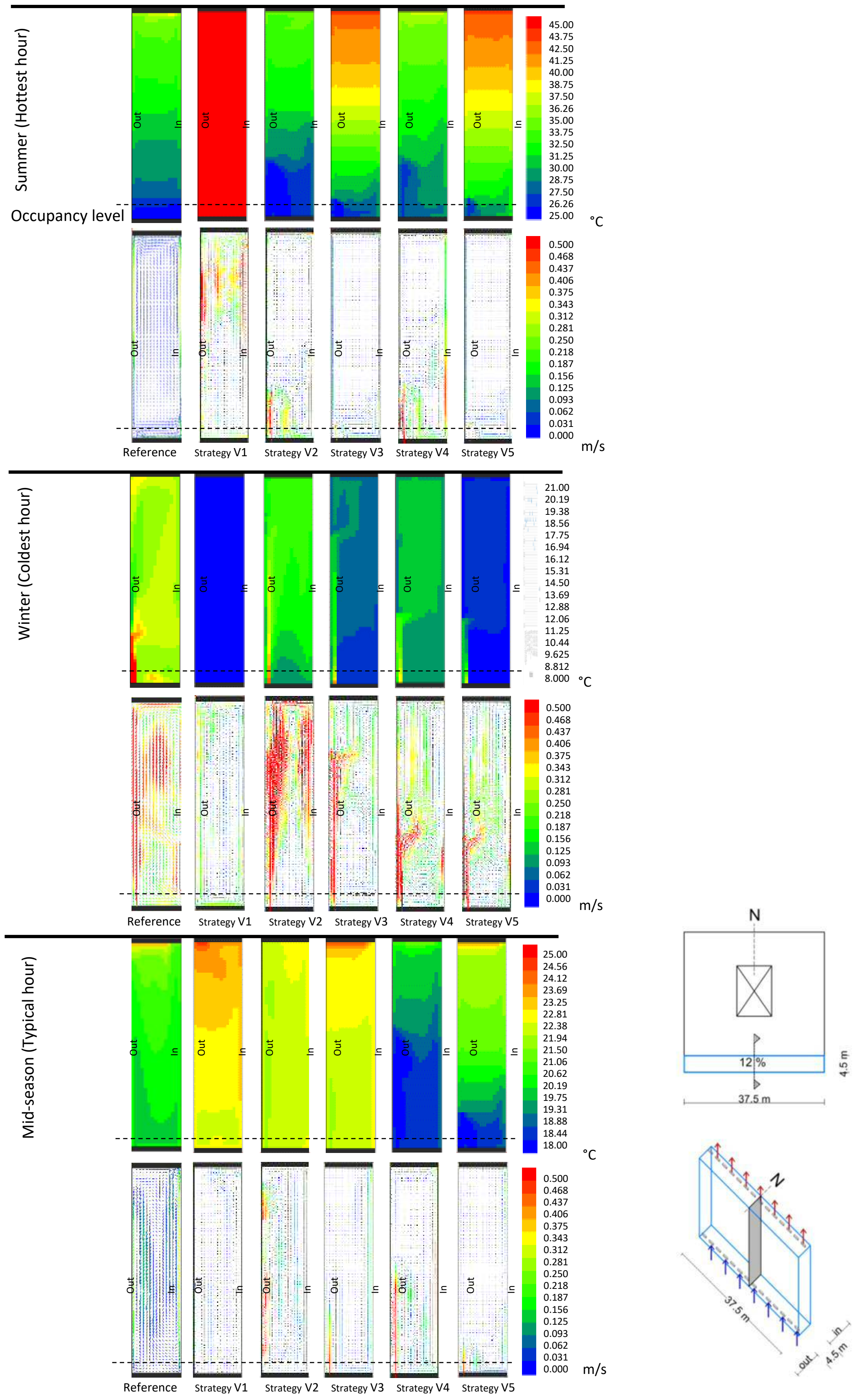


Figure 5-69. Thermal conditions in skycourt (C) at the hottest hour in summer, the coldest hour in winter and typical hour in mid-season: ventilation strategies

5.4.2 The Sensitivity Analysis Results

The sensitivity analysis for the key factors that affect the sided skycourts' geometry and ventilation performance showed that energy performance of the building and thermal conditions at the skycourt have been affected.

A comparison of the annual heating and cooling demand for the building (Figure 5-70), in addition to air temperature and airspeed at the occupied level of the skycourt, are illustrated in Figures 5-71, 5-72, and 5-73 respectively. Detailed results of CFD thermal conditions inside the skycourt are shown in Appendix D.

In terms of the skycourt orientation, results of heating and cooling demands showed that the south-east-west skycourt consumed the least energy, i.e. 90.9 kWh/m^2 per year. However, other orientations caused a slight increase, less than 0.1% of this demand. The north-east-west orientation provided the most accepted level of thermal comfort at the occupied area of the skycourt in summer, i.e. 26.4°C of 0.16 m/s, while other cases showed an increase of about 1°C. Therefore, the south-east-west and the north-east-west orientations are recommended for this skycourt.

Results of heating and cooling consumptions indicated that increasing the skycourt height provided more reduction in heating and cooling demands. In addition, more accepted levels of temperature ranges were achieved. Considering the three-floor skycourt as a case of comparison, it is apparent that a nine-floor skycourt height caused reductions in heating and cooling demands by an average 0.4 kWh/m^2 per year for each office floor. In addition, this reduced the skycourt summer temperature by about 0.4°C, and increased it in winter by about 0.4°C. Yet, these are connected with the increase in airspeed. The six-floor height of the skycourt provided accepted levels of both temperature and airspeed comfort.

Skycourt area ratios of 12% GIA and 8% GIA were tested. The results indicated that the smaller floor area provided conditions conducive to the air temperature comfort range, with less energy demands for heating and cooling.

Regarding the dimensions of the skycourt, the 4.5 m and 3 m depths showed similar air temperatures. However, the smaller depth ensured less energy consumption for heating and cooling, i.e. about 0.1% per 1 m^2 office area per year. Therefore, the 37.5 m × 4.5 m and 37.5 m × 3 m models are advised for the optimal configuration stage.

The results of investigating the effects of the different locations of air openings indicated that the distribution of all air inlet openings at the floor level of the skycourt, and all air outlet openings at the ceiling of the skycourt, ensures a comfort air temperature and an average airspeed in the occupied area of the skycourt. In addition, there were positive influences on thermal conditions for the adjacent offices.

However, in the other alternatives the air temperature ranges were higher in summer and lower in winter. Moreover, better thermal conditions have been achieved when air inlet openings were positioned opposite to the outlet openings. Therefore, it is suggested that the inlet openings should be placed closer to the external facade of the skycourt, and the outlet openings closer to the internal wall of the skycourt, to ensure the occupants' thermal comfort at the occupied level in the different seasons.

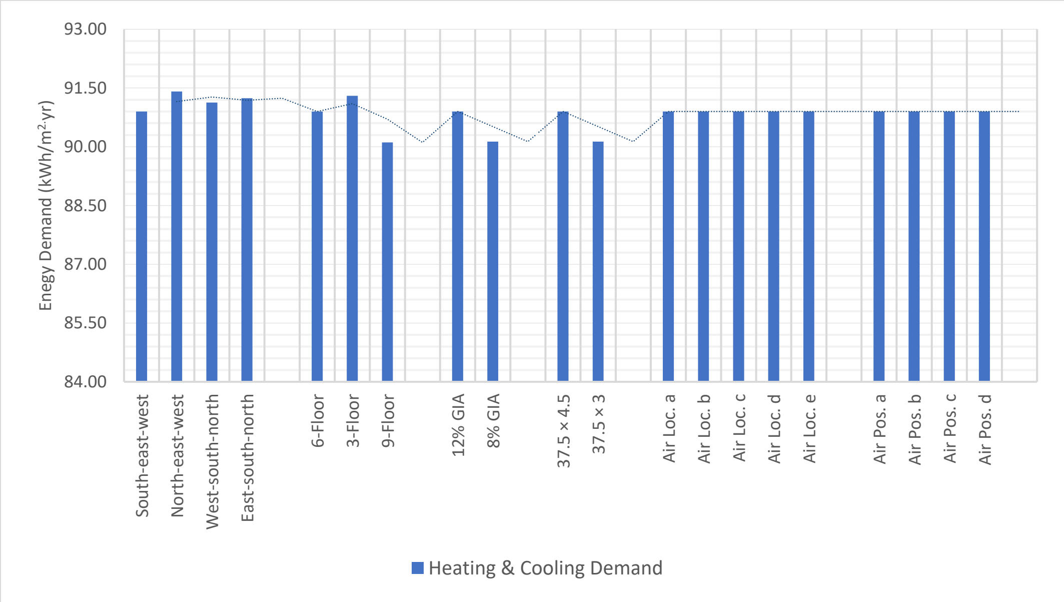
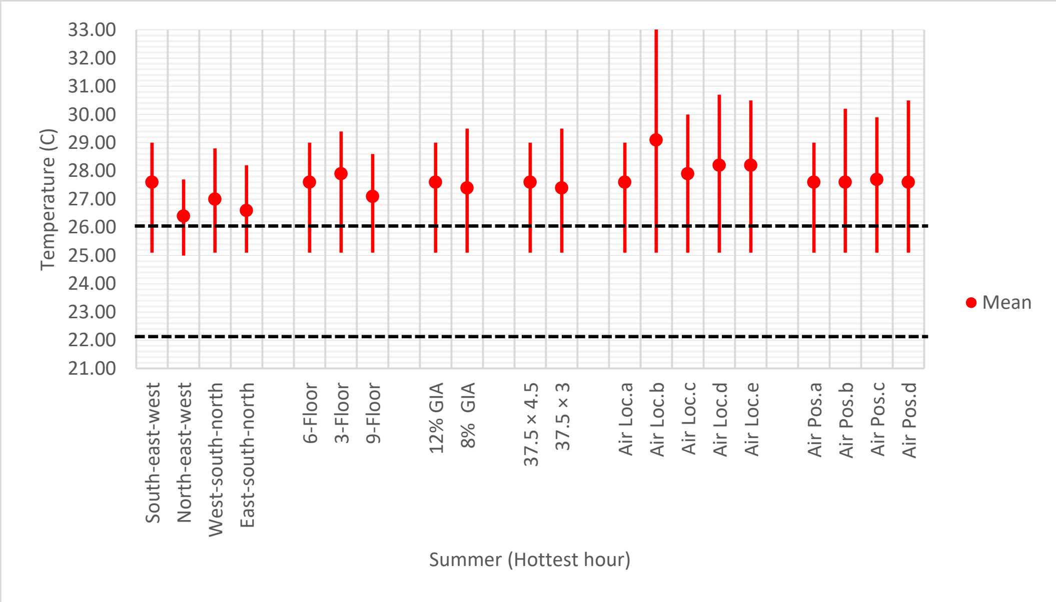


Figure 5-70. Annual total heating and cooling comparison for the building in the sided skycourt (C) building: sensitivity analysis



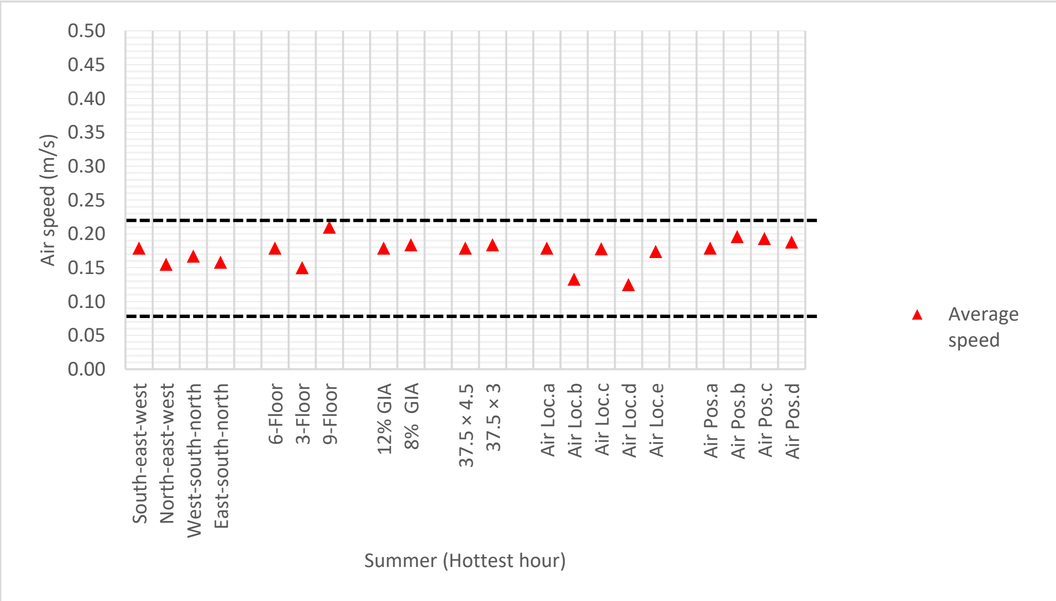
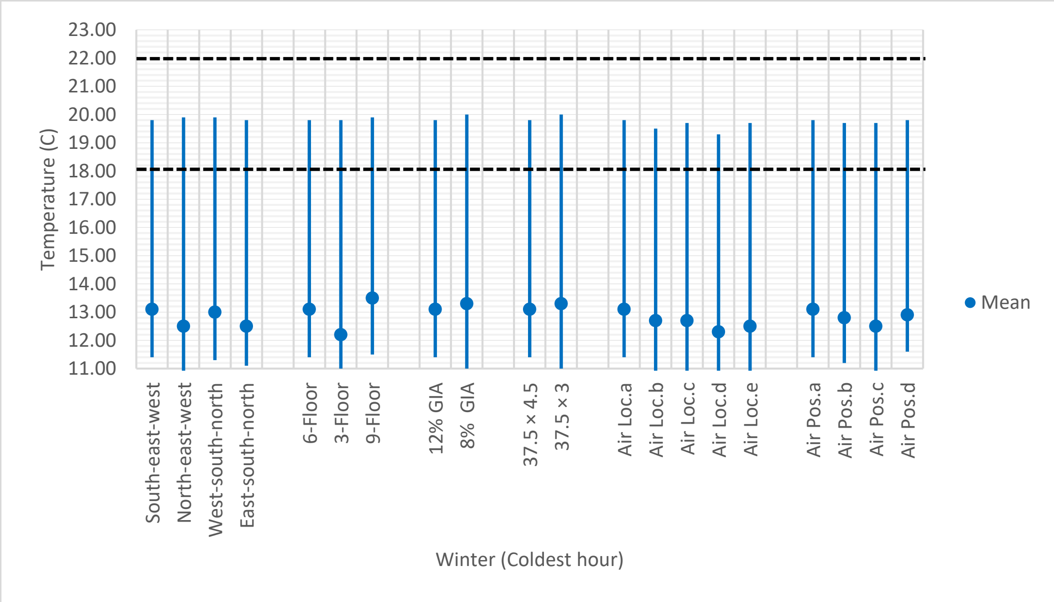


Figure 5-71. Air temperature and airspeed comparison at the occupancy level of the sided skycourt (C) in summer: sensitivity analysis



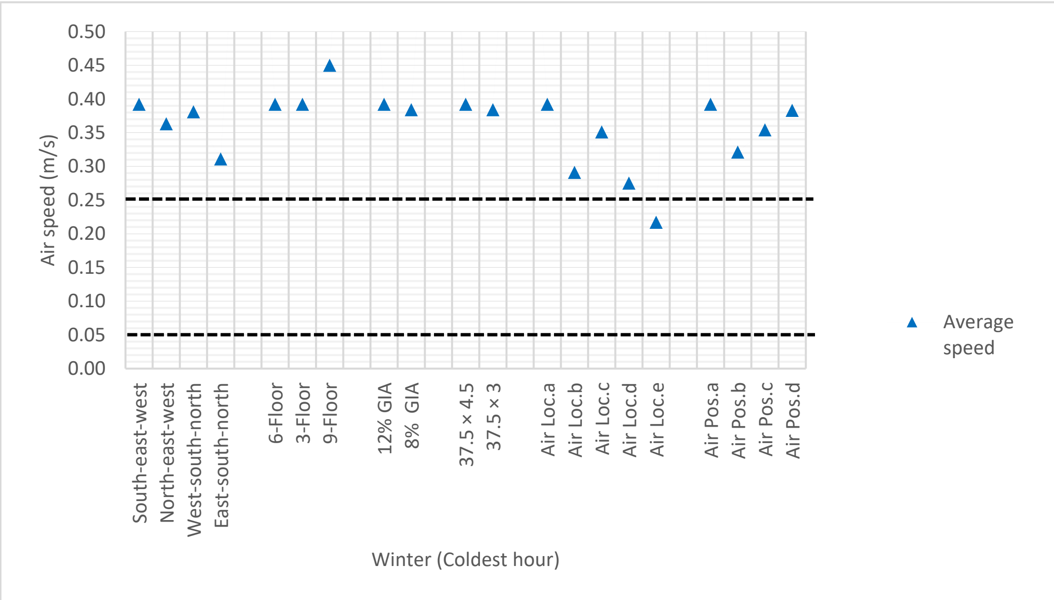


Figure 5-72. Air temperature and airspeed comparison at the occupancy level of the sided skycourt (C) in winter: sensitivity analysis

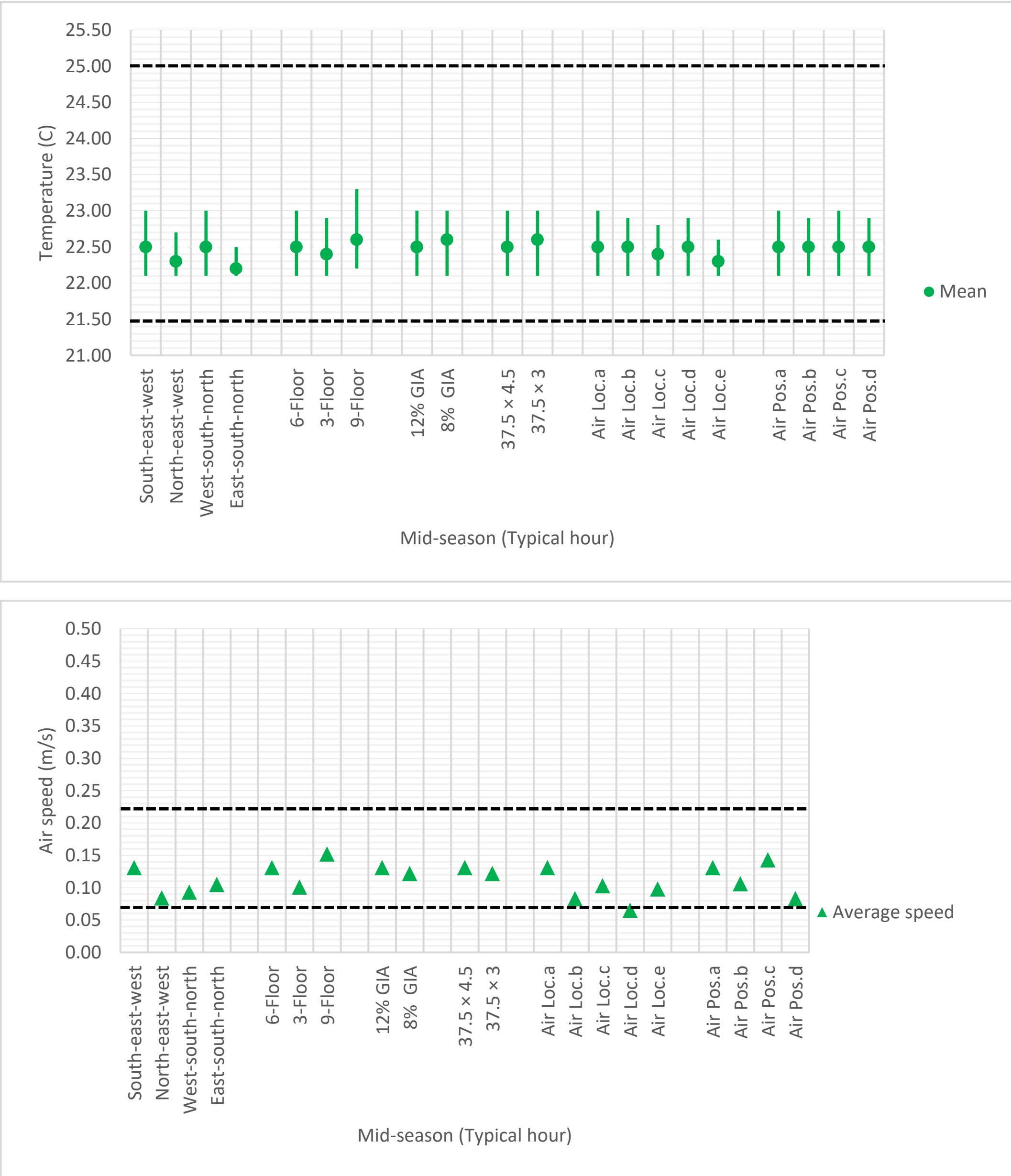


Figure 5-73. Air temperature and airspeed comparison at the occupancy level of the sided skycourt (C) in mid-season: sensitivity analysis

5.4.3 The Improved Configuration Results

In this stage, the optimum configurations of skycourt (C) were correlated. The south-east-west orientation, the 8% area to GIA, the 37.5 m length, and the 3 m depth affected the energy efficiency positively. However, the north-east-west orientation, the 12% area to GIA, the length and depth of 37.5 m × 4.5 m enhanced levels of thermal comfort inside the skycourt. Therefore, four models were examined to assess the actual improvement that the optimised skycourt can achieve regarding thermal and energy performance (Figure 5-74).

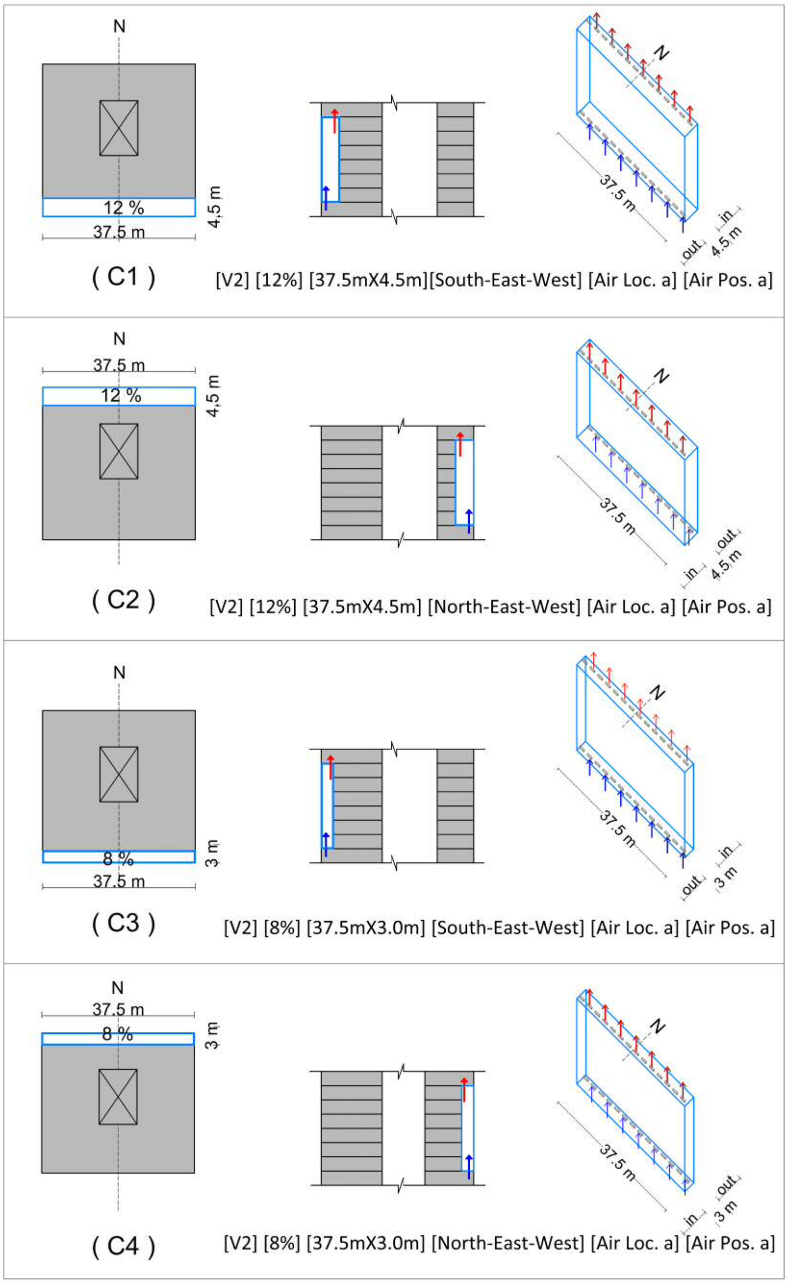


Figure 5-74. Schematic diagrams of models concluded from stage three for skycourt (C) geometry design: alternative one (C1), alternative two (C2), alternative three (C3) and alternative four (C4)

The results of energy performance indicated that differences in heating and cooling demands occurred with the variation of the orientation and the depth of the skycourt (Figure 5-75). The south-east-west skycourt had less energy demands for heating and cooling the building. For example, model (C3) consumed 90.13 kWh/m^2.yr, whereas model (C4) used 90.57 kWh /m^2.yr. This accounts for a 3095 kWh saving per year.

In addition, correlations between the annual heating and cooling demands, the skycourt area, and its depth, showed that energy demands decreased when the skycourt area decreased while the length remained constant. These findings correspond with the sensitivity analysis results.

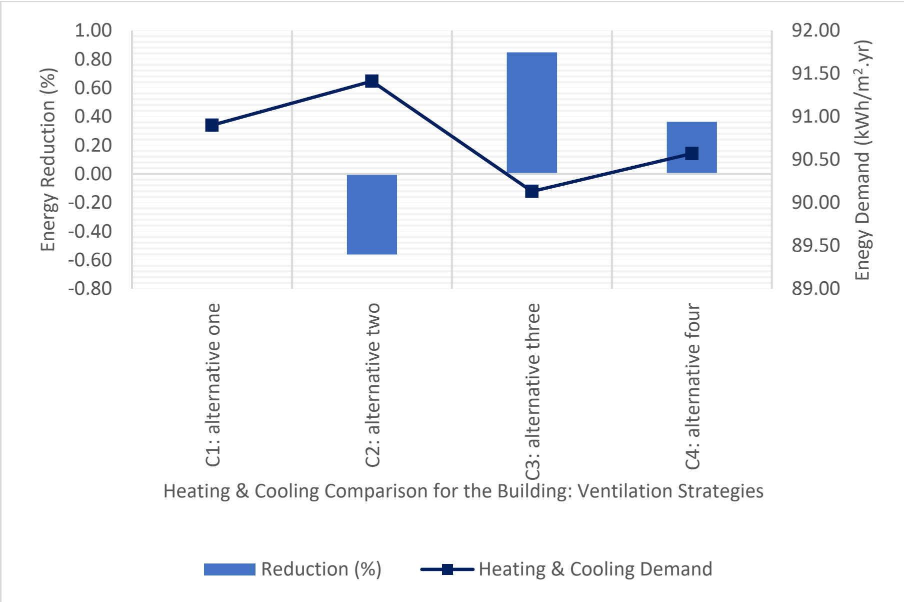


Figure 5-75. Annual energy comparison in the sided skycourt (C) building: improved configurations

Regarding thermal conditions at the occupied area of the skycourts, results showed that temperatures were higher for the south-east-west orientation by 1°C in summer than in other cases, which recorded about 26.5°C of 0.2 m/s in summer (Figure 5-76, Figure 5-77 and Figure 5-78). In winter, temperatures ranged between 11°C and 20°C; and about 22.5°C of 0.1 m/s in the mid-seasons. In addition, the results indicated that smaller area skycourt models achieved better thermal conditions at the occupied level of the skycourt. These findings are consistent with those of the sensitivity analysis.

Energy and thermal performance results showed that alternative (C3) is the best configuration of the skycourt (C) that yields the smallest energy demands for heating and cooling of the building, and provided an accepted thermal comfort level at the occupied area of the skycourt. However, the 3 m depth for the skycourt is considered small for transitional movement in high-rise buildings, while the 4.5 m is more favourable for such spaces.

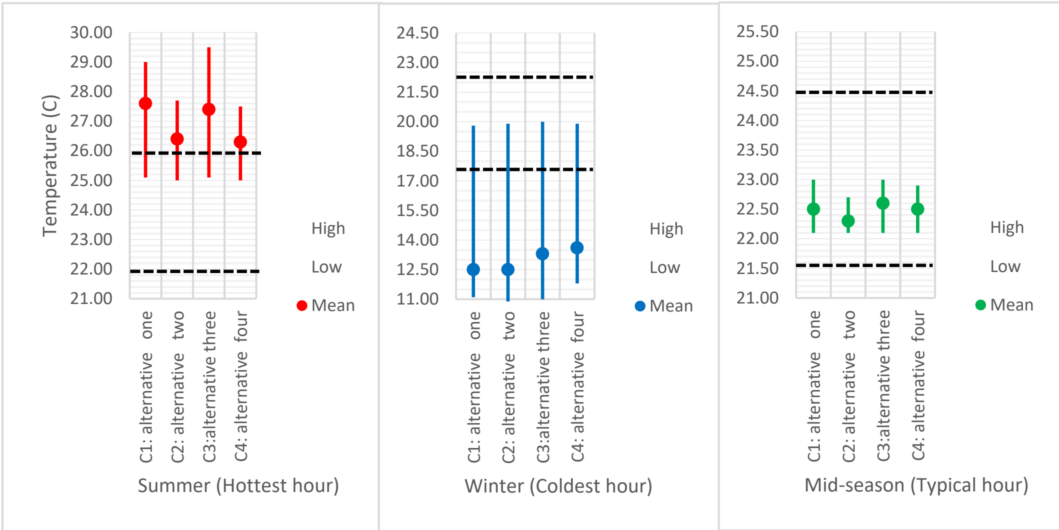


Figure 5-76. Air temperature comparison at the occupancy level in skycourt (C) (dashed lines show comfort air temperature ranges): improved configurations

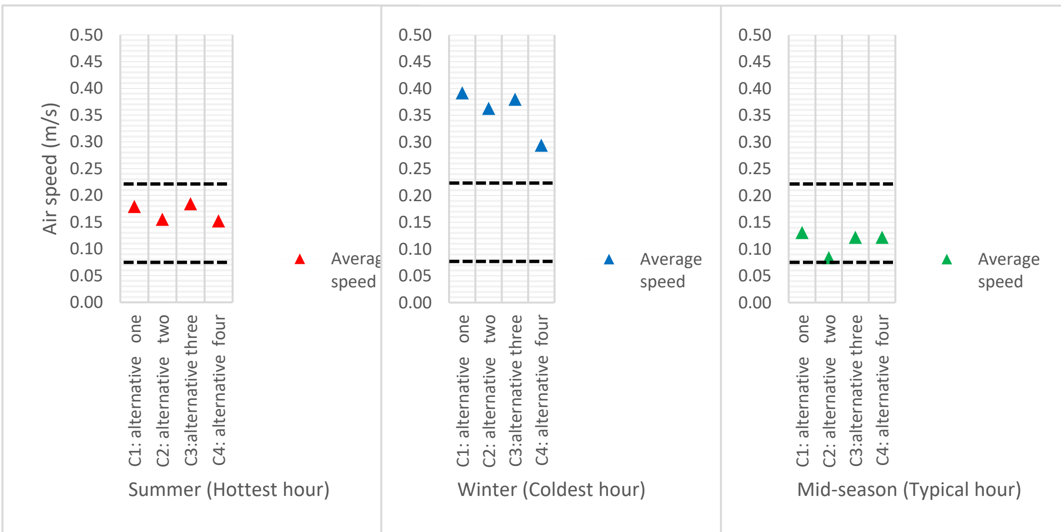


Figure 5-77. Airspeed comparison at the occupancy level in skycourt (C) (dashed lines show comfort airspeed ranges): improved configurations

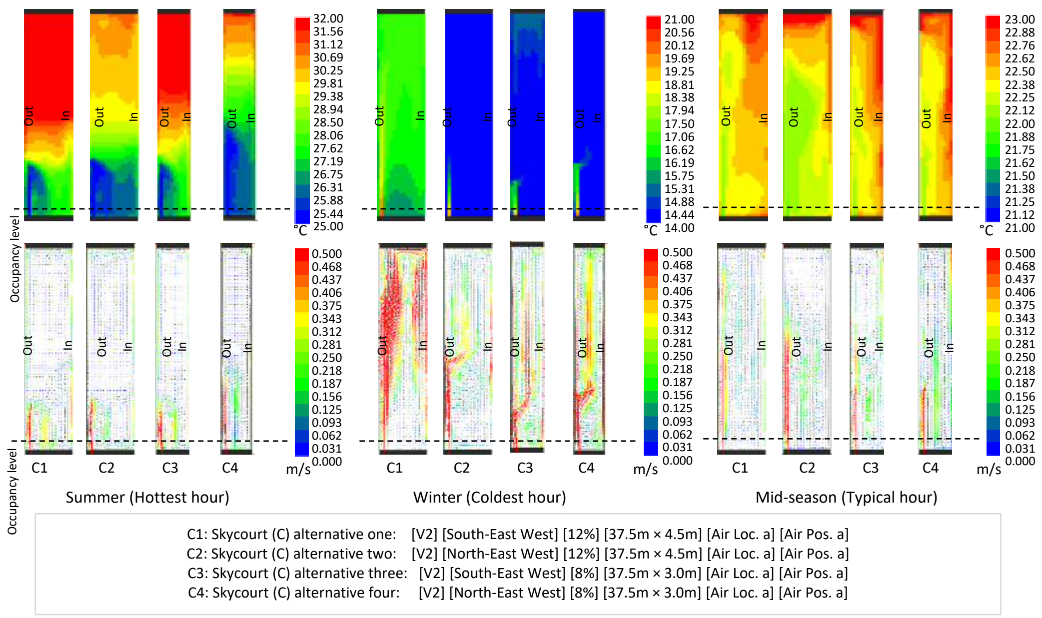


Figure 5-78. Air temperature comparison at the occupancy level in skycourt (C) (dashed lines show comfort air temperature ranges): improved configurations

5.4.4 The Optimal Sided Skycourt

According to the results from the previous stage, the optimal design for the sided skycourt is defined as the following: the skycourt is a six-floor height, occupies 12% of each floor; extends south along the main façade, and covers the surrounding west and east corner façades. Moreover, it is an unheated and uncooled space, only ventilated by air exhausts from the adjacent offices through inlet openings located at the floor level closer to the external façade. The air extracts from this space through outlet openings located at the ceiling level closer to internal wall.

The optimal model achieved significant results in terms of energy reduction for the building and a satisfactory thermal performance at the occupied area of the skycourt compared to the reference case. This is related to the different ventilation mechanisms between the two models (Table 5-5).

Table 5-5. Summary of design parameters, energy demand and thermal conditions for the reference model and optimal case among simulation cases for the sided skycourt

	Reference (C) Model Heated and Cooled Skycourt	**Optimal (C) Model Unheated and Uncooled Skycourt**
Ventilation strategy for the skycourt	Isolated ventilation: air-conditioned	Strategy two (V2): combined-exhaust
Geometric attributes of the skycourt		
Height	Six-floor height	Six-floor height
Orientation	South-east-west	South-east-west
Area (%) to GIA	12% GIA	12% GIA
Length and depth	37.5 m × 4.5 m	37.5 m × 4.5 m
Air inlet and outlet vertical locations inside the skycourt	Alternative (a): air inlet openings located at the floor level, and air outlet openings located at the ceiling level of the skycourt	Alternative (a): air inlet openings located at the floor level, and air outlet openings located at the ceiling level of the skycourt
Air inlet and outlet horizontal positions inside the skycourt	Alternative (a): air inlet openings positioned closer to the external façade, and air outlet openings closer to the internal wall of the skycourt	Alternative (a): air inlet openings positioned closer to the external façade, and air outlet openings closer to the internal wall of the skycourt
Energy demand of the building		
Annual heating and cooling demand of the building	330 kWh/m^2.yr	91 kWh/m^2.yr
Thermal conditions at the occupied area of the skycourt		
Summer, at external temperature 28°C	25°C of 0.08 m/s	27.6°C of 0.2 m/s
Winter, at external temperature -5°C	18.8°C of 0.3 m/s	12.5°C of 0.3 m/s
Mid-season, at external temperature 13°C	20.6°C of 0.03 m/s	22.5°C of 0.1 m/s

The energy saving was found to be up to 73% per year for the optimal building compared to the isolated heating and cooling system in the reference building (Figure 5-79). This provides a clear picture for the effectiveness of the free-cooling and free-heating mechanism for the sided skycourt to reduce the high energy demands of the building.

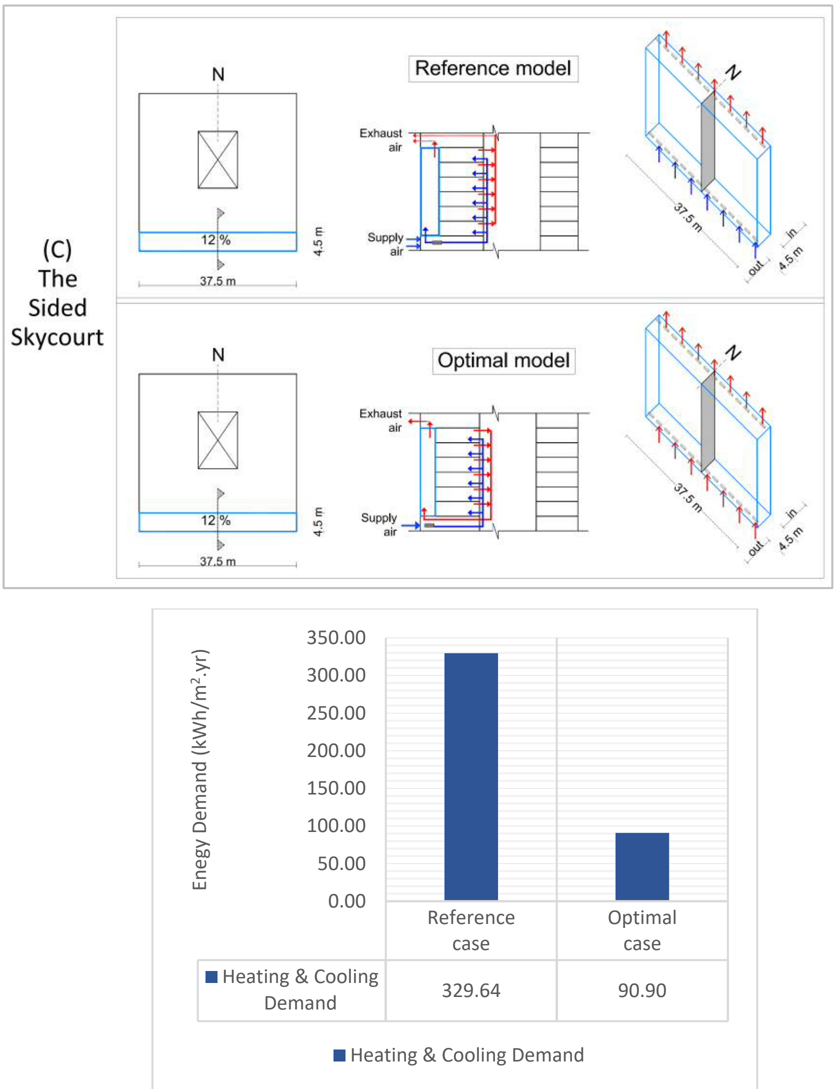


Figure 5-79. Annual energy comparison in the sided skycourt building: reference and optimal models

In addition, thermal comfort at the skycourt was attained in summer, winter and mid-seasons with the application of the combined-exhaust ventilation strategy between the skycourt and the adjacent offices. When comparing temperatures for the optimal skycourt to those found in the reference skycourt, about a 2.5°C increase in summer; a 6°C decrease in winter; and about 1°C increase in mid-seasons were recognised (Figure 5-80).

The results of air temperature and airspeed at the occupied area for the optimal skycourt were the following: 25°C to 29°C of 0.2 m/s in the summer case; 11°C to 20°C of 0.3 m/s in the winter case; and 22°C to 23°C of 0.1 m/s in the mid-season case. Whereas the isolated strategy of the reference case resulted in the following conditions: 18°C to 28°C of 0.08 m/s in summer; 16°C to 24°C of 0.3 m/s in winter; and 20°C to 21°C of 0.03 m/s in mid-seasons.

In conclusion, the optimal skycourt prototype under the combined-exhaust ventilation strategy accomplished significant improvements regarding energy performance for the building, and achieved accepted thermal performance inside the skycourt.

(C) The Sided Skycourt

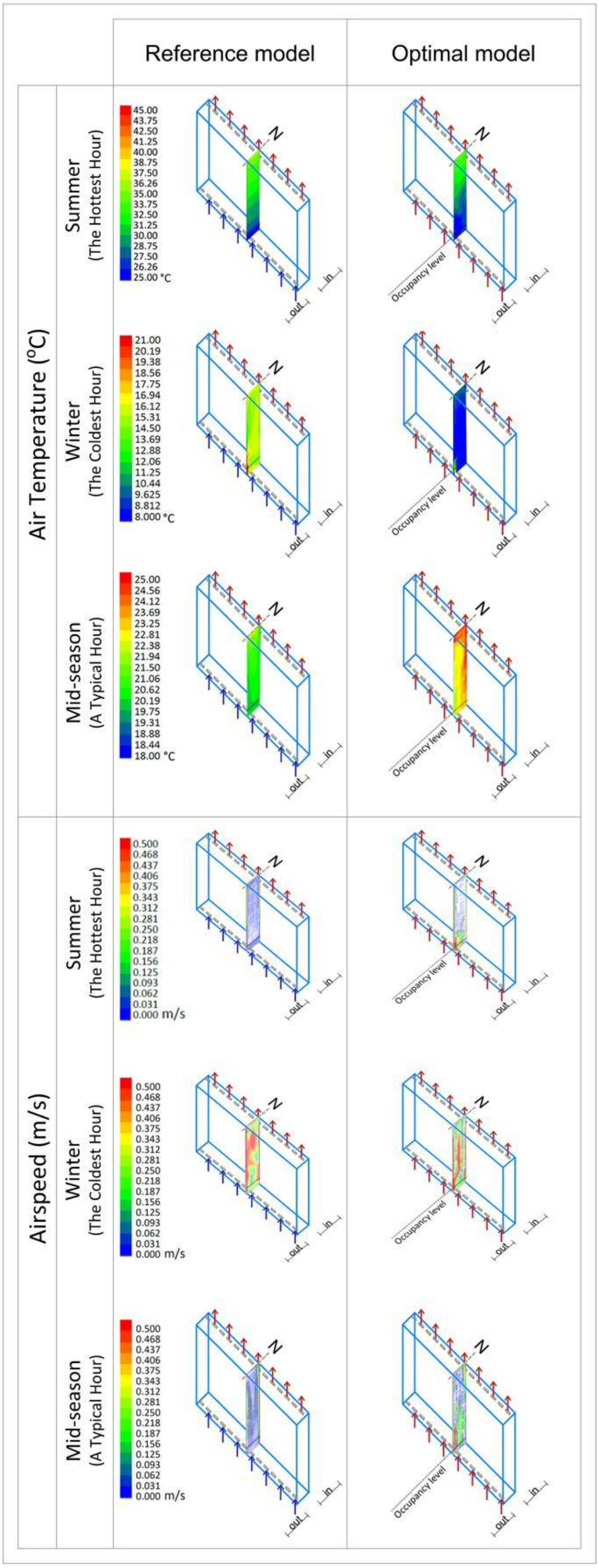


Figure 5-80. Thermal conditions in the sided skycourt at the hottest hour in summer, the coldest hour in winter and typical hour in mid-season: reference and optimal models

5.5 SUMMARY

This chapter presented the results of the simulation phase for the three prototypes of skycourts.

The energy performance for office buildings with or without skycourts were compared. The conclusion is that the use of an enclosed air-conditioned skycourt during working hours in a temperate climate will increase the annual energy demand, and significantly increase the cooling loads. Cooling of the skycourt accounts for more than 50%, while cooling adjacent offices accounts for less than 30% of the total energy cost. This is due to the extensive solar radiation through the glazed façades of the skycourt.

However, a skycourt when acting as a ventilated, free-heated and free-cooled zone has potential to reduce heating and cooling demands for the building by more than 50% per year. In addition, a combined ventilation strategy between the skycourt and the adjacent conditioned offices will be able to achieve comfort temperatures at the occupied area of the skycourt at the different seasons.

The strategy that is based on supplying all extract air from offices to the skycourt achieved the most positive impact. However, influences of this strategy account for different impacts on heating and cooling demands and temperatures inside the skycourt, based on its geometric properties. Consequently, these impacts affect the energy consumption and the indoor thermal conditions inside the building.

The optimised configuration of the skycourt has potential to increase levels of thermal comfort conditions in the skycourt and provide more energy savings for the building. However, considering the function of the skycourt as a transitional space where wider limits of temperature are accepted, the optimum configuration should be based on an energy efficient design.

In the next chapter, the main results of the study will be compared for the three prototypes. Moreover, a detailed discussion will be provided.

CHAPTER SIX: COMPARATIVE ANALYSIS AND DISCUSSION

CONSTRUCTING PERFORMATIVE DESIGN GUIDELINES FOR VENTILATED SKYCOURTS

6 COMPARATIVE ANALYSIS AND DISCUSSION

6.1 INTRODUCTION

This chapter discusses the main results obtained from the previous chapter for the three prototypes of skycourts: (A) the hollowed-out skycourt, (B) the corner skycourt, and (C) the sided skycourt. The thermal performance of skycourts, and their influence on the energy performance of buildings are compared and discussed. Next

The first section deals with the performance of skycourts under the ventilation strategies. The second part compares the influence of skycourts' geometry and air inlet and outlet openings on the ventilation performance. Then, the results obtained from investigation of the improved configuration for each prototype are compared. The influence of climate change on future performance of ventilated skycourts, in addition to the effect of the urban heat island on the energy and thermal performance of such skycourts, are afterward explored. The final section develops an outline for the design and performance of ventilated skycourts as transitional buffers in high-rise office buildings located in temperate climates, such as London. Such guidelines provide flexibility for designers to design skycourts that have the potential to reduce heating and cooling demands for the building, and also afford accepted levels of thermal comfort in the occupied area of the skycourt.

6.2 THE INFLUENCE OF THE VENTILATION STRATEGY

6.2.1 Skycourt as a Ventilated Buffer Zone

Ventilation in a skycourt is influenced by buoyancy pressure due to the air temperature difference and the height of stack. When the skycourt performs as a buffer zone between the internal offices in the building and the external environment, solar radiation and thus solar gains cause a rise in the air temperature inside the skycourt. Therefore, convective heat transfer, which occurred inside the skycourt, causes air motion (Figure 6-1). This mechanism influences the thermal conditions inside the skycourt, which in turn has an impact on the thermal conditions of the adjacent offices.

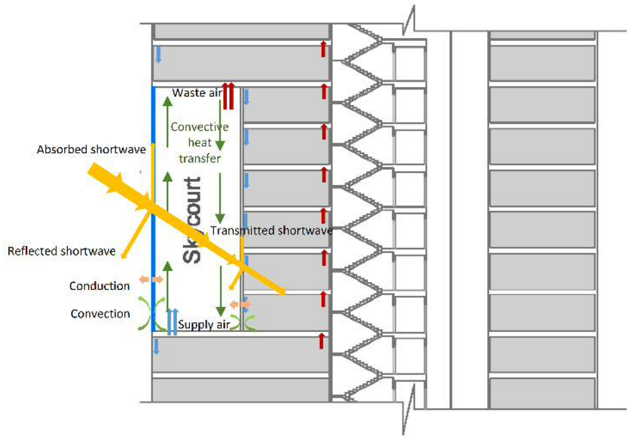


Figure 6-1. Heat transfer and airflow mechanisms in skycourt and adjacent offices

The study investigated the three prototypes of a skycourt under two main conditions. Firstly, when it is an air-conditioned space, heated and cooled separately from the adjacent offices. Secondly, when the skycourt is an unheated and uncooled space that is ventilated based on combined ventilation with the adjacent offices.

Overall, a high cooling demand is required to achieve an accepted level of thermal comfort in skycourts when skycourts are treated as air-conditioned spaces. This result agrees with previous studies, which reported that cooling becomes dominant in contemporary buildings in the UK (Hitchin and Pout 2001), particularly, for transitional buffer zones, which consume more energy than other spaces of similar size to accomplish the same level of thermal comfort (Pitts *et al.* 2008; Pitts and Saleh 2007; Göçer *et al.* 2006). Energy consumption to cool such skycourts required more than 50% of the total cooling and heating use of the adjacent offices. The sided skycourt consumed the highest percentage of energy for cooling, which is about 65% of the total demand of heating and cooling of the building. However, the hollowed-out skycourt consumed the least percentage for cooling (Figure 6-2).

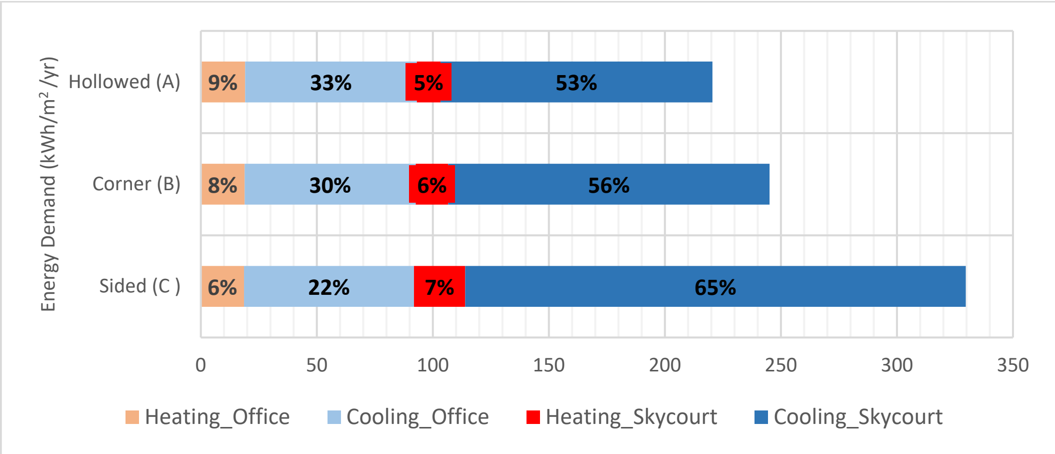


Figure 6-2. Annual heating and cooling demand comparison for the buildings of (A) hollowed-out skycourt, (B) corner skycourt and (C) sided skycourt: air-conditioning

Therefore, when skycourts are free-cooled, the energy demand of the building decreased significantly (Figure 6-3). However, an airflow is required to achieve an accepted level of thermal comfort in the skycourt.

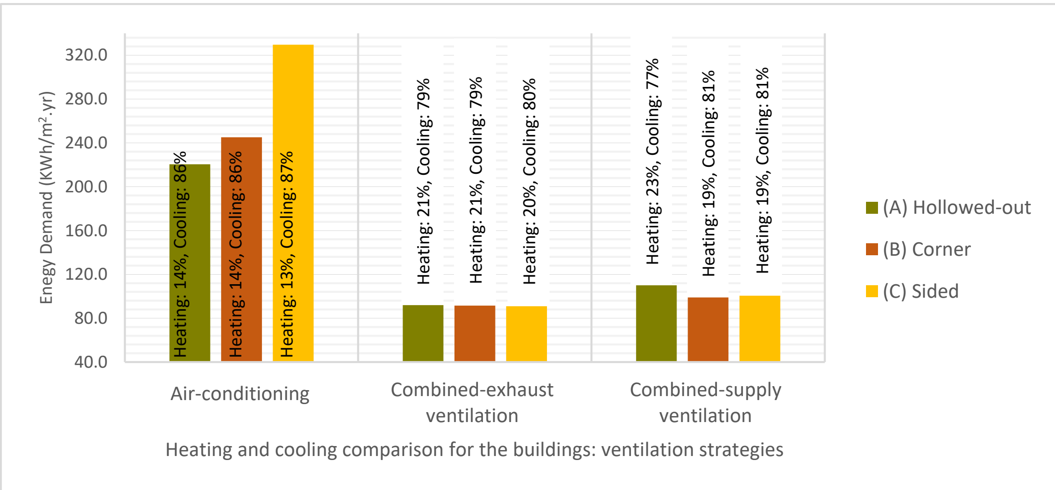


Figure 6-3. Annual total heating and cooling demand comparison for the buildings of (A) hollowed-out, (B) corner and (C) sided skycourts: air-conditioned skycourt, combined-exhaust ventilated skycourt, and combined-supply ventilated skycourt

The comparison of the total heating and cooling demand between the buildings of the three skycourt prototypes shows the following:

(i) Mechanical cooling and heating for the skycourt shows effectiveness to remove heat gain. This result agrees with (Lv *et al.* 2018) study, which concluded that mechanical ventilation is effective for cooling in a mild climate. The difference between the three buildings under the first ventilation strategy that considers the skycourt as an air-conditioned space could be explained due to the area of the external façades of the skycourts. Solar radiation that penetrates through these façades warms up the air inside the skycourt and increases the demand for cooling (Figure 6-4). The sided skycourt is exposed to the external environment through three glazed façades. This counts for more than double the glazed surface of the hollowed-out skycourt. Therefore, the building that integrates a sided skycourt uses the highest cooling demand. This illustration could be confirmed by the work of (Kosir *et al.* 2018) and (Wang *et al.* 2017), who investigated the effect of glazed areas on the performance of enclosed spaces, and concluded that larger areas of glazed façades receive more solar radiation. Moosavi *et al*. (2015) stated that the impact of solar radiation should be considered in the design of external façades for enclosed buffer spaces. Increase of glazed area causes increase of cooling demand.

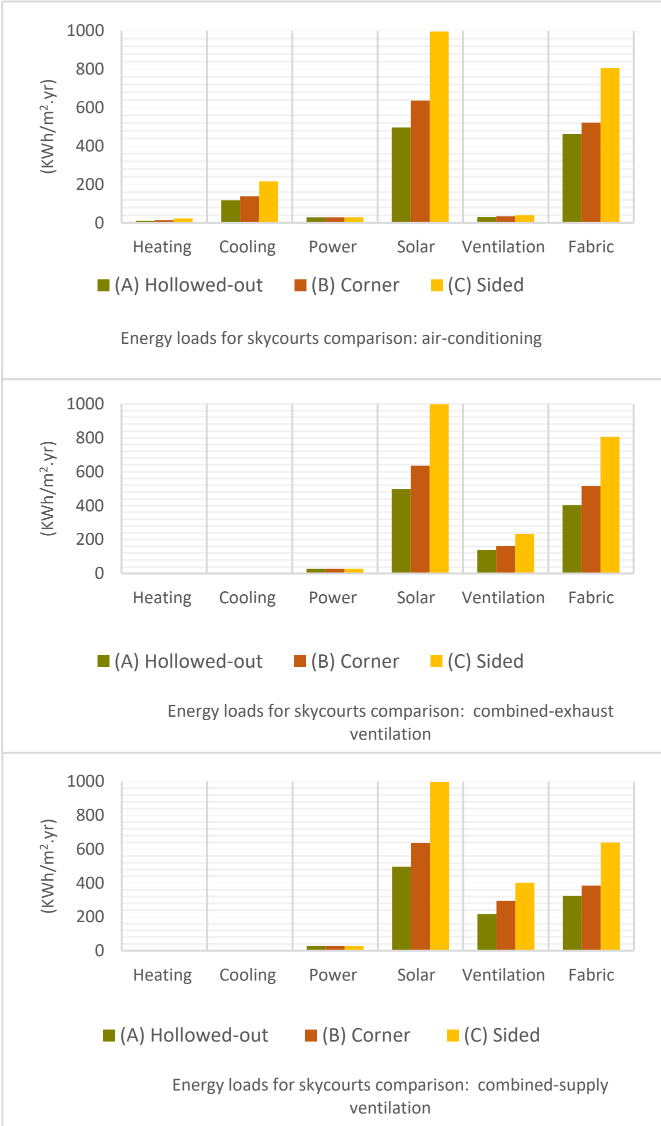


Figure 6-4. Annual heating, cooling, solar, fabric, ventilation and power loads comparison for the (A) hollowed-out, (B) corner and (C) sided skycourts: air-conditioned skycourt, combined-exhaust ventilated skycourt, and combined-supply ventilated skycourt

(ii) On the other hand, the annual heating and cooling demands for the buildings under the combined ventilation strategies (combined-exhaust and combined-supply) are less than half of the total demand of the previous case (air-conditioned skycourts). This is because heating and cooling are only required for offices in the combined ventilation strategies, as skycourts are free-heated and free-cooled spaces.

(iii) Under the combined-exhaust ventilation strategy, the (A) hollowed-out, (B) corner and (C) sided skycourts accounted, respectively, for 58.3%, 62.7% and

72.4% of the annual savings in heating and cooling demands, compared to the total demand in the buildings that integrate air-conditioned skycourts. On the other hand, these buildings recorded an increase between 4% and 9% in total demands when applying the combined-supply strategy.

(iv) The influence of the ventilation strategies on the adjacent offices individually shows that the offices on the different floors consume similar percentagrs of total heating and cooling. However, offices on upper floors have less demands by about 1% to 2% (Figure 6-5). These results could be explained due to the fact that tall spaces, such as skycourts, affect thermal conditions in adjacent offices. For example, upper offices receive less solar radiation due to the impact of the skycourt as a shading element for the offices. In addition, temperature stratification in tall spaces influences mainly lower and upper adjacent offices. Similar impacts were found for atria spaces on thermal conditions of adjacent spaces (Gilani *et al.* 2016).

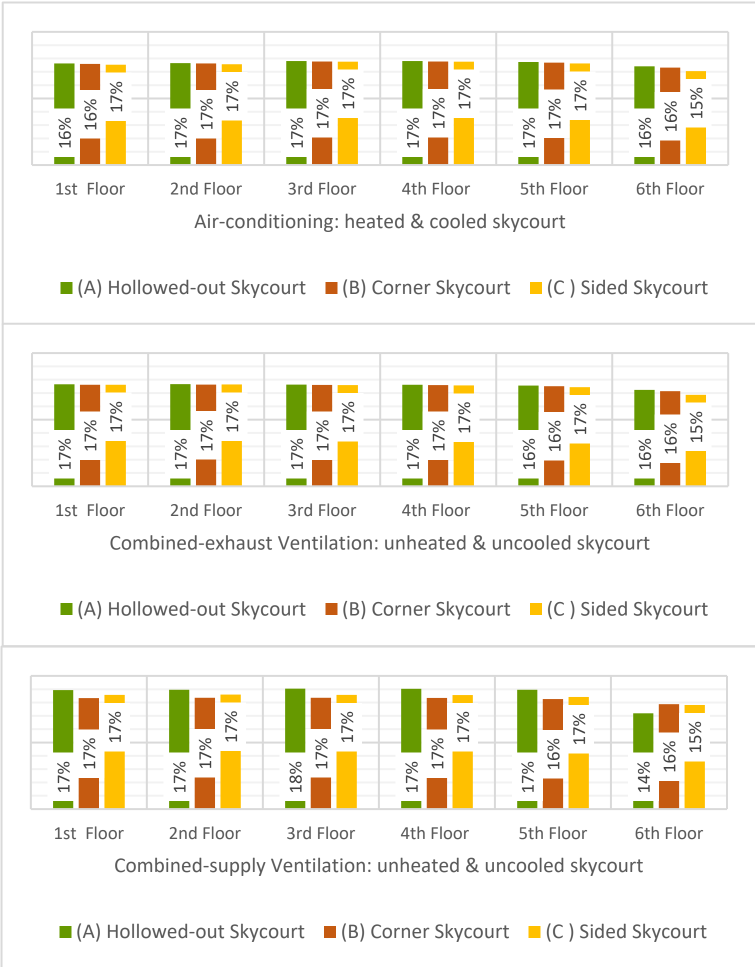


Figure 6-5. Percentages of total heating and cooling demand comparison between the adjacent offices of the skycourts

Results of air temperature and airspeed at the occupied area for the three prototypes of skycourt (Figures 6-6, 6-7 and 6-8), under the ventilation strategies indicate the following:

(i) Overall, the hollowed-out skycourt performs the best regarding the level of thermal comfort. It is colder in summer and warmer in winter. This is followed by the corner skycourt, where two sides are connected to the outside weather. Finally, the sided skycourt, which has three outer façades, provides the lowest level of thermal comfort .

(ii) The air-conditioning is effective to produce thermal comfort conditions in the occupied area of the skycourt in summer and winter. The mean air temperature at the occupied area of the three skycourts in summer recorded about 25°C of less than 0.1 m/s.

However, in winter case the airspeed was higher, i.e. about 0.3 m/s. This causes low temperature. Results of the simulation in winter provided temperature of about 19°C. In the mid-season air temperatures ranged between 20°C and 22°C with about 0.05 m/s.

(iii) The combined ventilation strategies achieved accepted thermal conditions in the different prototypes of skycourts. Yet the combined-exhaust ventilation strategy indicated significant effectiveness to produce comfortable air temperature and airspeed in the occupied area of the skycourt in all prototypes.

Results of the summer conditions indicated the following temperatures: (a) 26.7°C of 0.2 m/s for the hollowed-out skycourt, (b) 26.8°C of 0.2 m/s for the corner skycourt, and (c) 27.6°C of 0.2 for the sided skycourt. Winter conditions provided the following temperatures: (a) 16°C of 0.3 m/s for the hollowed-out skycourt, (b) 14.5°C of 0.4 m/s for the corner skycourt, and (c) 12.5°C of 0.4 m/s for the sided skycourt. However, in the mid-season air temperatures ranged between 22°C and 23°C with 0.15 m/s.

(iv) The occupied area of the skycourts under the combined-supply strategy recorded higher temperatures in summer, i.e. about 2°C, lower temperatures in winter, i.e. about 2°C, and lower temperatures in the mid-seasons i.e. about 3°C, when compared to the combined-exhaust ventilation.

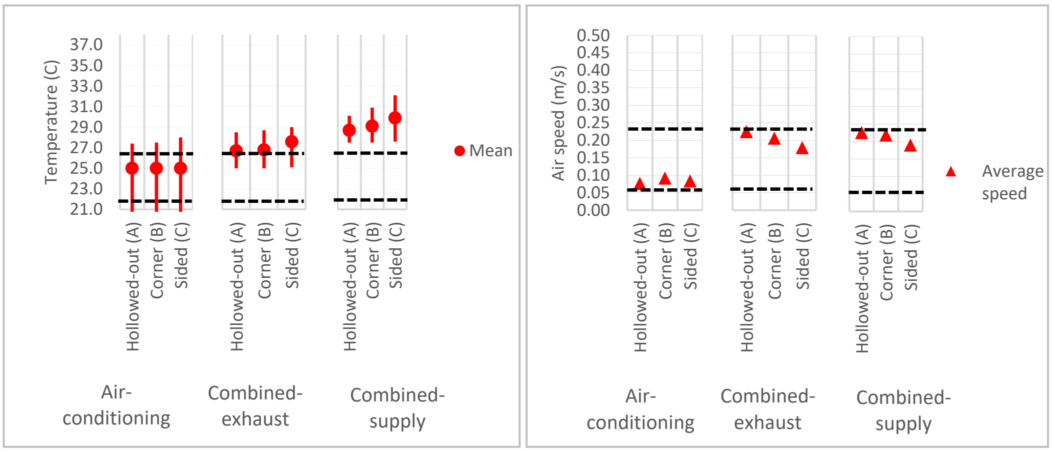


Figure 6-6. Thermal conditions comparison at the occupancy level of the (A) hollowed-out, (B) corner and (C) sided skycourts in summer case: air-conditioned skycourt, combined-exhaust ventilated skycourt and combined-supply ventilated skycourt

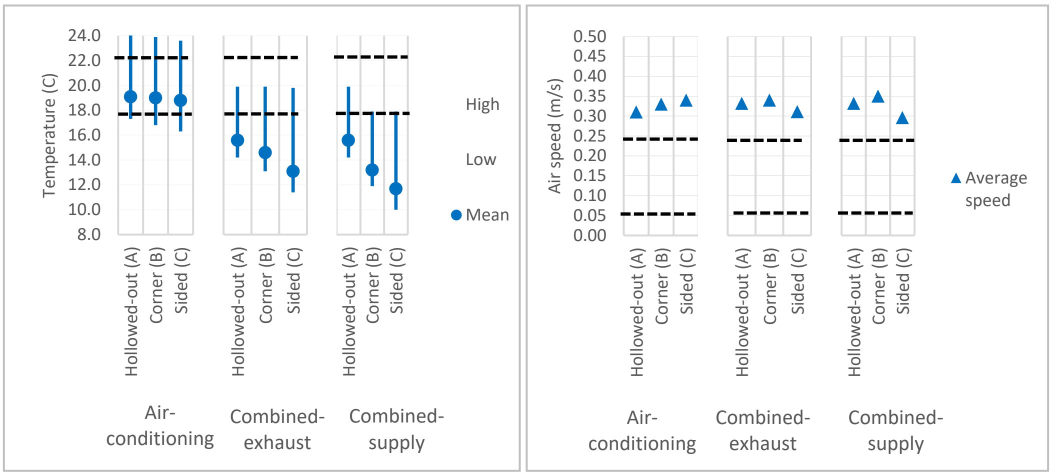


Figure 6-7. Thermal conditions comparison at the occupancy level of the (A) hollowed-out, (B) corner and (C) sided skycourts in winter case: air-conditioned skycourt, combined-exhaust ventilated skycourt and combined-supply ventilated skycourt

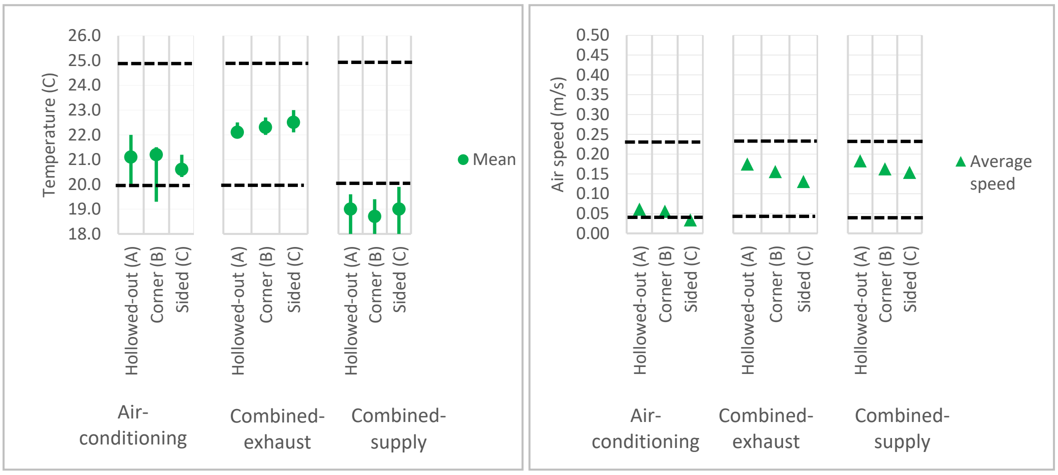


Figure 6-8. Thermal conditions comparison at the occupancy level of the (A) hollowed-out, (B) corner and (C) sided skycourts in mid-season case: air-conditioned skycourt, combined-exhaust ventilated skycourt and combined-supply ventilated skycourt

The internal environment of the skycourt is influenced by the temperature of the supply air (Khedari *et al.* 2000). This affects the ventilation effectiveness. In the combined ventilation strategies, the difference between the temperatures of the skycourt space and the supply air is less in the case of the combined-exhaust ventilation. In this strategy, the exhaust air is extracted from adjacent offices and pushed into the skycourt. This air has the same temperature as the temperature of the office spaces. Therefore, this strategy is sufficient to deliver the skycourt with similar conditions to those of the offices. Also, this achieves less energy demands compared to the combined-supply ventilation strategy. In the combined-supply ventilation, the skycourt is supplied with fresh air of 18°C in winter and mid-seasons and up to 28°C in hot days in summer. Then this air is extracted and pushed into the adjacent offices. The fresh air is warmed in hot days, or gets cold in cold days through the skycourt volume before entering the offices. Therefore, more energy is needed to heat or cool air in adjacent offices to achieve a comfort temperature (Figure 6-9).

Another factor that influences the thermal conditions of the skycourt is airflow volume rate. When airflow rate increases, the thermal comfort level rises significantly in the occupied area of the skycourt. This finding has been confirmed in the work of Cao *et al*. (2014), which provided a review of literature about air distribution methods and ventilation effectiveness for many airflow distribution systems.

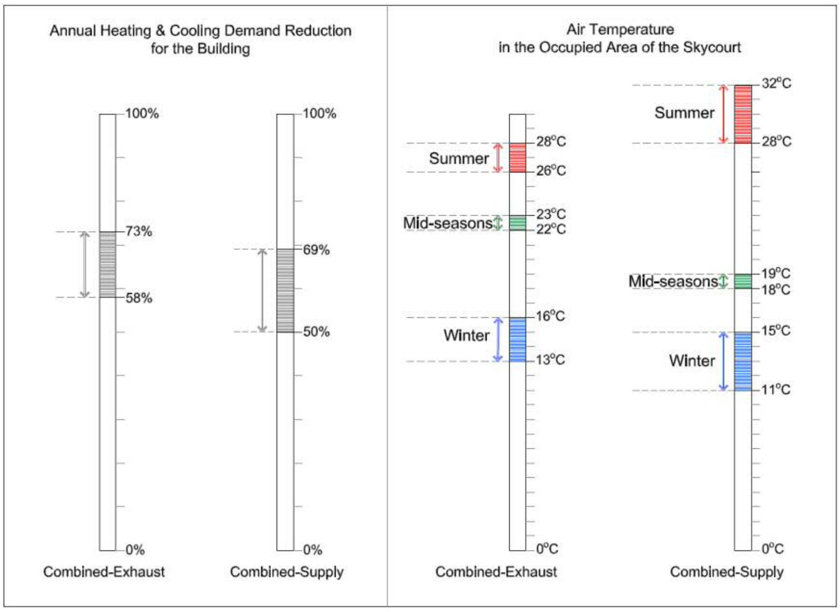


Figure 6-9. Comparison between compined-exhaust ventilation and compined-supply ventilation in terms of annual heating and cooling demand savings for building and air temperature at occupied skycourt

6.2.2 A Combined Ventilation Strategy for Skycourts

According to the previous section, the combined ventilation strategy between the skycourt as a ventilated transitional buffer space and the air-conditioned adjacent offices shows positive advantages for the different skycourts. The assessment of the proposed ventilation strategy might be difficult due to the wide range of variables that affect ventilation. Therefore, discussions about the performance of the proposed strategy will consider the aim of this study, which is connected with improving energy saving potentials for the building while ensuring indoor comfort conditions in transitional skycourts. Energy efficiency, thermal comfort level, indoor air quality, and the ventilation effectiveness of the strategy are discussed below, while considering principles of air distribution systems.

(i) **Energy efficiency:** Results of the study demonstrate that the ventilated buffer of the free-heated and free-cooled skycourt is sufficient to reduce heating and cooling demands, and thus, enhance the energy efficiency of the building. This agrees with the findings suggested in other studies that investigated buffer and transitional zones and found that ventilation in such spaces has a significant impact on the total building energy demands (Kwong *et al.* 2013; Kray *et al.* 2013). Potentials of energy savings differ according to the ventilation system (Cao *et al.* 2014). Such variations depend significantly on the difference between the temperatures of the supply air and the air-conditioned space (Pomponi *et al.* 2016; Oesterle *et al.* 2001). This situation agreed with the findings of the current study. For example, the difference between the two temperatures was lower in the office under the combined-exhaust ventilation strategy, which in turn caused more heating and cooling savings compared to the combined-supply strategy.

New buildings should provide an Energy Performance Certificate (EPC) based on predictions of energy consumption and the actual measured performance data, as part of the Energy Performance Building Directive (EPBD) in Europe. According to the climatic conditions of London, a "best practice" office building can achieve a 40% reduction in the total energy consumption under a standard air-conditioned model, when compared to a "good practice" building (Building Research Energy Conservation Support Unit (BRECSU) 2003). The proposed combined ventilation strategy is much more powerful in creating energy savings, i.e. an above 55% reduction in the annual heating and cooling demand.

(ii) **Thermal comfort:** Ventilation is required to achieve balanced thermal comfort, significantly, in the occupied levels and breathing zones of spaces (Conceição *et al.* 2013). Limits of acceptable thermal comfort in offices recommended by the BCO Guide (2014), are linked with air temperature, which ranges between 24°C ± 2°C in summer, and 20°C ± 2°C in winter, and airspeed, which ranges between 0.1 m/s and 0.2 m/s. However, for mechanically ventilated spaces airspeeds could be higher than 0.2 m/s in areas near air inlets (McMullan 2017; Chen 2010).

Previous studies found that ranges of accepted air temperatures for transitional spaces can be higher than ranges for working places (offices). For example, 80% of occupants were satisfied at air temperatures between 26°C and 28.8°C in transitional areas, whereas the standard comfort temperature in offices does not exceed 26°C (Ghaddar *et al*. 2011).

The occupied area in the skycourt under the combined-exhaust ventilation strategy recorded the following air temperature and airspeed: (a) 25°C to 28°C of 0.24 m/s, at external temperature of 28°C in summer, (b) 16°C to 20°C of 0.4 m/s, at external temperature of -5°C in winter, and (c) 22°C to 23°C of 0.2 m/s, at external temperature of 13°C in mid-seasons.

Although these ranges are higher than comfort ranges in general office spaces, they can be accepted in transitional skycourts, as a deviation of ±2°C from the standard temperature was recognised by the majority of occupants in transitional spaces in previous studies (Alonso *et al*. 2011). In addition, it should be mentioned that these temperatures were recorded at peak external temperatures.

In addition, thermal conditions, including air temperatures and airspeed of the skycourt under the proposed ventilation strategy, were still found to be favourable compared to the reference case (air-conditioned skycourt).

(iii) **Indoor air quality:** The ventilation rate is important to satisfy health and comfort criteria (Brohus and Nielsen 1994; Xing *et al.* 2001). The increase in the ventilation rate (L/s per person) and air change rate (ac per hour) (a) can improve the indoor air quality (Etheridge and Sandberg 1996; Sandberg *et al.* 1986). Also, it can (b) reduce the symptoms of sick building syndrome (SBS) (Sundell *et al.* 2011), (c) reduce risk of allergic manifestations and spread of infectious diseases (Cao *et al.* 2014), and (d) increase productivity in office spaces (Olesen *et al.* 2008).

The proposed ventilation strategy provided a high air ventilation rate, i.e. about 6 m^3/s. Based on this ventilation rate skycourts could be classified in category A, according to the European CEN pre-standard ENV 1752. In this category less than 15% of occupants are predicted dissatisfied (PD), as discussed in Awbi (1998a).

In addition, this ventilation strategy provides high indoor air quality (IDA1) according to the British Standard BS EN 13779. This standard provides four classifications of indoor air quality based on air ventilation range (L/s per person). This classification indicates that the approximate indoor CO_2 concentration in the skycourt is about 700 to 750 (ppm), based on CIBSE Guide A (Clark 2013). According to the previous section, the proposed ventilation strategy can provide standard air quality in the occupied zone of the skycourt, and keep balanced conditions of oxygen supplied and carbon dioxide absorbed.

(iv) **Ventilation effectiveness:** Ventilation effectiveness depends highly on the air distribution system that is used for driving air in spaces (Olesen *et al.* 2011; Karimipanah *et al.* 2008).

Three key air distribution systems can be implemented in office spaces: the mixing, the displacement system, and the hybrid system. In the case of the mixing system, ventilation effectiveness might be around 70% (<1) (Arghand *et al.* 2015). Therefore, when the air is extracted to the skycourt it will have the same containment effectiveness, as well as the same air temperature because of the uniform mixing. However, due to the stack effect of air through the skycourt volume, and the displacement system that is set in the skycourt, the ventilation effectiveness is expected to be between 70% and 100% in the occupied zone of the skycourt.

On the other hand, when a displacement air distribution system is applied in offices, a high ventilation effectiveness is expected in the skycourt space, i.e. 120% (Awbi 2017) . In addition, the hybrid air distribution system, which combines the positive characteristics of the mixing and the displacement systems, is predicted to be able to provide the desired heat and contaminant removal effectiveness (Awbi 2015).

Therefore, the ventilation effectiveness of the proposed strategy in the skycourt is confirmed in this study. It is predicted to be between 70% and 120% in the skycourt, and will significantly satisfy the occupancy level, as the effectiveness for heat and contaminant removal is determined based on air extracted from offices as a supply air to the skycourt.

The previous discussion shows that a combined-exhaust ventilation strategy between a transitional skycourt and offices is considered effective in terms of energy consumption for office buildings. In addition, it is beneficial for creating occupants' thermal comfort in the skycourt during the different seasons, and significantly in hot and mid-seasons. This strategy can be applied all over the year (Figure 6-10).

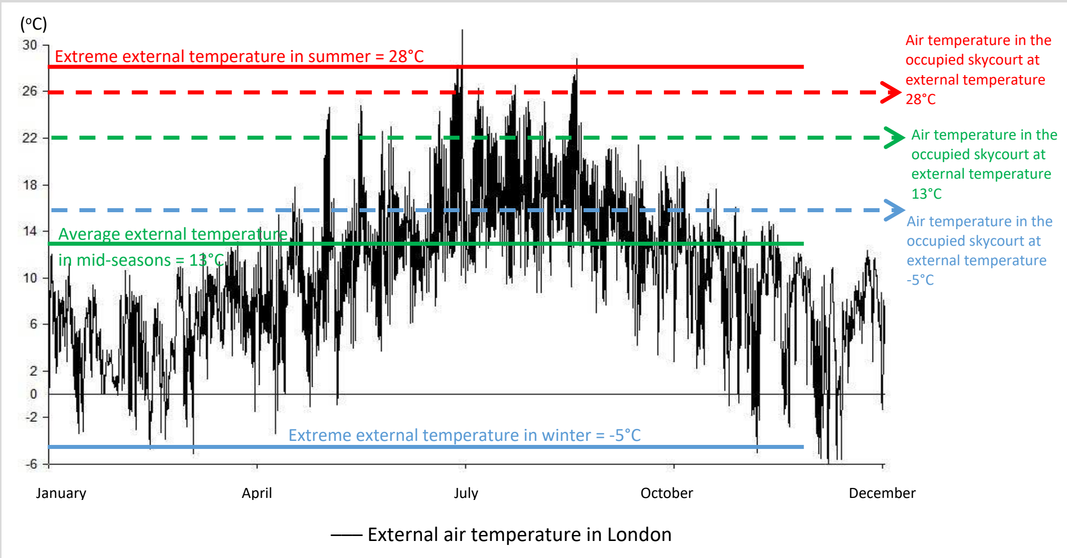


Figure 6-10. External air temperatures, and air temperatures in the occupied area in skycourts under the combined-exhaust ventilation strategy

For example, in summer hot days, when external temperature is over 28°C, air temperature in skycourts at the occupied area records between 26°C and 28°C. On the extreme coldest temperature, which is -5°C, skycourts achieve an air temperature between 13°C and 19°C. On a typical external temperature in spring and autumn, skycourts record an air temperature between 22°C and 23°C. In London, the average high temperature of summer is 22°C and rarely rise above 30°C. In winter, the average daytime temperature reaches 6.7°C in the coldest days. Transitional seasons in London achieve average temperatures between 13.3°C and 14.3°C during the day. Therefore, the combined-exhaust ventilation strategy is effective to provide comfort air temperatures in skycourts all over the different seasons in a temperate climate, such as in London.

6.3 THE INFLUENCE OF SPATIAL AND GEOMETRIC CONFIGURATIONS OF THE SKYCOURT

The spatial configurations (prototypes) of the ventilated skycourt show positive impacts on reducing the energy consumption of heating and cooling of the building. This impact is affected by the area of the external façades of the skycourt.

This impact can be noticed through analysing the relationship between the three prototypes of skycourt and the annual heating and cooling demand profiles, as shown in Figure 6-11. The building which integrates a sided skycourt consumed the least energy for heating and cooling. These results are due to the location of skycourts as buffer zones, which intermediate between the air-conditioned offices and the external environment. Such skycourts can provide shading to the adjacent offices from three façades. These have positive effects on the reduction in demands of heating and cooling for offices.

This result agrees with the arguments of Tabesh and Sertyesilisik (2015), who reviewed the relation between an atrium and energy consumption and summarised that glazed atria are able to provide shade to adjacent spaces and have the potential to reduce building cooling consumption.

It is clear that the skycourts account for similar annual heating and cooling demands. The base models of the (A) hollowed-out, (B) corner and (C) sided skycourts in buildings accounted for the following, respectively: 91.9 kWh/m^2.yr, 91.5 kWh/m^2.yr and 90.9 kWh/m^2.yr. These results are explained due to the fact that according to the proposed ventilation strategy (combined-exhaust ventilation), the total heating and cooling demand of the building is determined for offices only, as skycourt is considered a free-heated and free-cooled buffer zone, ventilated by the air exhausts from adjacent offices. The different parameters recorded annual energy savings between 57% and 59% for hollowed-out, 60% and 62% for corner skycourt and between 70% and 73% for sided skycourt.

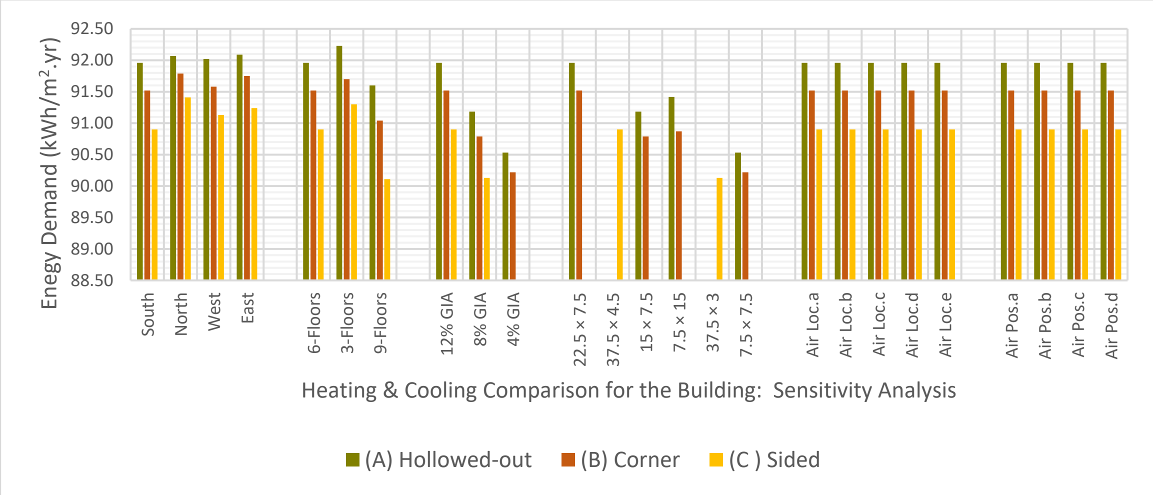


Figure 6-11. Annual heating and cooling demand for the (A) hollowed-out, (B) corner and (C) sided ventilated skycourts buildings

The three prototypes of ventilated skycourts show positive performance in terms of thermal conditions at the occupied area.

(i) In summer, the sided skycourt recorded the highest temperature. However, this is only about 1°C above the internal temperature of the hollowed-out skycourt. This is due to the high amount of solar loads gained in the sided skycourt. These results support the findings of Kwong and Ali (2011), which showed that when the external façade increases, the solar heat increases. The corner skycourt accounted for higher internal temperatures than the hollowed-out skycourt of about 0.5°C. The average airspeed reported a range between 0.1 m/s and 0.2 m/s in the three prototypes.

(ii) In winter, the sided skycourt reported the lowest temperature. This temperature is about 3°C lower than the temperature inside the hollowed-out skycourt, and 2°C lower than the temperature inside the corner skycourt at the same time. The exposure of the sided skycourt to the external conditions caused high fabric loss for the different cases due to the temperature difference between the indoors and outdoors of the skycourt. In addition, airspeed in winter cases is affected with the cold temperature of supply air. These results corresponds with (Chen 2010) who elaborated that air movement in spaces is perceived as discomfort when combined by cold temperature. The various cases reported an airspeed range between 0.3 m/s and 0.4 m/s when the external temperate was -5°C.

(iii) In the mid-season, the three skycourts reported similar results of air temperature range at the occupancy level in the three skycourts, i.e. 22°C to 23°C. However, the sided skycourt accounted for a higher range of 0.5°C in the different cases. Accordingly, the airspeed range was between 0.1 m/s and 0.2 m/s, where the hollowed-out skycourt recorded the higher speed.

On the other hand, comparing the impact of each geometric parameter separately showed similar influences in the three skycourt prototypes. For example, models of orientations showed that the south oriented skycourt (south-east, and south-east-west) are recommended to reduce energy demands. On the other hand, the north orientations (north-east and north-east-west) ensure better thermal comfort conditions. This result is evident in the work of Ho (1996), which found that atria in Europe with south facades have high temperatures in summer due to excessive heat gain but low temperatures in winter due to substantial heat loss. In addition to the study of Danielski and his colleagues (2016) that found similar results as the lower angle of the sun causes direct radiation onto the vertical surfaces at the south façade in spring and autumn.

The results indicated that the average height of six floors for the skycourt achieved more comfortable conditions. The average thermal conditions at the occupied area was below 27°C of 0.2 m/s in summer, and up to 20°C of about 0.3 m/s in winter. However, increasing the size of the skycourt improves level of comfort air temperature in the skycourt. One major factor influences this result is related to the fact that large size of vertical enclosed spaces attains a better buoyancy-driven airflow effect in high-rise buildings (Lan *et al.* 2017).

The skycourt area of 8% of total floor area was found to be more comfortable, particularly for the skycourt with a larger depth compared to a larger skycourt area, i.e. 12%. This is due to the fact that the inlet airflow rate increases, which enhances the airflow effectiveness inside the skycourt. The effectiveness of the air volume rate has been reported by Cao *et al.* (2014). Also, the heating and cooling demand dropped when the skycourt area became smaller, due to the reduced exposed surface area per unit floor area. This was illustrated briefly in the work of Liu et al. (2017).

The skycourt performs the function of a shelter for the adjacent offices. Therefore, increasing the length of the skycourt is useful to reduce heat gain for adjacent offices. Thus, it has the potential to reduce cooling demand for offices. On the other hand, increasing the depth of the skycourt causes a decline of direct solar radiation gain for this space and a rise of solar gain for adjacent offices. Thus, causes an increase of the energy demand required to cool the office zones. This provides an advantage to the shallow skycourt compared to deep skycourt in reducing the energy consumption for offices in summer. However, a shallow skycourt with a small length is exposed to overheating in summer. These results agree with previous studies (Aldawoud 2013; Rundle *et al.* 2011) that investigated impact of geometric parameters of enclosed glazed spaces that are integrated in buildings.

Overall, the thermal conditions at the occupied area of the skycourt recorded accepted level of comfort compared to CIBSE Guide A and BCO Guide benchmark for air temperature in general office spaces. The different parameters recorded air temperature between 26°C and 28°C in summer hot hours, 14°C and 18°C in winter extreme coldest hours, and 22°C and 23°C in mid-season. This is explained due to the mechanism of the proposed ventilation strategy, which supplies air to the skycourt from adjacent offices. The ventilation rate in offices is determined based on the occupancy density. Therefore, the air volume rate that entered the skycourt depends on the total area of adjacent offices. However, differences in offices' total area were small due to the change of geometric parameters of skycourts, which cause approximation in air temperate results. These results provide an evidence of the efficiency of the proposed ventilation strategy.

Detailed figures comparing thermal conditions at occupancy level of the (A) hollowed-out, (B) corner and (C) sided ventilated skycourts in summer case for geometric configurations are illustrated in Appendix D.

6.4 THE INFLUENCE OF AIR OPENINGS

Air inlet openings are inserted at the floor level of the skycourt. Previous studies claimed that a bottom-supply air system is able to meet the requirements of human thermal comfort in office buildings (Zheng *et al.* 2017). For example, the floor level air distribution can handle a full space heat load in an acceptable manner; it can balance between buoyancy and momentum forces (Karimipanah and Awbi 2000). In addition, it is recommended to apply low-level air supply systems for achieving energy savings (Karimipanah *et al.* 2006). These conclusions agree with the findings of the present study.

It was found that positions of the air inlet and outlet openings at the floor level of the skycourt turned out to be less problematic regarding levels of thermal comfort. This agrees with Moosavi *et al.* (2014), who found that the air inlet and outlet openings are important to enhance airflow. However, the horizontal position of these elements has no effect on the thermal performance, whereas distributing inlet openings between floor and ceiling levels of the skycourt reduces the efficiency of the airflow inside the skycourt.

Therefore, locating all air inlets at the occupancy level of the skycourt closer to its external wall, and all air outlet openings at the ceiling level closer to the internal wall of the skycourt, provides accepted levels for comfortable air temperature and average airspeed in the occupied area. Also, this alternative has a positive influence on the thermal conditions in the adjacent offices. When air is supplied at lower levels from the floor and extracted at upper levels, a buoyancy effect drives the stratified flow. In addition, when supply and exhaust air openings are positioned in opposite directions this creates upward air movement to improve the ventilation effectiveness.

Detailed figures comparing thermal conditions at occupancy level of the (A) hollowed-out, (B) corner and (C) sided ventilated skycourts in summer case for alternatives of air openings distribution are illustrated in Appendix D.

6.5 THE OPTIMAL CONFIGURATIONS OF SKYCOURTS

It was apparent that the optimal design of the ventilated skycourts that produces the highest heating and cooling demand reduction includes the following factors: the six-floor height; the south orientation; the 8% ot floor area; the air inlet openings located at the floor level closer to the external façade; and the outlet openings located at the ceiling closer to the internal wall of the skycout.

Comparing the optimal configurations of the three skycourts (Figure 6-12) show that there are small differences between the cases in terms of energy impact (Figure 6-13) and thermal conditions (Figure 6-14). For example, the hollowed-out skycourt was about 1°C cooler in summer, and about 3°C warmer in winter compared to the sided skycourt. In addition, this building was 1% above in annual heating and cooling demand. Thermal conditions and energy performance for the corner skycourt were found to be intermediate between the hollowed-out and the sided skycourts.

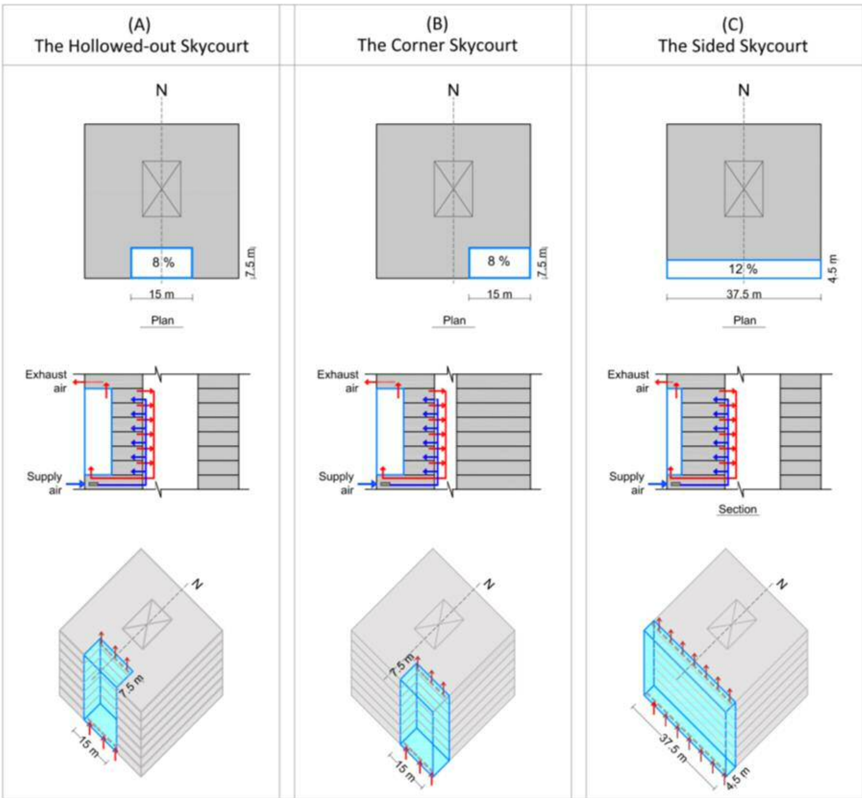


Figure 6-12. Optimal configurations for the (A) hollowed-out, (B) corner and (C) sided ventilated skycourts in buildings

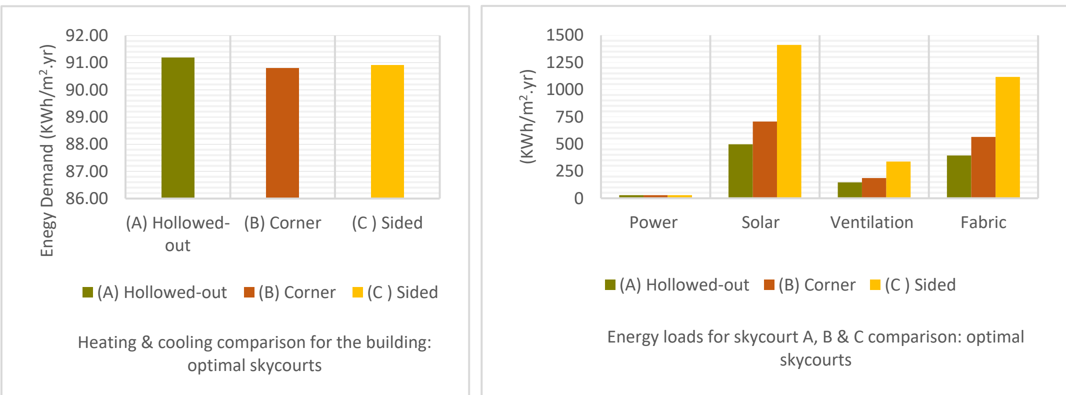


Figure 6-13. Annual energy comparison for the (A) hollowed-out, (B) corner and (C) sided ventilated skycourts buildings: optimal configurations

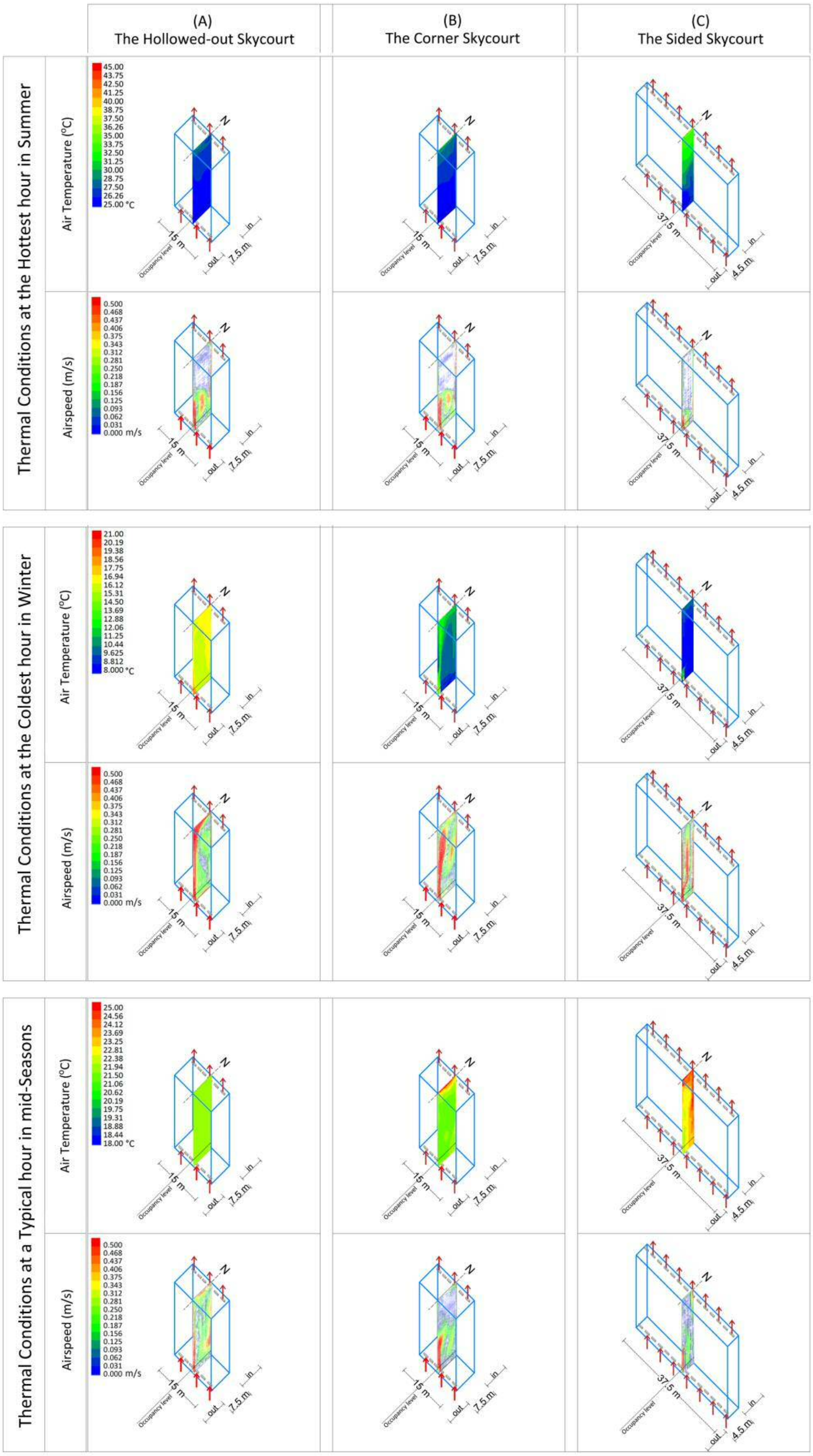


Figure 6-14. Thermal conditions at the occupancy level of the (A) hollowed-out, (B) corner and (C) sided ventilated skycourts in several seasons: optimal configurations

The optimal configurations of the three ventilated skycourts indicate the high potential of this ventilation strategy to achieve efficient energy saving in terms of heating and cooling demands of the building. Other potential of energy saving of ventilated skycourt can be due the implication of daylighting. Results of simulation that investigated this influence indicate that partial implication of daylighting in the optimal configuration of the ventilated hollowed-out skycourt for only three hours per day during the occupancy period of the building, i.e. 9.00 to 18.00, can achieve about 15% reduction in the total energy demand of lighting for the building (Figure 6-15).

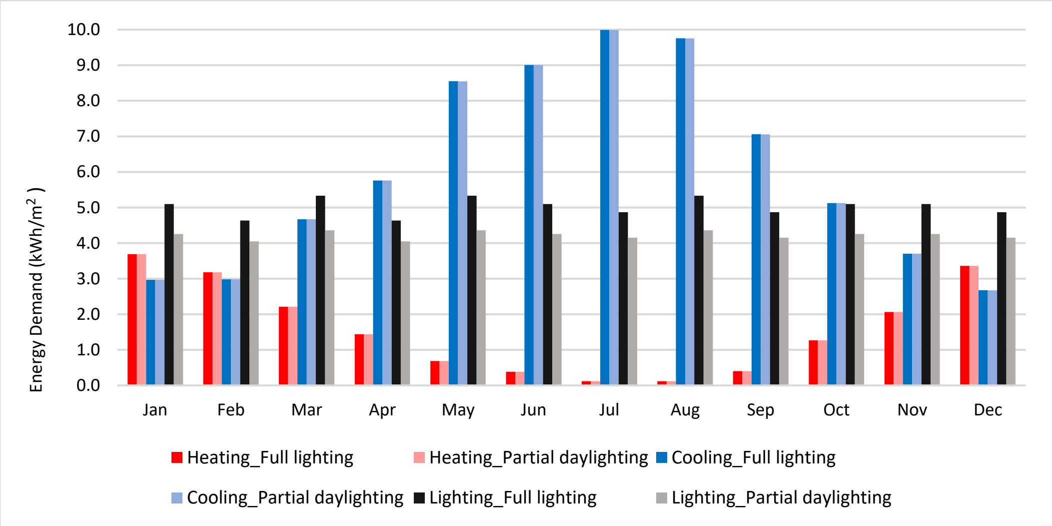


Figure 6-15. Monthly heating, cooling and lighting demands comparison for the building of ventilated hollowed-out skycourt: skycourt (Full lighting) and skycourt (Partial daylighting)

This result provides an evidence of the impact of implication of daylighting in skycourts to deliver reduction in energy demand for the building. However, more focus studies are needed in future.

The potential of global warming, in addition to the effect of urban heat island (UHI) in major cities such as London, must be taken into account in energy simulation studies. These two issues are important to manage energy consumption in buildings located in cities (Ginzburg and Demchenko 2017), significantly, cooling loads (Napier 2015). Therefore, to predict the efficiency of the optimal configuration of skycourt, the next two sections explore the energy and thermal performance of ventilated skycourt considering infuence of potential climate change scenarios and impact of UHI. The smulation investigations will consider the optimal configuration of the hollowed-out skycourt.

6.6 THE INFLUENCE OF CLIMATE CHANGE ON PERFORMANCE OF VENTILATED SKYCOURT

The global warming effect is observed in London, and a future increase in temperatures is predicted. The current standard weather data sets, which are based on data from the past such as reference years and EnergyPlus standard weather data, are likely to underestimate overheating (Roetzel *et al.* 2011). On the other hand, building design should be able to deal with such global climate scenarios (Al Qadi *et al.* 2017).

Therefore, it is important to predict the future performance of skycourt in future summer overheating, to determine whether the proposed ventilation strategy will be beneficial in future weather scenarios.

Future weather scenarios are represented by future weather files. These files are used for predicting future energy demand and thermal performance in buildings (Cox *et al.* 2015).

Future weather files can be created using weather generators tools that adopt numerical analysis to generate time-series of climatic variables that are statistically similar to the real climate to be used in building energy simulation (Wilks and Wilby 1999). Other methods are based on the mathematical transformation of historical weather data (morphing) to produce future weather predictions (Belcher *et al.* 2005).

However, the performance gap can increase when predicting future energy performance of the building. Future weather data are based upon statistics derived from historical observations of weather, which assume that future weather patterns will be the same as those observed historically (Herrera *et al.* 2017). In addition, this approach ignores probable changes in social characteristics of users and physical deterioration of buildings (Al Qadi *et al.* 2017).

6.6.1 Future Weather Data

In this study, to predict future performance of skycourt, the future weather file for simulation has been generated using the Climate Change World Weather File Generator (CCWorldWeatherGen). CCWorldWeatherGen has been adopted widely in energy prediction studies to convert local weather files to future weather files for thermal and energy simulations (Pajek and Košir 2018; Triana *et al.* 2018; Invidiata and Ghisi 2016; Peng and Elwan 2014; Yu *et al.* 2013).

This tool was developed by the Sustainable Energy Research Group at the University of Southampton to generate hourly climate change adapted weather data for the UK and any location worldwide. It addresses different sources to transform present hourly day CIBSE TRY / DSY weather data into climate change adapted weather data, considering the majority of parameters given in a standard TMY2 / EPW file. This software is based on a catalogue of meteorological data and corresponding interpolation models (Belcher *et al.* 2005). Additionally, it offers the possibility to predict future typical meteorological years, such as 2020, 2050 and 2080 (Moazami *et al.* 2017).

The study addressed original weather data that was considered in previous simulation cases. Then this was converted using CCWorldWeatherGen to generate 2020, 2050 and 2080 typical years. The 2020s represents the era from 2011 to 2040, the 2050s represents the era from 2040 to 2070 and the 2080s represents the era from 2071 to 2100. The analysis considered the optimal configuration of the hollowed-out skycourt.

6.6.2 Energy and Thermal Performance of Ventilated Skycourt in Future

The energy simulation results predicted a rise of cooling demand of air-conditioned skycourt in the future. This cooling demand is predicted to increase by 35% during the 2020s period and by over 45% during the 2050s period (Figure 6-16). However, considering the skycourt as an unheated and uncooled space, that is ventilated based on the combined-exhaust ventilation strategy, has a positive impact to reduce the total energy demand for heating and cooling for the building by more than 65% per year in future.

Although the energy simulation results reported a continuous increase of cooling demand for the building that integrated a ventilated skycourt in future, this increase will be less than 4% for the 2020s period and up to 11% for the 2050s period. In addition, this is connected with a 9% decline for the 2020s period and over 20% decrease for the 2050s period in of the heating demand for the building (Figure 6-17).

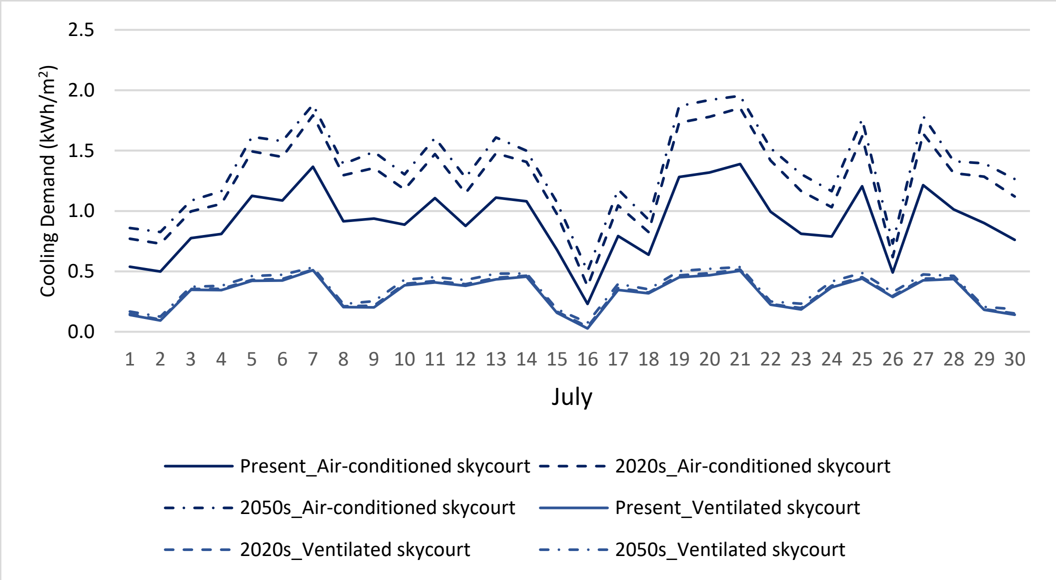


Figure 6-16. Cooling demand comparison for the building of hollowed-out skycourt in the present, 2020s and the 2050s scenarios: air-conditioned skycourt and ventilated skycourt

It is important to mention that the average increase of total demand for both heating and cooling for the building will be less than 4.5% during the building life, as 50 years period is assumed to represent building life cycle (Triana *et al.* 2018).

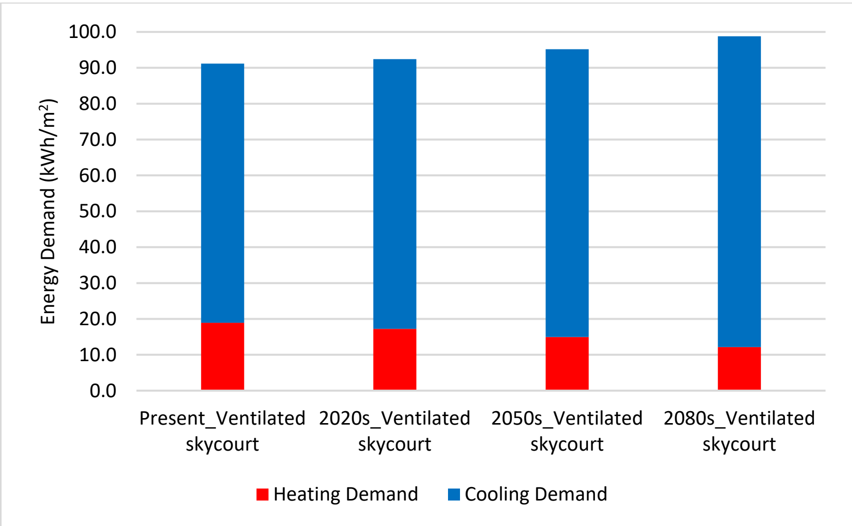


Figure 6-17. Energy demand comparison for the building of hollowed-out ventilated skycourt: the present, the 2020s, the 2050s and the 2080s scenarios

The level of thermal comfort at the skycourt will remain accepted in future during the occupancy profile of the building starting at 09.00 to 18.00. It is predicted that there will be no observed change in indoor temperatures in skycourt in future in the different seasons (Figure 6-18). Overall, the air temperature ranged between 25°C and 27°C in the hot days in summer; 18°C and 25°C in the cold days in winter; and 20°C and 23°C in the transitional seasons skycourt in the present, the 2020s, the 2050s and the 2080s scenarios.

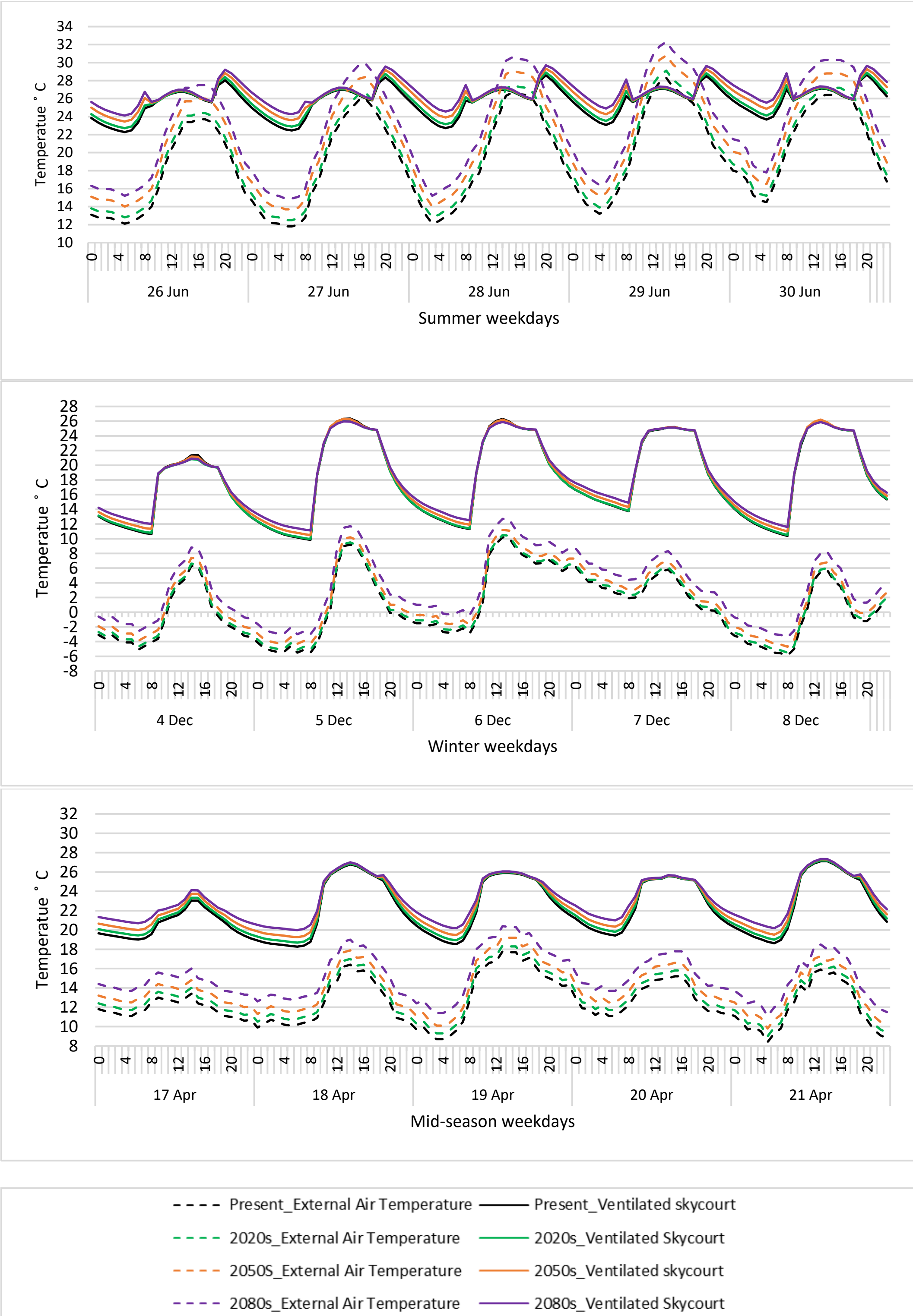


Figure 6-18. Comparison of air temperature in the occupied area of ventilated hollowed-out skycourt: the present, the 2020s, the 2050s and the 2080s scenarios

According to these results, a ventilated skycourt can be effective during the life cycle of present building and even more for the end of this century. It can ensure minimum energy demands for heating and cooling for the building and accepted level of thermal comfort at the skycourt.

6.7 THE EFFECT OF URBAN HEAT ISLAND ON VENTILATED SKYCOURT

There are many environmental issues that are associated with the influence of surrounding microclimate on buildings. Environmental considerations include the influence of micro-wind, air temperature, air quality and pollutant dynamics environments.

One of the main factors of the micro-environment surrounding buildings is the wind. Wind pressure distribution around buildings varies greatly due to wind direction and various phenomena of wind field (Meng *et al.* 2018). These aspects are important in wind resistance design and natural ventilation studies. Wind pressure impact is lower in city centre areas in comparison to boundary areas. A previous study (Elshaer *et al.* 2016) found that there are differences in wind pressure and dynamic responses when considering a single isolated building and a building surrounded by other high-rise buildings. The surrounded building has a lower mean pressure values, i.e. 30% and higher torsional responses values, i.e. 15%; than those of the isolated building. Thus makes cities are significantly warmer than its boundary areas and increase the effect of urban heat island.

Density of building blocks, distance between buildings, height of buildings and other urban design factors have impact on urban heat island, which in turn modifies the local microclimate surrounding buildings (Niu 2004).

Urban heat island effect can significantly alter external temperatures, wind speed and direction (Roetzel *et al.* 2011). For example, a novel study explored the impact of urban heat island effect at different locations of London city found that UHI causes differences in external temperature between these locations. Central London can be 2°C to 3°C warmer than its boundary areas (Du *et al.* 2017a). These weather conditions have an impact on the energy consumption of heating and cooling for buildings and the thermal conditions of the built environment. It has been recognised that a building in London city centre consumes higher cooling demand, i.e. over 40%, than the same building located at

London's boundaries. In contrast, UHI reduces heating demand for this building by over 30% in summer and over 10% in winter (Du *et al.* 2017a).

Furthermore, UHI could cause overheating on the indoor temperature of the building located in city centre of London compared to the same building located at London boundary (Du *et al.* 2017b). It is important to use local weather data of buildings in energy simulation to predict near future performance (Du *et al.* 2016), significantly, for studies that investigate ventilation design strategies of buildings located in cities (Virk *et al.* 2015).

Therefore, the influence of heat island effect for urban areas, such as central London on the heating and cooling demand of buildings that integrate skycourt, as well as, on the thermal conditions of the skycourt is considered in this study.

Two locations were considered to explore the influence of the surrounding microclimate of UHI on skycourts. These are; London weather centre (Latitude = 51.5°, Longitude = 0.09°) and London Gatwick (Latitude = 51.15°, Longitude = -0.18°). The weather files for these locations were produced by available Meteonorm 6.1.0.23. This is a climate database combined with a weather generator based on more than 30 years of the development of meteorological databases for energy applications and it can deliver typical meteorological years for any site. Details of weather data about these locations are provided in Appendix A. The optimal configuration of ventilated hollowed-out skycourt building is used in this simulation case as mentioned previously.

6.7.1 Energy and Thermal Performance of Ventilated Skycourt under Effect of UHI

A difference of external air temperature was found between the considered locations. London city location is 1°C to 1.4°C warmer than Gatwick location. This can be explained due to the influence of the microclimate, which impacts on UHI effect and cause differences in external air temperature (Virk *et al.* 2015). The effect of urban heat island in London's city would increase the requirement for cooling and heating of buildings (Figure 6-19). The total heating and cooling demand of the building that integrates an air-conditioned skycourt, and significantly, the cooling load was found to be 5% more than the same building that is located in Gatwick region. While, heating demand of the building in the city location was less about 3% less than the building in the other location.

On the other hand, the investigation indicates that the ventilation strategy, which depends on the maximum airflow rate exhaust from the adjacent offices to the skycourt, accounts high energy savings. This strategy has a potential to provide significant energy savings in both locations. The building that integrates a ventilated skycourt achieved over 50% reduction in the total heating and cooling demand per year in comparison with the building of air-conditioned skycourt in the city.

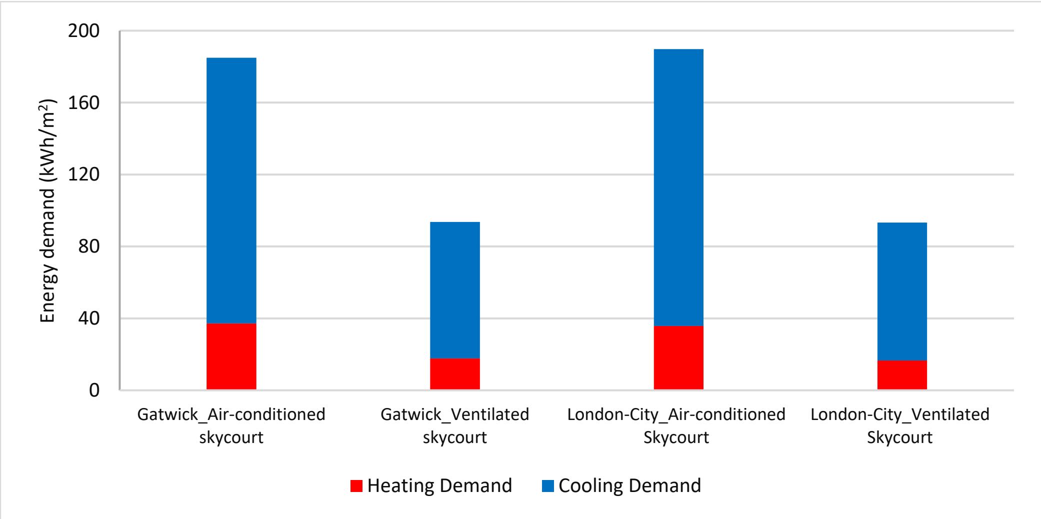


Figure 6-19. Annual heating and cooling demand comparison for buildings of hollowed-out skycourt: London-city (London weather centre) and Gatwick area

In addition, the thermal conditions comparison at the occupancy level of the ventilated skycourt in summer days shows that the ventilated skycourt can be efficient in both areas; London city and Gatwick boundary (Figure 6-20). In general, air temperature ranges between 25°C and 26°C during the weekdays of summer. However, the ventilated skycourt in the building that located in the city was about 0.4°C warmer than more than the same building that is located in Gatwick region.

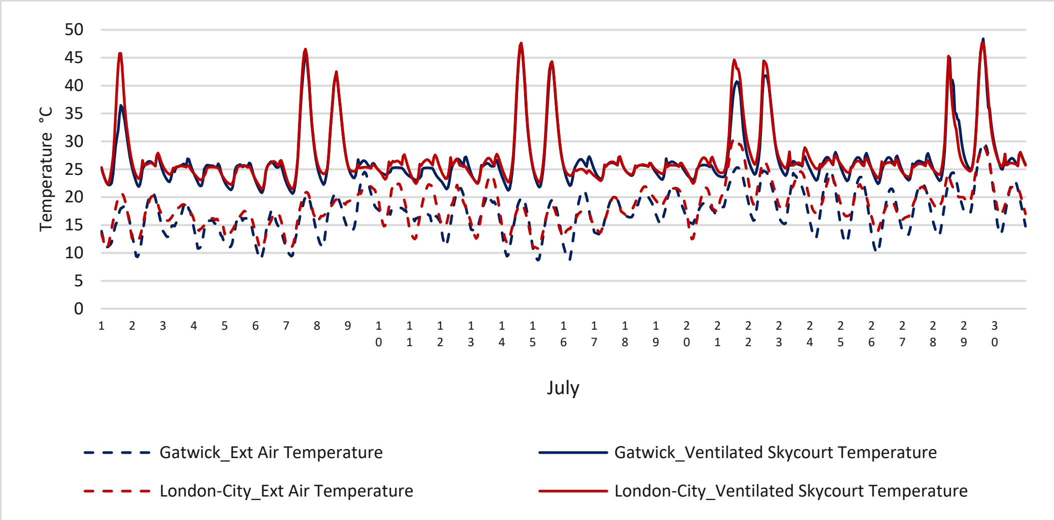


Figure 6-20. Comparison of air temperature in the occupied area of ventilated hollowed-out skycourt in weekdays of summer: London-city (London weather centre) and Gatwick area

The simulation results highlighted that the ventilated skycourt have potentials for saving energy and achieving thermal comfort in several areas. The combined ventilation strategy for the skycourt is beneficial to reduce the effect of urban heat island in cities. Thus, can minimise requirements for energy of buildings, besides ensuring thermal comfort at the skycourt.

6.8 PERFORMATIVE DESIGN GUIDELINES FOR VENTILATED SKYCOURTS IN OFFICE BUILDINGS IN TEMPERATE CLIMATE – LONDON

The results of the research study provided a matrix that offers guidance for designers on integrating a ventilated skycourt in a high-rise office building in a temperate climate (Figure 6-21).

The upper part of the chart provides an overall performance of the three prototypes of skycourts when adopting the combined-exhaust ventilation strategy. This shows the expected percentage of annual heating and cooling demand reduction for the building in reference to a building that has air-conditioned skycourt, and the expected air temperature in the occupied area of the skycourt. The impact of air ventilation rate on the energy demand and air temperature is presented. In addition, this part compares the performance between the three skycourts.

The second and the third parts of the matrix show the expected energy performance and air temperature for the different investigated values of skycourts. Columns of the matrix represent geometric parameters (such as orientation, height, length, and depth) of each prototype of skycourts. The rows are categorised in two main parts. The first focuses on the impact of geometric parameters on annual heating and cooling demand reduction. The second emphases on the air temperature in the occupied area of the skycourt in relation to its geometric parameters. These predictions are based on the extreme external temperatures in summer and winter, which are 28°C and -5°C, respectively. The reference temperatures are 26°C in summer, when external temperature is 28°C; 16°C in winter, when external temperature is -5°C; and 22°C in mid-seasons, when external temperature is 13°C.

Both the energy demand reductions of adjacent offices and air temperatures in the occupied skycourts are based on the combined-exhaust ventilation strategy, as it is the most effective mechanism for achieving energy saving and thermal comfort. However, in order to maximise the benefits of this strategy in terms of air temperature, the air ventilation rate needs to be increased as indicated in the air ventilation rate comparison.

The suggested design process requires the user to define, firstly, a suitable prototype (spatial configuration) for the skycourt. Then, the designer can select a value for each geometric attribute according to the design brief. The selection process is linked with amounts of energy reduction for the building, and the air temperature as an indicator for thermal comfort inside the skycourt. If higher or lower values have been selected, the percentages of demand reduction and the air temperatures could be predicted. For example, when length of the skycourt decreased less than 7.5 m, it is assumed that reduction in cooling and heating demand increased. Therefore, a holistic picture about the impact of the integration of a skycourt could be predicted.

In the suggested design recommendations, airspeed in the skycourt has been excluded from the matrix, as designers can control this issue through changing the number and layout distribution of air inlet and outlet openings.

It is important to mention that the recommended values for the different design attributes allow flexibility for the design process. For instance, if the design brief requires three-floor skycourt, the architect can change other attributes (orientation, length, and depth of the skycourt) to achieve the desired air temperature in the skycourt. Therefore, the expected energy saving of heating and cooling of the building could be achieved.

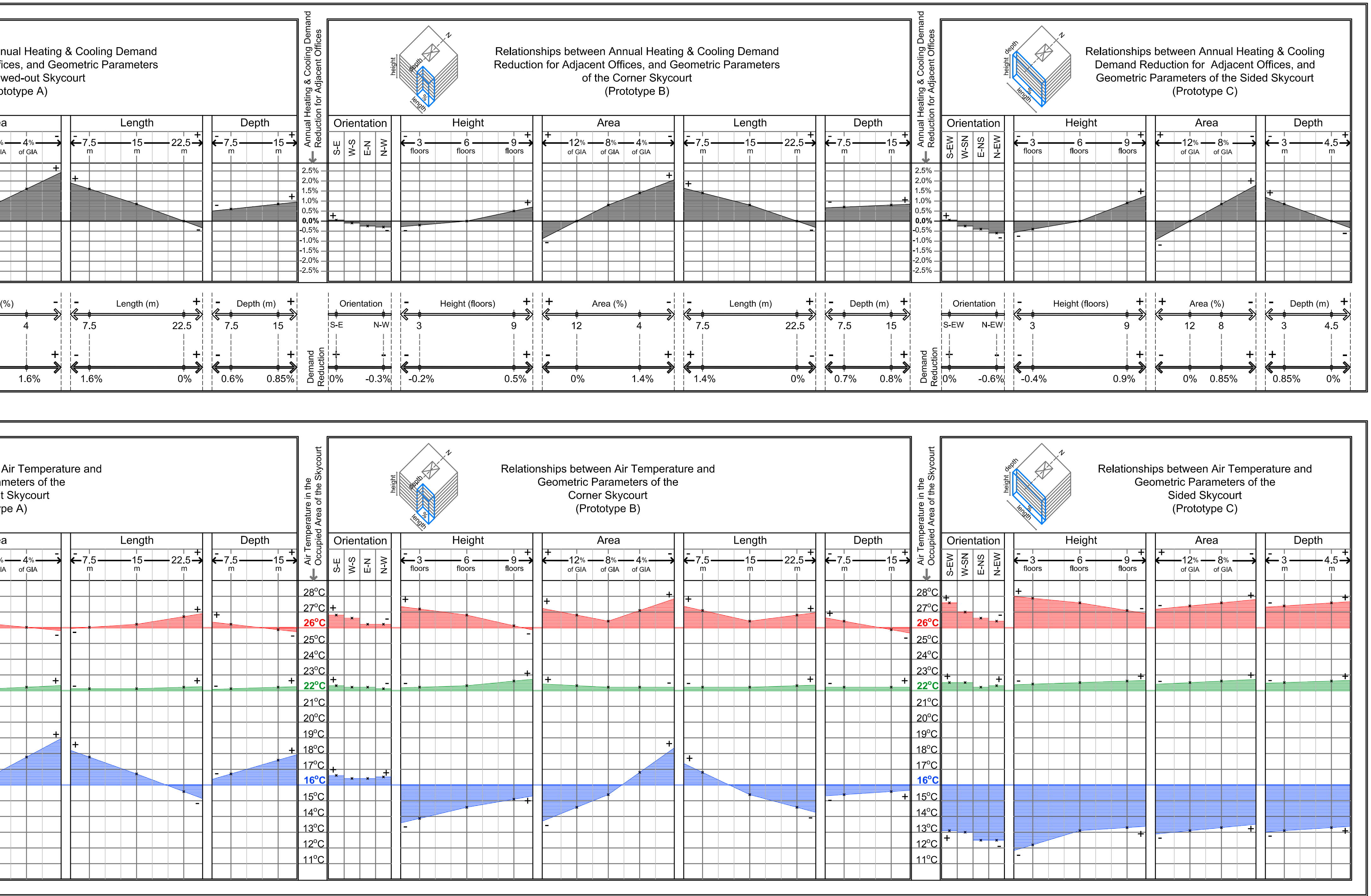


Figure 6-21. Relationships between design parameters for ventilated skycourts, annual heating and cooling demand reductions for adjacent offices, and air temperatures in the occupied skycourts

6.9 SUMMARY

Based on the findings of the research it was concluded that the design attributes of a skycourt affect its interior environment, which in turn has an impact on its energy performance. Consequently, the interior environment of the skycourt affects the total energy demand of the building.

The performance of skycourts was investigated under several design parameters, including the ventilation strategy, spatial configuration (prototype), geometry (orientation, height, area, and dimensions) of skycourts, and distributions of ventilation openings in the skycourt.

The discussion indicated that ventilation is the main responsible parameter that influences the heating and cooling demand of buildings that integrate skycourts. In addition, it influences the air temperatures and airspeed in skycourts. Applying a combined ventilation strategy between the skycourt and adjacent offices has potential to reduce the cooling and heating demands of the building, and at the same time, achieve the level of thermal comfort in the occupied area of skycourts.

The findings showed that a higher ventilation flow to skycourts reduces the effect of extensive solar heat, and enhances their thermal conditions. Also, the temperature of supply air affects the internal environment of the skycourts, which influences the energy consumption of the building. The favourable temperature is the one that is similar to comfort conditions.

The effect of the spatial configurations (hollowed-out, corner and sided) of skycourts is related to the amounts of solar gain through their glazed façades. However, the geometric attributes of skycourts that are ventilated by exhaust air from adjacent offices have less impact on the building energy consumption, and on the thermal conditions of the skycourts. The simulation results of each parameter separately show similar trends of influence for the three skycourt prototypes. It is efficient to position air inlet openings at the floor level of the skycourt closer to its external façade and the outlet openings at the ceiling level closer to the internal wall of the skycourt.

Furthermore, ventilated skycourt was found to perform effectively under future weather scenarios, i.e. 2020s, 2050s and 2080s. In addition, it has a great impact to reduce the effect of urban heat island. The results for the variety of weather files due to climate change and UHI confirmed the beneficial role of such skycourt on reducing the risk of future overheating in urbanised regions.

Based on these findings, a guideline for the design and performance of a ventilated skycourt in office buildings was developed. These guidelines were presented in the form of a matrix table. This is a useful outline for architects and building developers to decide the prototype and geometry of the skycourt and to predict the air temperature of such a skycourt. In addition, the guidelines are expected to achieve savings in energy consumption for heating and cooling for the building.

The conclusions of the study, including implications for ventilated skycourts in temperate climate regions, limitations of the current study, and directions for future research, will be discussed in the next chapter.

CHAPTER SEVEN: CONCLUSION

7 CONCLUSION

7.1 INTRODUCTION

High-rise buildings are seen as the future of cities. Such developments, particularly offices, are responsible for high energy consumption. One reason is the extensive use of air conditioning systems to provide the occupants with thermal comfort.

The skycourt is becoming increasingly integrated into the design of high-rise office buildings to create more sustainable and liveable environments. This feature performs as a transitional node, and a space for social interaction. Previous literature indicated that skycourts could play a promising role in reducing energy consumption for buildings. However, there are few studies providing evidence of their influence on the total energy demand in buildings. On the other hand, such areas require a high energy demand for cooling to sustain thermal comfort when integrated as air-conditioned buffer zones that are located between the indoor offices and the outdoor environment. Such a contradiction requires clarification. Therefore, this study answered the following question:

In what ways can the skycourt be considered as a transitional buffer space that enhances energy efficiency in high-rise office buildings, focusing on ventilation?

7.2 CONTRIBUTION OF THE RESEARCH

7.2.1 Potential of Skycourts in High-rise Office Buildings

In the present study, the aim to prove the potential of skycourts to accomplish sustainability was successfully addressed. The study answered the question of: ''*Can skycourts enhance and drive efficient heating and cooling demands in office buildings*, *in addition achieve accepted level of thermal comfort in these spaces?''* by developing a ventilation strategy that is able to reduce the heating and cooling demands of the building, and ensure an accepted level of thermal comfort in the skycourt. The positive influence of the skycourt on the offices was confirmed.

In addition, the main objectives of the study were accomplished. The common prototypes of skycourts as transitional buffer spaces in high-rise office buildings in the research context were defined. These include (A) the hollowed-out skycourt, which is connected with the external environment by one edge, (B) the corner skycourt, which includes two external edges, and (C) the sided skycourt that incorporates three external façades. Full glazed façades and the intermediate location between offices and external walls are the most common properties for skycourts in temperate regions.

Then, different geometric and spatial parameters for skycourts were investigated through conducting a systematic and detailed sensitivity analysis. This process aimed to determine the important ventilation conditions to produce the greatest savings in heating and cooling demand, and thus, provide thermal comfort for the skycourt's occupants during summer, winter and mid-seasons.These parameters include the skycourts' spatial prototype, orientation, height, percentage of the area to the total floor area of the office zones on every single floor, length, depth, and vertical locations and horizontal positions of the air inlet and outlet openings within the skycourt. As a result, this answered the research's question regarding the optimal designs for ventilated, unheated and unooled skycourts in temperate climates such as in the London context.

By employing a skycourt as a ventilated, free-heated and free-cooled buffer zone in an office building, the energy consumption due to heating and cooling was significantly reduced by a more than 55% saving per year. In addition, thermal comfort conditions in the occupied area of the skycourt were attained. The air temperature inside the skycourt was about 27°C in hot hour, which is over 28°C, of summer, and about 15°C in extreme coldest temperature, which is -5°C, of winter. The air temperature in mid-season recorded about 22°C. The average airspeed was found to be within the comfort levels by 0.2 m/s. That makes the skycourt a thermally comfortable environment all over the different seasons in a temperate climate, such as in London.

7.2.2 Combined Ventilation Strategy for Enclosed Transitional Zones

It is obvious that ventilation has a significant effect on the indoor thermal conditions and energy consumption. However, a good indoor environment can be achieved, not by introducing extravagant concepts, but by developing a balanced approach to identify ventilation needs and apply the necessary tools to deal with these requirements.

This study makes a novel contribution to the knowledge through providing a new vision concerning low energy designs focusing on ventilation. It introduces an efficient ventilation strategy for skycourts as transitional buffer zones in high-rise office buildings in a temperate climate that is a combined ventilation strategy between air-conditioned spaces and buffered zones.

The study found that the combined-exhaust strategy, which depends on cooling the skycourt by air exhausted from the adjacent office's spaces is an efficient approach. The findings have confirmed that this strategy can induce heating and cooling savings for high-rise office buildings and provide occupants' thermal comfort in enclosed transitional buffer areas such as skycourts, compared to typical air-conditioning strategies. Furthermore, such ventilation strategy has beneficial role on reducing risk of global warming in city centre areas, which is believed to be a real threat. This outcome has significant implications for future practices.

This strategy can be considered as a sustainable mechanism according to the fact that efficient air flow systems, which achieve reductions in energy consumption without limiting thermal comfort, provide better indoor air quality (IAQ) and enhance sustainability.

7.2.3 Design of Ventilated Skycourts in High-rise Buildings

One principal objective of the study was to outline guidelines for designing skycourts in high-rise office buildings in temperate climates to ensure the highest reduction of heating and cooling loads for the office building, and to provide thermal comfort for occupants in the occupied area of the skycourt.

The study has successfully achieved this intention through establishing a matrix for design and performance of the skycourt. This allows designers and developers the ability to decide on the appropriate prototype and geometric properties of the skycourt and predict the impact of the selected parameters. The design performance is based on providing a combined-exhaust ventilation strategy in the skycourt. This mechanism influences heating and cooling demands for the building, and air temperatures in the skycourt. It is favourable to locate air inlet openings at the occupancy level of the skycourt, closer to the external façade. Air outlet openings are recommended to be positioned at the upper level of the skycourt, closer to its internal wall, and opposite to air inlet openings to enhance airflow. However, increased airflow ventilation produces increased airspeed.

In terms of the geometric properties of the skycourt, the study suggested a variety of options that could achieve energy savings for the building, and an acceptable level of thermal conditions inside the skycourt.

Performance regarding the orientation of the skycourt shows that there will be a rise in the energy demand for heating and cooling in all orientations when compared to the south direction. In summer, northern skycourts have lower temperatures, while in winter, southern façades for skycourts are preferable to provide higher temperatures.

Regarding the dimensions of the skycourt, a positive correlation was found between the length of the skycourt, and energy savings for the building. Rectangular shapes for skycourts are more effective for ventilation than square shapes; moreover, they could achieve thermal comfort and acceptable air temperatures in the occupied area of the skycourt.

In terms of the height of the skycourt, heating and cooling demands decrease when the skycourt becomes taller.

The study recommended optimised geometric attributes for the design of ventilated skycourts in temperate regions, which invlove the following:

(i) Skycourt to be medium height; between three-floor height to six-floor height.

(ii) Skycourt to be oriented to the south and/or north.

(iii) Skycourt to occupy 12% to 8% of the office floor area.

(iv) Length to occupy 60% to 40% of the façade of the building in the case of integrating hollowed-out and corner skycourts, and 100% of the façade of the building when integrating sided skycourt.

(v) Depth of the hollowed-out and corner skycourts to be about 50% of the length. In the case of the sided skycourt, it is suggested to use a depth of 8% to 12% of its length.

However, it is important to mention that the investigated parameters of the three skycourts show small differences in terms of thermal conditions and energy impact. This provides a variety of spatial and geometric configurations of skycourts, and allows flexibility for the design. Thus, confirm the efficiency of the proposed combined ventilation strategy between the skycourt and adjacent offices to benefit the process for designing skycourts in the current and the future scenarios of weather conditions.

7.2.4 Coupling Models as a Tool to Investigate the Energy and Thermal Performance of Buildings

The coupling simulation system of Building Energy Simulation (BES) and Computational Fluid Dynamics (CFD) models were found to be a useful and quick prediction tool for studying thermal conditions and energy efficiency in this study. In addition, previous studies highly recommended this approach in ventilation studies due to its accuracy and effectiveness. BES and CFD produce detailed and converged solutions and inform accurate and efficient predictions of thermal and airflow patterns.

In this study, the building energy model using HTB2 and CFD models using WinAir were coupled for predicting the energy consumption for heating and cooling of the building, in addition to air temperature and air velocity at the occupancy level of the skycourt under different situations.

The thermal conditions for CFD (WinAir) simulations were obtained from previously calculated values from the energy modelling software (HTB2). It was anticipated that coupling of HTB2 and WinAir programs produced minimum temperature differences (nearly 1°C). That small difference is usually accepted for ventilation cases to continue the simulation for the next time step (Wang and Wong 2008). Therefore, one-step data exchange was sufficient to be adopted in the study. This result acknowledges the compatibility between the two programs. The technique used in this study to couple HTB2 and WinAir models could be applied to predict the indoor environment of other spaces.

The results from this study indicated that the coupling models system is a useful tool for investigating ventilation performance in buildings, particularly in studies that use simulation as a design tool as it provides an acceptable accuracy in prediction of thermal and energy performance with a small cost and time expenditure. It is also favourable for sensitivity analysis studies when there are a number of changes and variables concerned. Therefore, this method could be applied to investigate spaces that are large and high such as skycourts, atria, courtyards and plazas.

7.3 LIMITATIONS OF THE RESEARCH

Although the results of this research are encouraging, some limitations in the study need to be considered. These include the following:

- Due to time frame, this study considered results obtained from simulation only. However, the simulated data were predicted by coupling energy modelling HTB2 and CFD in WinAir. This approach is recommended to reduce simulation limitations and inform accurate and efficient predictions for thermal and airflow patterns. In addition, the two software show high validity in both academic research and practice. Furthermore, results of the research correspond with the results of previous studies.
- This study focused on the impact of skycourts on the energy performance of office buildings. In addition, it aimed to develop design guidelines for this space considering ventilation and geometric configuration. Therefore, the study was limited to a single isolated building and did not consider the influence of the surrounding urban context. However, the performance of skycourt under the effect of urban heat island was addressed in the study considering the variation of weather conditions between urban and rural areas.
- The main aim of the study considered ventilation improvement for office buildings due to the effect of the skycourt. Therefore, prototypes for skycourts have been represented as abstracted rectangular shapes without considering the actual layout. In addition, this abstraction allows for generalisation in the study context.

7.4 DIRECTIONS FOR FUTURE RESEARCH

The study has revealed two directions that need further investigation in the future. Such studies would help to derive detailed best practice guidelines for skycourts. The first direction considers skycourts' potential to improve energy efficiency and human comfort in building. The second considers potential influence of skycourts in terms of social dimension. Furthermore, a generic methodology processes is provided for each group.

Direction one: Energy efficiency

- Skycourts could allow the penetration of daylight and prevent undesirable direct solar heat gain. Therefore, future work should consider the potential of such spaces to improve daylight and reduce glare in adjacent offices. In this context, the impact of occupancy schedule, users' behaviour, time of the day, windows' glazing properties and design, weather conditions, significantly, rain and cloud should be considered. In addition, such studies should define the diverse daylight implication of skycourt with every floor level of offices. It would be efficient to build upon this present study and find a feasible combination for daylighting, heating and cooling demand for office buildings with skycourts.
- Theoretically, natural ventilation is possible between mid-April to mid-October in London. For this reason, further investigation and experimentation are recommended to determine the potential of implementing passive strategies, such as wind-induced and night ventilation mechanisms into the skycourt. It should be mentioned here that it is more complicated to apply such systems than mechanical ventilation, particularly in office buildings. However, it is considered that this issue warrants further study.

Measurement, statistical analysis and building energy modelling can be adopted to determine energy use and level of comfort and investigate the impact of skycourt on energy saving and human comfort. The proposed research design can consist of four main phases, these are:

First, to adopt field measurement and collect data of skycourts in reference high-rise office building.

Second, to construct simulation model and carry out numerical simulation. Then, to compare simulation results with site measurement to validate the simulation results.

Third, to investigate parameters performance using simulation and considering common prototypes of skycourts.

Finally, to identify an optimal solution that provide maximum results of energy savings and accepted level of thermal comfort.

Direction two: Social dimension

- Plants could be one of the main characteristics of skycourts in high-rise buildings. Green foliage can improve the environmental performance of this space and wellbeing of occupants. In addition, it could improve thermal comfort at the building and urban scales. Therefore, a future study investigating the influence of incorporating greenery in the skycourt performance would be interesting.
- One important function of skycourt is to facilitate social interaction among occupants and increase employees' wellbeing and productivity. Future studies investigate this potential in office buildings should be considered.

These two cases can be conducted based on longitudinal, mixed-methods including interviews and questionnaire to evaluate the perception of employees in offices integrated skycourts. The proposed methodology can consist of four main phases, these include:

First, to investigate significant factors that affect human comfort in skycourts through analysing spatial qualities of skycourts in terms of location, access, opening, geometric properties, landscape gardens and other design features.

Second, to conduct structured (questionnaire) and unstructured interviews with users of the buildings to determine their satisfaction in skycourt spaces, define preferences, advantages and disadvantages of such spaces, and potential for improving these spaces. Questions should be connected with occupants comfort conditions in these spaces.

Third, to establish correlations between skycourt and employees productivity gains by analysing the survey results and collecting statistical data about absence rates, sick leave and other related factors.

Fourth, to provide guidelines for skycourt design that improve skycourt benefits as a comfortable atmosphere that promotes social networking in office buildings.

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APPENDICES

Appendix A: London's weather data

Table A-1. Statistics for GBR_London.Gatwick.037760_IWEC *

Location	**LONDON/GATWICK - GBR {N 51° 9'} {W 0° 10'} {GMT +0.0 Hours}**
Elevation	62.0 m above sea level
Standard Pressure at Elevation	100582Pa
Data Source	IWEC Data
Displaying Design Conditions	Climate Design Data 2009 ASHRAE Handbook
Climate type (Köppen classification)	Cfb: Marine west coastal (warm summer, mild winter, rain all year, lat. 35-60°N)

* Source: EnergyPlus Weather Converter V7.1.0.010

Table A-2. Typical and extreme period determination

Summer is June to August
Extreme Summer Week (nearest maximum temperature for summer)
Extreme Hot Week Period selected: Aug 17:Aug 23, Maximum Temp= 31.30°C, Deviation=|12.677|°C
Typical Summer Week (nearest average temperature for summer)
Typical Week Period selected: Jun 29:Jul 5, Average Temp= 16.36°C, Deviation=| 0.115|°C
Winter is December to February
Extreme Winter Week (nearest minimum temperature for winter)
Extreme Cold Week Period selected: Dec 1:Dec 7, Minimum Temp= -5.90°C, Deviation=| 6.758|°C
Typical Winter Week (nearest average temperature for winter)
Typical Week Period selected: Jan 20:Jan 26, Average Temp= 4.50°C, Deviation=| 0.562|°C
Autumn is September to November
Typical Autumn Week (nearest average temperature for autumn)
Typical Week Period selected: Nov 10:Nov 16, Average Temp= 10.74°C, Deviation=| 0.101|°C
Spring is March to May
Typical Spring Week (nearest average temperature for spring)
Typical Week Period selected: Apr 19:Apr 25, Average Temp= 9.22°C, Deviation=| 0.397|°C

Table A-3. Monthly optical sky depth beam (taub) and diffuse (taud)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
taub (beam)	0.335	0.349	0.408	0.405	0.434	0.441	0.455	0.432	0.396	0.375	0.348	0.344
taud (diffuse)	2.262	2.222	1.998	2.042	1.973	1.991	1.974	2.052	2.157	2.167	2.227	2.225

taub = Clear Sky Optical Depth for Beam Irradiance
taud = Clear Sky Optical Depth for Diffuse Irradiance

Table A-4. Monthly dry bulb and mean coincident wet bulb temperatures (°C)

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Dry bulb	0.4%	2.1	3.2	16.9	0.7	5.1	7.9	30	0.5	5.3	0.3	5.6	3.2
Coincident Wet bulb	0.4%	10.5	10.5	11.3	13.4	16.5	18.4	19.5	20.2	17.9	16.1	13.6	11.7
Dry bulb	2.0%	11.2	1.7	14.2	17.8	22.9	25.2	27.3	27.1	22.9	18.1	14.2	12.5
Coincident Wet bulb	2.0%	10	9.9	10.2	11.9	15.8	17.5	18.7	19	17	14.8	12.8	11.3
Dry bulb	5.0%	10.6	10.8	12.6	15.8	20.4	23.1	25.3	24.9	20.9	16.9	13.4	11.8
Coincident Wet bulb	5.0%	9.5	9.2	9.5	10.8	14.7	16.7	17.9	18	15.9	14.3	12.1	10.7
Dry bulb	10.%	9.8	9.7	11.2	13.9	18	21	23.4	22.8	19.1	15.9	12.5	10.8
Coincident Wet bulb	10.%	8.9	8.3	8.9	9.9	13.3	15.5	17.2	17.1	15.2	13.8	11.2	9.7

Dry bulb 0.4%	= 0.4% Monthly Design Dry Bulb Temperature
Coincident Wet bulb 0.4%	= 0.4% Monthly Mean Coincident Wet bulb Temperature
Dry bulb 2.0%	= 2.0% Monthly Design Dry Bulb Temperature
Coincident Wet bulb 2.0%	= 2.0% Monthly Mean Coincident Wet Bulb Temperature
Dry bulb 5.0%	= 5.0% Monthly Design Dry Bulb Temperature
Coincident Wet bulb 5.0%	= 5.0% Monthly Mean Coincident Wet Bulb Temperature
Dry bulb 10.%	= 10.% Monthly Design Dry Bulb Temperature
Coincident Wet bulb 10.%	= 10.% Monthly Mean Coincident Wet Bulb Temperature

Table A-5. Monthly dry bulb and wet bulb daily ranges delta (°C)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Dry bulb	5.5	6.0	7.5	8.8	9.3	9.4	9.7	9.8	9.1	7.6	6.5	5.4
Dry bulb range - DB 5%	5.6	6.3	9.7	11.9	13.7	13.6	13.7	13.5	11.8	8.3	6.0	4.8
Wet bulb range - DB 5%	5.4	5.1	6.4	6.8	7.6	7.0	6.4	6.3	6.5	5.6	5.1	4.8

Dry bulb	= Mean Daily Dry Bulb Temperature Range
Dry bulb range - DB 5%	= Mean Daily Dry Bulb Temperature Range Coincident with 5% Design Dry Bulb Temperature
Wet bulb range - DB 5%	= Mean Daily Wet Bulb Temperature Range Coincident with 5% Design Dry Bulb Temperature

Table A-6. Average hourly statistics for dry bulb temperatures (°C)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0:01- 1:00	3.7	2.8	5.4	5.8	9.1	12.1	13.7	13.9	11.7	8.9	6.4	4.3
1:01- 2:00	3.6	2.7	5.3	5.6	8.5	11.7	13.4	13.5	11.4	8.9	6.1	4.1
2:01- 3:00	3.6	2.6	5.1	5.2	8.3	11.1	13.2	12.9	11.1	8.8	6.2	4.0
3:01- 4:00	3.6	2.4	5.1	5.0	7.9	10.9	12.9	12.8	10.9	8.6	6.1	3.9
4:01- 5:00	3.5	2.4	5.0	4.9	7.9	11.1	12.9	12.5	10.6	8.3	6.1	3.9
5:01- 6:00	3.4	2.4	4.9	5.2	8.9	11.8	13.8	13.0	10.7	8.3	6.0	3.8
6:01- 7:00	3.5	2.5	5.1	6.0	10.4	12.8	15.3	14.3	11.3	8.3	6.0	3.8
7:01- 8:00	3.5	2.3	5.8	7.5	11.9	13.8	16.7	15.7	12.7	9.1	6.3	3.8
8:01- 9:00	3.8	3.0	6.6	8.9	13.3	14.6	18.0	17.2	14.2	10.3	7.3	4.2
9:01-10:00	4.3	3.9	7.5	9.9	14.5	15.7	19.1	18.5	15.5	11.5	8.4	4.9
10:01-11:00	5.0	4.9	8.3	10.4	15.4	16.7	19.9	19.4	16.3	12.6	9.6	6.0
11:01-12:00	5.6	5.8	8.7	11.1	16.0	17.7	20.5	19.8	16.7	13.5	10.3	7.1
12:01-13:00	6.0	6.1	9.1	11.4	16.2	18.2	21.1	20.0	17.0	13.6	10.7	7.6
13:01-14:00	6.1	6.3	9.4	11.7	16.6	18.7	21.5	20.7	17.2	13.6	10.9	7.8
14:01-15:00	6.0	6.2	9.4	11.8	16.6	19.0	21.4	20.7	17.1	13.4	10.5	7.5
15:01-16:00	5.6	6.1	9.2	11.6	16.4	18.9	21.3	20.4	16.9	12.9	9.8	6.7
16:01-17:00	5.2	5.5	8.7	11.1	15.9	18.7	20.9	19.9	16.4	12.1	9.0	5.9
17:01-18:00	4.8	4.9	8.0	10.4	15.4	18.2	20.3	19.3	15.7	11.2	8.3	5.5
18:01-19:00	4.5	4.3	7.1	9.4	14.3	17.4	19.4	18.4	14.7	10.6	7.9	5.1
19:01-20:00	4.4	4.1	6.6	8.5	13.0	16.2	18.2	17.5	13.8	10.2	7.7	4.7
20:01-21:00	4.2	3.9	6.4	7.9	11.8	15.0	16.9	16.3	13.3	10.0	7.4	4.7
21:01-22:00	4.1	3.6	6.1	7.3	10.9	14.1	15.8	15.5	12.8	9.8	7.2	4.6
22:01-23:00	3.9	3.2	5.8	6.8	10.2	13.3	15.1	14.8	12.2	9.6	6.9	4.4
23:01-24:00	3.8	2.9	5.4	6.3	9.9	12.6	14.4	14.3	12.0	9.2	6.5	4.4
Max Hour	14	14	15	15	15	15	14	15	14	13	14	14
Min Hour	6	8	6	5	4	4	4	5	5	7	6	7

Table A-7. Average hourly statistics for dew point temperatures (°C)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0:01- 1:00	1.4	1.1	3.4	3.8	7.1	8.9	12.2	11.8	9.0	7.6	5.1	2.8
1:01- 2:00	1.4	1.0	3.2	3.7	6.9	8.9	12.1	11.5	9.0	7.7	4.8	2.6
2:01- 3:00	1.3	1.1	2.9	3.6	6.8	8.9	11.9	11.2	8.8	7.5	5.0	2.6
3:01- 4:00	1.5	0.9	2.9	3.4	6.6	8.9	11.6	11.0	8.7	7.4	5.0	2.6
4:01- 5:00	1.5	1.0	2.8	3.3	6.5	9.0	11.7	10.9	8.7	7.2	5.0	2.6
5:01- 6:00	1.2	1.0	3.0	3.5	7.0	9.1	12.3	11.3	8.9	7.2	4.9	2.6
6:01- 7:00	1.2	0.9	3.2	4.0	7.5	9.1	12.8	12.0	9.2	7.1	4.9	2.6
7:01- 8:00	1.3	0.8	3.5	4.5	7.8	9.3	12.7	12.4	9.8	7.6	5.0	2.6
8:01- 9:00	1.2	1.0	3.7	4.6	7.8	9.3	12.8	12.6	10.2	8.3	5.8	2.8
9:01-10:00	1.2	1.5	3.5	4.3	7.5	9.2	12.5	12.5	9.9	8.8	6.2	3.3
10:01-11:00	1.6	2.0	3.3	4.1	7.4	8.9	12.5	11.9	9.5	8.8	6.5	3.8
11:01-12:00	1.7	2.5	3.4	3.9	7.4	9.2	12.5	11.8	9.2	8.9	6.7	4.4
12:01-13:00	1.7	1.9	2.9	4.1	7.3	9.2	12.7	12.1	9.0	8.9	6.7	4.5
13:01-14:00	1.5	2.1	2.6	3.9	7.3	9.3	12.3	12.0	9.2	8.8	6.6	4.5
14:01-15:00	1.7	2.3	2.3	4.0	7.4	9.4	12.3	11.8	9.0	8.7	6.4	4.4
15:01-16:00	1.9	2.0	2.1	3.9	7.4	9.4	12.2	12.0	8.7	8.8	6.3	4.1
16:01-17:00	2.0	2.1	2.4	4.0	7.4	9.2	12.4	12.0	8.9	8.7	6.2	4.0
17:01-18:00	1.9	1.9	2.8	4.0	7.5	9.3	12.5	12.0	9.0	8.6	5.9	3.7
18:01-19:00	1.7	1.7	2.8	4.1	7.5	9.3	12.9	12.2	9.3	8.6	5.9	3.5
19:01-20:00	1.8	1.7	3.3	4.1	7.5	9.7	12.9	12.2	9.5	8.6	5.8	3.4
20:01-21:00	1.7	1.5	3.3	4.0	7.4	9.6	12.9	12.2	9.3	8.5	5.7	3.4
21:01-22:00	1.6	1.4	3.5	4.1	7.5	9.4	12.8	12.3	9.3	8.4	5.6	3.2
22:01-23:00	1.5	1.3	3.5	4.1	7.5	9.3	12.6	12.1	9.1	8.3	5.5	3.1
23:01-24:00	1.4	1.0	3.5	4.0	7.4	9.2	12.5	11.9	9.0	8.0	5.2	3.0
Max Hour	17	12	9	9	8	20	21	9	9	13	13	14
Min Hour	7	8	16	5	5	3	4	5	5	7	2	8

Table A-8. Average hourly relative humidity (%)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0:01- 1:00	85	89	87	87	88	81	90	87	84	92	92	90
1:01- 2:00	85	89	87	88	90	84	91	88	85	92	92	91
2:01- 3:00	85	90	86	89	91	86	92	90	86	92	92	91
3:01- 4:00	86	90	86	89	92	88	92	89	87	93	93	91
4:01- 5:00	86	91	86	90	91	87	93	90	88	93	93	91
5:01- 6:00	85	90	87	89	88	84	90	89	89	93	93	92
6:01- 7:00	85	90	87	87	84	79	85	86	87	92	93	92
7:01- 8:00	85	90	85	82	77	75	78	81	83	91	92	92
8:01- 9:00	83	87	82	75	70	72	73	75	77	88	90	91
9:01-10:00	80	84	76	69	64	67	67	69	70	84	86	89
10:01-11:00	79	82	72	66	61	62	64	63	65	79	82	86
11:01-12:00	76	79	71	63	59	60	62	62	62	75	79	83
12:01-13:00	74	75	66	62	59	58	60	62	61	74	77	81
13:01-14:00	73	75	64	61	56	57	58	59	61	74	76	80
14:01-15:00	74	77	62	60	56	56	58	58	60	74	76	81
15:01-16:00	77	76	62	60	57	57	58	60	60	77	79	84
16:01-17:00	80	79	65	63	59	57	60	62	63	80	83	87
17:01-18:00	81	81	71	66	61	59	63	65	66	84	85	88
18:01-19:00	82	83	75	70	65	61	67	69	71	88	87	89
19:01-20:00	83	84	80	74	71	67	72	72	76	90	88	91
20:01-21:00	84	85	81	77	76	71	78	78	77	91	89	91
21:01-22:00	84	86	84	80	81	74	82	82	80	91	90	91
22:01-23:00	85	87	85	83	84	77	85	84	82	91	91	91
23:01-24:00	84	87	88	86	85	81	89	86	83	92	91	91
Max Hour	5	5	24	5	4	4	5	5	6	6	4	7
Min Hour	14	13	16	15	15	15	15	15	15	14	14	14

Table A-9. Average hourly statistics for wind speed (m/s)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0:01- 1:00	3.1	2.8	3.7	2.6	2.2	2.2	1.3	1.9	2.8	1.9	2.0	2.9
1:01- 2:00	3.0	2.4	3.7	2.3	1.6	2.2	1.4	1.8	2.6	2.2	2.0	2.8
2:01- 3:00	3.1	2.4	3.7	2.2	2.0	2.4	1.4	1.8	2.4	2.2	2.0	2.9
3:01- 4:00	3.0	2.3	3.8	2.3	1.9	2.1	1.3	1.7	2.6	2.6	1.9	3.0
4:01- 5:00	3.1	2.5	3.7	2.5	1.9	2.2	1.5	1.8	2.3	2.6	1.8	3.0
5:01- 6:00	2.9	2.6	3.6	2.5	2.2	2.6	1.6	1.9	2.5	2.5	1.7	3.1
6:01- 7:00	3.1	2.5	3.7	3.0	2.9	3.3	1.9	2.3	2.7	2.4	1.8	3.0
7:01- 8:00	3.3	2.5	4.0	3.6	3.4	3.8	2.5	2.5	2.9	2.4	1.9	2.9
8:01- 9:00	3.5	2.6	4.6	4.4	4.0	4.0	3.0	3.1	3.7	3.0	2.0	3.1
9:01-10:00	3.6	2.9	5.5	4.7	4.1	4.1	3.2	3.5	4.1	3.5	2.3	3.3
10:01-11:00	3.8	3.5	5.7	4.9	4.5	4.1	3.7	3.8	4.3	3.9	2.7	3.6
11:01-12:00	4.4	3.6	5.5	5.1	5.0	4.4	3.7	4.2	4.6	4.2	3.3	3.8
12:01-13:00	4.5	3.9	5.7	5.3	4.6	4.5	3.7	4.1	4.8	4.3	3.3	4.1
13:01-14:00	4.7	3.8	5.8	5.0	4.6	4.4	4.0	4.2	4.6	3.9	3.5	3.8
14:01-15:00	4.4	3.7	5.7	5.1	5.0	4.3	4.0	4.3	4.5	3.7	3.4	3.5
15:01-16:00	4.2	3.8	5.4	5.0	5.0	4.4	4.2	4.3	4.5	3.5	2.6	3.2
16:01-17:00	4.2	3.5	5.2	5.1	4.7	4.4	3.9	3.9	4.3	3.3	2.0	3.0
17:01-18:00	4.3	3.0	4.4	4.7	4.4	4.2	3.3	3.4	3.8	2.8	2.3	2.9
18:01-19:00	4.2	3.1	3.9	4.1	4.0	3.6	3.0	2.8	3.6	2.6	2.3	3.2
19:01-20:00	4.2	2.8	3.8	3.3	3.4	3.2	2.6	2.5	3.2	2.6	2.1	3.1
20:01-21:00	3.9	2.9	3.7	3.2	2.9	2.7	2.5	2.4	3.1	2.5	2.1	3.0
21:01-22:00	3.7	2.6	3.6	2.9	2.8	2.4	2.0	2.1	2.9	2.4	2.2	2.9
22:01-23:00	3.6	2.6	3.5	2.7	2.6	2.3	1.8	2.2	2.8	2.3	2.1	3.1
23:01-24:00	3.6	2.5	3.5	2.7	2.4	2.0	1.6	1.8	2.8	2.1	1.9	3.1
Max Hour	14	13	14	13	15	13	16	16	13	13	14	13
Min Hour	6	4	24	3	2	24	1	4	5	1	6	2

Table A-10. Monthly statistics for solar radiation (direct normal, diffuse, global horizontal) (Wh/m²) **

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Direct Avg	1024	1222	1309	2785	3441	2730	3118	3203	2306	1775	928	527
Direct Max	**3685**	**5093**	**5861**	**7890**	**8645**	**8690**	**8255**	**7766**	**6904**	**5817**	**3911**	**2100**
Day	19	21	2	24	30	28	20	4	6	1	5	4
Diffuse Avg	**461**	**780**	**1492**	**1983**	**2680**	**2954**	**2885**	**2337**	**1732**	**1011**	**692**	**423**
Global Avg	**710**	**1194**	**2116**	**3637**	**4911**	**4906**	**5020**	**4351**	**2973**	**1748**	**969**	**549**

** Maximum Direct Normal Solar of 8690 Wh/m² on June 28

Table A-11. Average hourly statistics for direct normal solar radiation (Wh/m²)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0:01- 1:00	0	0	0	0	0	0	0	0	0	0	0	0
1:01- 2:00	0	0	0	0	0	0	0	0	0	0	0	0
2:01- 3:00	0	0	0	0	0	0	0	0	0	0	0	0
3:01- 4:00	0	0	0	0	0	0	0	0	0	0	0	0
4:01- 5:00	0	0	0	0	0	0	0	0	0	0	0	0
5:01- 6:00	0	0	0	3	60	31	40	5	0	0	0	0
6:01- 7:00	0	0	0	52	159	82	110	104	26	0	0	0
7:01- 8:00	0	0	34	138	225	129	182	177	120	64	5	0
8:01- 9:00	17	65	77	225	273	170	244	251	168	156	40	5
9:01-10:00	71	155	140	254	289	241	258	289	218	222	121	48
10:01-11:00	166	195	156	309	299	291	300	312	264	256	167	78
11:01-12:00	196	202	147	306	317	340	318	318	278	288	166	117
12:01-13:00	184	182	215	314	306	306	317	313	280	256	158	137
13:01-14:00	200	159	189	325	319	256	329	376	268	204	149	97
14:01-15:00	136	144	145	312	346	263	305	371	270	182	101	44
15:01-16:00	54	102	112	272	303	237	262	330	240	126	21	0
16:01-17:00	0	18	76	192	280	185	222	240	148	22	0	0
17:01-18:00	0	0	18	84	212	144	166	105	25	0	0	0
18:01-19:00	0	0	0	1	57	56	65	12	0	0	0	0
19:01-20:00	0	0	0	0	0	0	0	0	0	0	0	0
20:01-21:00	0	0	0	0	0	0	0	0	0	0	0	0
21:01-22:00	0	0	0	0	0	0	0	0	0	0	0	0
22:01-23:00	0	0	0	0	0	0	0	0	0	0	0	0
23:01-24:00	0	0	0	0	0	0	0	0	0	0	0	0
Max Hour	14	12	13	14	15	12	14	14	13	12	11	13
Min Hour	1	1	1	1	1	1	1	1	1	1	1	1

Table A-12. Average hourly statistics for diffuse horizontal solar radiation (Wh/m²)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0:01- 1:00	0	0	0	0	0	0	0	0	0	0	0	0
1:01- 2:00	0	0	0	0	0	0	0	0	0	0	0	0
2:01- 3:00	0	0	0	0	0	0	0	0	0	0	0	0
3:01- 4:00	0	0	0	0	0	0	0	0	0	0	0	0
4:01- 5:00	0	0	0	0	8	13	9	1	0	0	0	0
5:01- 6:00	0	0	0	12	48	57	48	19	2	0	0	0
6:01- 7:00	0	0	9	61	101	122	110	73	34	7	0	0
7:01- 8:00	0	6	53	117	166	186	159	127	92	47	9	0
8:01- 9:00	16	43	112	166	210	241	213	180	147	91	49	13
9:01-10:00	54	80	166	192	248	279	250	214	191	123	87	45
10:01-11:00	67	94	182	195	274	295	279	248	217	150	111	70
11:01-12:00	83	113	204	227	295	296	307	268	225	142	115	84
12:01-13:00	87	128	203	231	306	291	323	269	212	140	126	87
13:01-14:00	75	125	190	239	281	294	296	266	196	126	104	71
14:01-15:00	52	104	158	188	230	269	272	218	170	99	65	41
15:01-16:00	26	64	125	159	194	220	230	186	131	61	26	11
16:01-17:00	2	23	70	118	152	183	174	147	83	23	1	0
17:01-18:00	0	1	20	65	107	124	129	90	30	1	0	0
18:01-19:00	0	0	1	13	52	67	69	29	2	0	0	0
19:01-20:00	0	0	0	0	7	17	15	2	0	0	0	0
20:01-21:00	0	0	0	0	0	0	0	0	0	0	0	0
21:01-22:00	0	0	0	0	0	0	0	0	0	0	0	0
22:01-23:00	0	0	0	0	0	0	0	0	0	0	0	0
23:01-24:00	0	0	0	0	0	0	0	0	0	0	0	0
Max Hour	13	13	12	14	13	12	13	13	12	11	13	13
Min Hour	1	1	1	1	1	1	1	1	1	1	1	1

Table A-13. Average hourly statistics for global horizontal solar radiation (Wh/m²)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0:01- 1:00	0	0	0	0	0	0	0	0	0	0	0	0
1:01- 2:00	0	0	0	0	0	0	0	0	0	0	0	0
2:01- 3:00	0	0	0	0	0	0	0	0	0	0	0	0
3:01- 4:00	0	0	0	0	0	0	0	0	0	0	0	0
4:01- 5:00	0	0	0	0	8	13	9	1	0	0	0	0
5:01- 6:00	0	0	0	13	60	64	56	20	2	0	0	0
6:01- 7:00	0	0	9	72	155	153	148	99	38	7	0	0
7:01- 8:00	0	6	60	167	276	253	249	198	128	57	9	0
8:01- 9:00	17	53	135	279	381	352	366	317	221	137	57	13
9:01-10:00	65	121	225	349	460	462	440	405	312	212	119	54
10:01-11:00	108	164	263	411	516	539	523	479	383	272	167	89
11:01-12:00	140	195	289	453	564	594	580	518	412	290	173	116
12:01-13:00	142	204	331	464	565	560	596	518	400	269	180	124
13:01-14:00	128	187	296	467	537	510	567	549	365	218	148	94
14:01-15:00	78	151	229	381	480	471	503	469	318	165	87	48
15:01-16:00	31	87	167	296	379	378	400	373	234	93	28	11
16:01-17:00	2	25	89	189	286	282	290	251	125	26	1	0
17:01-18:00	0	1	22	84	176	180	192	120	34	1	0	0
18:01-19:00	0	0	1	14	62	80	84	31	2	0	0	0
19:01-20:00	0	0	0	0	7	17	15	2	0	0	0	0
20:01-21:00	0	0	0	0	0	0	0	0	0	0	0	0
21:01-22:00	0	0	0	0	0	0	0	0	0	0	0	0
22:01-23:00	0	0	0	0	0	0	0	0	0	0	0	0
23:01-24:00	0	0	0	0	0	0	0	0	0	0	0	0
Max Hour	13	13	13	14	13	12	13	14	12	12	13	13
Min Hour	1	1	1	1	1	1	1	1	1	1	1	1

Table A-14. Average hourly statistics for total sky cover (%)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0:01- 1:00	65	74	75	54	46	67	49	53	57	64	59	59
1:01- 2:00	66	75	77	61	51	63	49	55	55	65	59	64
2:01- 3:00	70	80	81	63	52	66	54	57	58	70	63	66
3:01- 4:00	66	77	85	63	55	72	58	56	56	70	67	67
4:01- 5:00	62	78	84	67	56	72	65	58	58	65	65	66
5:01- 6:00	62	78	87	68	63	79	71	63	70	61	70	67
6:01- 7:00	67	75	84	74	66	78	72	61	70	65	75	67
7:01- 8:00	67	76	82	74	68	77	72	65	71	68	77	74
8:01- 9:00	70	71	82	72	67	75	70	65	72	68	78	77
9:01-10:00	72	72	79	74	69	68	71	67	73	67	78	78
10:01-11:00	74	74	82	70	68	66	69	67	72	68	75	81
11:01-12:00	70	76	84	71	67	63	70	69	73	69	78	76
12:01-13:00	73	78	76	71	68	67	68	69	71	74	78	73
13:01-14:00	71	80	79	68	66	72	67	60	72	77	75	77
14:01-15:00	74	78	83	69	62	70	68	60	68	73	79	77
15:01-16:00	73	74	84	66	62	70	69	60	63	72	78	73
16:01-17:00	76	74	80	65	56	71	67	61	62	69	77	70
17:01-18:00	77	74	78	66	51	68	64	67	64	74	72	66
18:01-19:00	69	69	83	62	47	69	64	65	60	67	70	66
19:01-20:00	71	68	77	61	45	65	62	57	58	63	66	66
20:01-21:00	69	66	75	62	43	67	60	56	57	62	70	65
21:01-22:00	70	64	74	55	41	67	51	53	58	65	73	64
22:01-23:00	75	73	70	55	47	64	47	52	55	69	68	61
23:01-24:00	74	75	70	54	43	62	47	54	58	64	62	60
Max Hour	18	3	6	8	10	6	8	13	10	14	15	11
Min Hour	6	22	23	24	22	24	23	23	2	6	1	1

Table A-15. Weather data for London weather centre area (Latitude = 51.5°, Longitude = 0.09°), generated from Meteonorm Version 6.10.23

METEONORM Version 6.1.0.23

Name of site = LONDON UK

Latitude [°] = 51.500, Longitude [°] = 0.090, Altitude [m] = 36, Climatic zone = III, 2

Radiation model = Default (hour); Temperature model = Default (hour)

Temperature: New period = 1996-2005

Radiation: New period = 1981-2000

Nearest 3 stations: Gh: London Weather C. (14 km), Kew (28 km), Hoddesdon (32 km)

Nearest 3 stations: Ta: London Weather C. (14 km), GRAVESEND BROADNES (15 km), NORTHOLT RAF (35 km)

Month	G_Gh	G_Bn	G_Dh	Lg	Ld	N
	[W/m2]	[W/m2]	[W/m2]	[W/m2]	[W/m2]	[octas]
Jan	27	36	19	2875	2239	7
Feb	50	62	28	5304	3387	6
Mar	92	79	57	9858	6685	6
Apr	142	109	81	15403	9723	6
May	184	125	111	20136	13278	6
Jun	202	149	114	22248	13864	5
Jul	191	138	107	21195	13340	6
Aug	166	142	87	18401	10982	5
Sep	120	103	69	13331	8527	6
Oct	70	82	40	7742	4991	6
Nov	35	49	22	3905	2869	6
Dec	21	32	13	2235	1710	7
Year	108	92	62	11886	7633	6
Month	Ta	Td	RH	p	DD	FF
Month	[C]	[C]	[%]	[hPa]	[deg]	[m/s]
Jan	5.8	2.7	81	1009	246	4.4
Feb	6.3	2.2	75	1009	79	4.6
Mar	8.2	3.4	71	1009	246	4.0
Apr	10.2	4.2	66	1009	24	3.8
May	13.6	7.2	65	1009	35	3.9
Jun	16.9	10.0	64	1009	246	3.6
Jul	18.4	11.8	65	1009	267	3.4
Aug	18.9	12.6	67	1009	225	3.1
Sep	15.9	10.8	71	1009	246	3.4
Oct	12.3	8.1	75	1009	246	3.9
Nov	8.5	5.2	80	1009	225	3.6
Dec	6.1	3.0	81	1009	246	4.0
Year	11.8	6.8	72	1009	252	3.8

Legend:
Gh: Mean irradiance of global radiation horizontal
Bn: Irradiance of beam
Dh: Mean irradiance of diffuse radiation horizontal

N: Cloud cover fraction
Lg: Global luminance
Ta: Air temperature RH: Relative humidity
Td: Dewpoint temperature DD: Wind direction
FF: Wind speed p: Air pressure

Table A-16. Weather data for London Gatwick area (Latitude = 51.15°, Longitude = -0.18°), generated from Meteonorm Version 6.10.23

METEONORM Version 6.1.0.23

Name of site = Gatwick UK

Latitude [°] = 51.150, Longitude [°] = -0.180, Altitude [m] = 36, Climatic zone = III, 2

Radiation model = Default (hour); Temperature model = Default (hour)

Temperature: New period = 1996-2005

Radiation: New period = 1981-2000

Nearest 3 stations: Gh: London-Gatwick/Crawl (0 km), Crawley, Great Bri (8 km), Kew (37 km)

Nearest 3 stations: Ta: London-Gatwick/Crawl (0 km), SHOREHAM-BY-SEA (36 km), London Weather C. (41 km)

Month	G_Gh	G_Bn	G_Dh	Lg	Ld	N
	[W/m2]	[W/m2]	[W/m2]	[W/m2]	[W/m2]	[octas]
Jan	29	48	18	3092	2195	6
Feb	57	56	38	6085	4474	6
Mar	92	76	59	9900	6834	6
Apr	156	141	77	16830	9397	5
May	193	141	108	21112	13108	6
Jun	202	147	112	22245	14008	6
Jul	209	166	108	23038	13564	5
Aug	176	150	91	19455	11483	5
Sep	121	98	73	13430	9146	6
Oct	71	69	45	7895	5632	6
Nov	38	44	26	4218	3283	6
Dec	22	29	16	2417	1946	7
Year	114	97	64	12476	7922	6
Month	Ta	Td	RH	p	DD	FF
Month	[C]	[C]	[%]	[hPa]	[deg]	[m/s]
Jan	5.2	3.0	86	1009	225	3.9
Feb	5.5	2.5	81	1009	225	4.0
Mar	7.2	3.7	78	1009	225	3.3
Apr	9.1	4.7	74	1009	45	3.3
May	12.5	7.8	73	1009	225	3.4
Jun	15.6	10.5	72	1009	225	3.0
Jul	17.2	12.3	73	1009	225	2.9
Aug	17.7	13.0	74	1009	225	2.5
Sep	14.9	11.0	77	1009	225	2.8
Oct	11.3	8.4	82	1009	225	3.4
Nov	7.6	5.5	86	1009	225	3.1
Dec	5.4	3.2	86	1009	225	3.5
Year	10.8	7.1	79	1009	225	3.3

Legend:
Gh: Mean irradiance of global radiation horizontal
Bn: Irradiance of beam
Dh: Mean irradiance of diffuse radiation horizontal

N: Cloud cover fraction
Lg: Global luminance
Ta: Air temperature RH: Relative humidity
Td: Dewpoint temperature DD: Wind direction
FF: Wind speed p: Air pressure

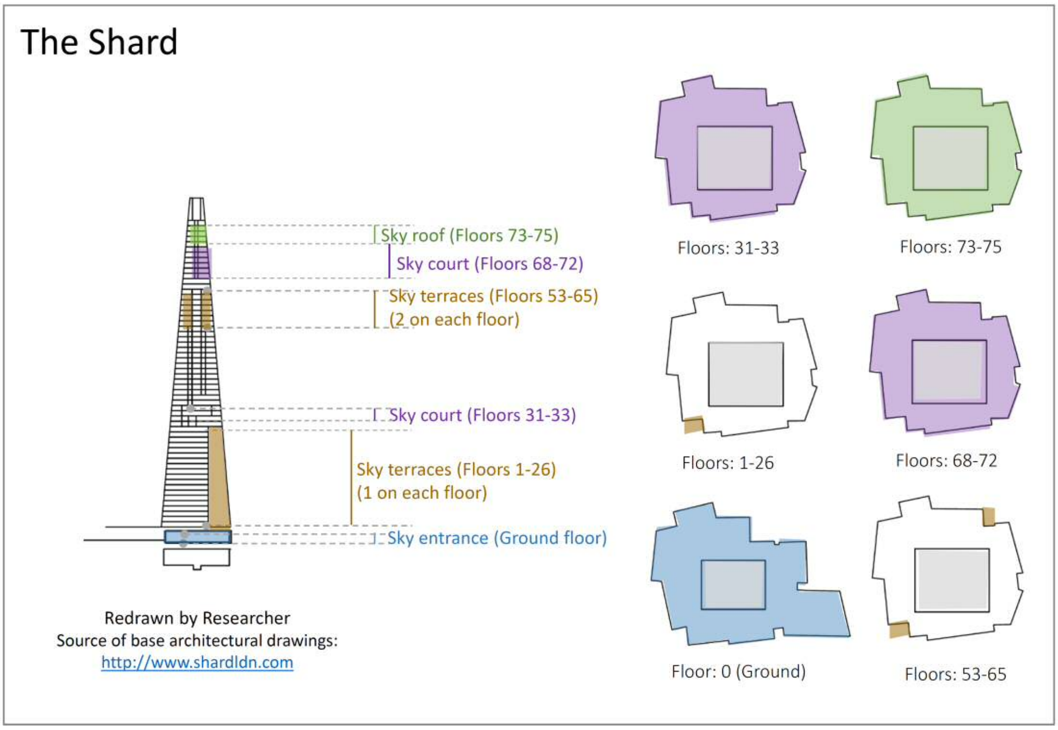
Appendix B: Extracting Prototypes of Skycourts

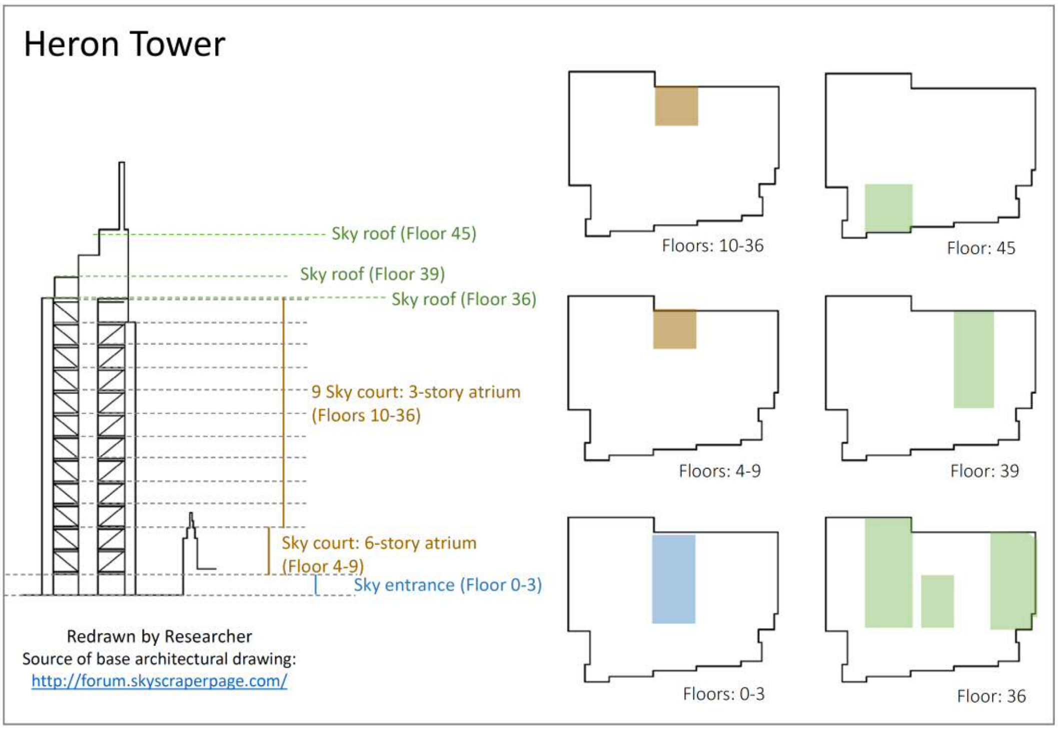
Table B-1. Examples of high-rise office buildings with skycourts, located in London

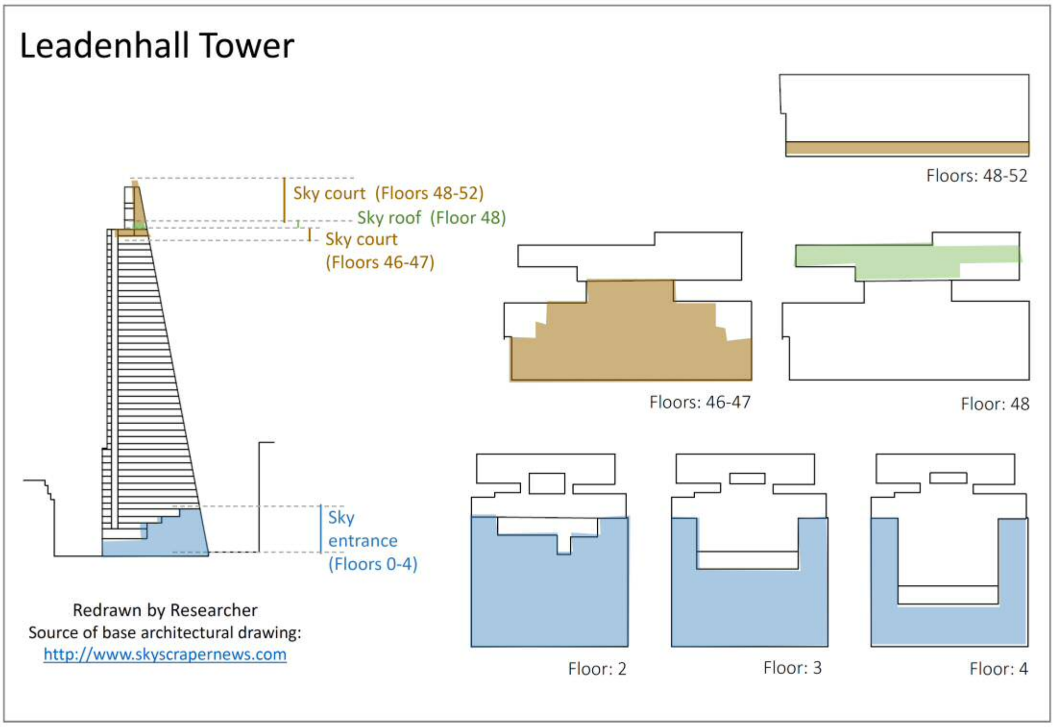
Building Name	**The Shard** (London Bridge Tower)	**Heron Tower** (110 Bishopgate)	**The Leadenhall Building** (The Cheese grater)	**30 St. Mary Axe** ''Gherkin / Swiss Re''	**The Broadgate Tower**	**20 Fenchurch Street** London's sky arden, Walkie talkie	**51 Lime Street** (Willis Building)	**The Lloyds Building** (One lime street)	**Rothschild Bank Headquarters** (New Court)	**6 Bevis Marks**	**10 Brock Street** (Regent's Place)
Building photo											
Completion Year	2012	2011	2014	2004	2008	2014	2007	1986	2011	2014	2013
Use	Mixed: Residential/ Hotel/Office	Offices	Offices	Offices	Offices	Mixed (Offices/Retail)	Offices	Offices	Offices	Offices	Offices
Architect	Renzo Piano Building Workshop	Kohn Pedersen Fox	Rogers Strick Harbour & partners	Foster + partners	Skidmore, Owings & Merril (SOM)	Rafael Vinoly Architects PC	Foster + Partners	Richard Rogers Partnership	Office for Metropolitan Architecture	Fletcher Priest Architects	Wilkinson Eyre Architects

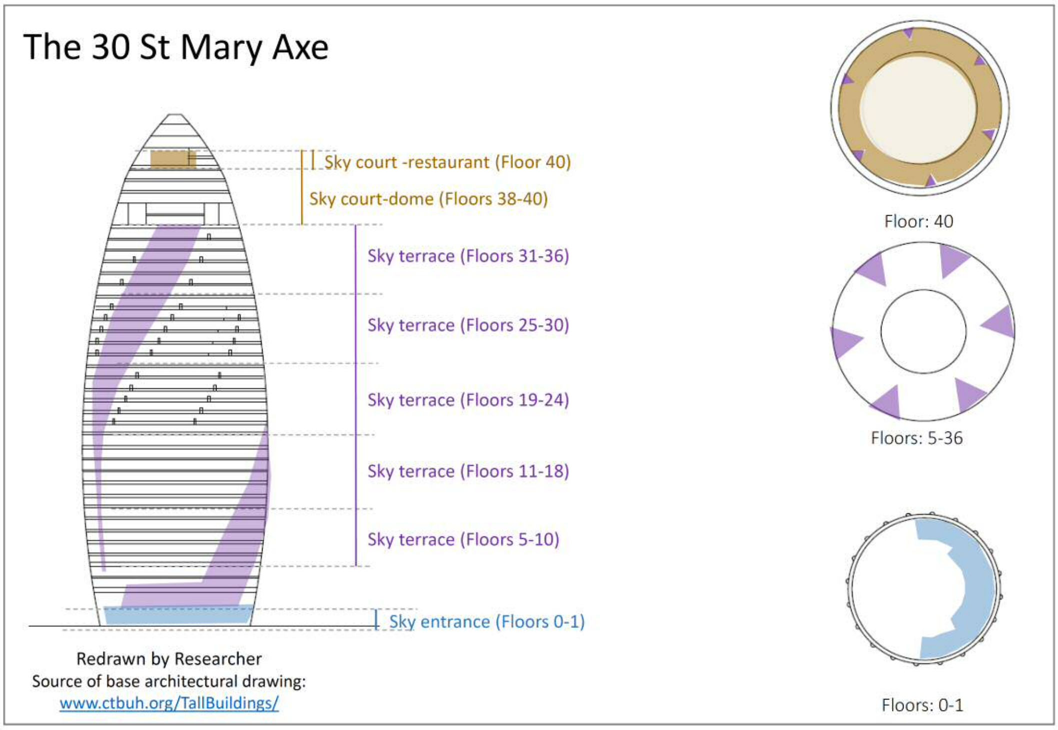
Building Name	**The Shard** (London Bridge Tower)	**Heron Tower** (110 Bishopgate)	**The Leadenhall Building** (The Cheese grater)	**30 St. Mary Axe** "Gherkin / Swiss Re"	**The Broadgate Tower**	**20 Fenchurch Street** London's sky arden, Walkie talkie	**51 Lime Street** (Willis Building)	**The Lloyds Building** (One lime street)	**Rothschild Bank Headquarters** (New Court)	**6 Bevis Marks**	**10 Brock Street** (Regent's Place)
Awards / Rating	Winner- CTBUH Best Tall Building Europe /2013	Finalist- CTBUH Best Tall Building Europe /2011 BREEAM Excellent	BREEAM Excellent Home City of London Prize/2015	.Winner- CTBUH 10 Year Award /2013 .the Stirling prize, UK, Royal Institute of British Architects/2004	Winner- CTBUH Best Tall Building Europe /2009	Nominee- CTBUH Best Tall Building Europe /2015 BREEAM Excellent	Winner- CTBUH Best Tall Building Europe /2008 BREEAM Excellent			Nominee- CTBUH Best Tall Building Europe /2014 BREEAM Excellent	Nominee- CTBUH Best Tall Building Europe /2013
Height (m)	309.6 m	230 m	224m	180 m	165 m	177 m	124.8 m	95.1 m	75.4 m	74 m	72 m
No. Floors	75	46	52	42	35	38	28	14	16	17	16
Area (sq m)	111000 sq m	42873 sq m	56000 sq m	64470 sq m	37000 sq m	64100 sq m	44128 sq m			20700 sq m	49239 sq m

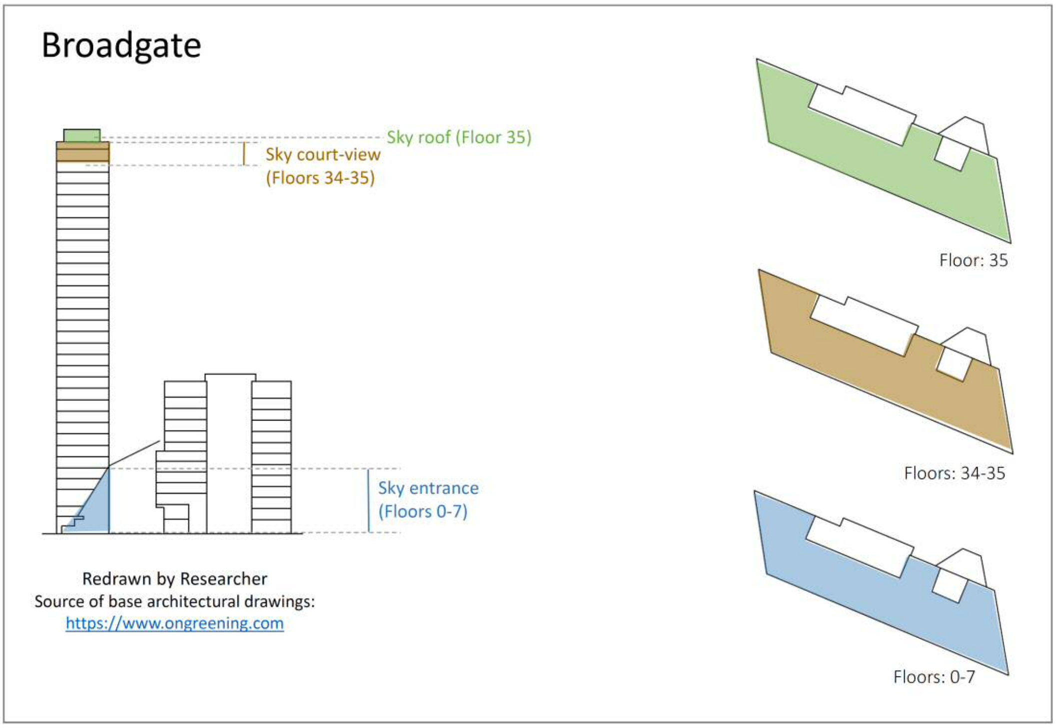
Figure B-1. Skycourts in the selected high-rise office buildings located in London

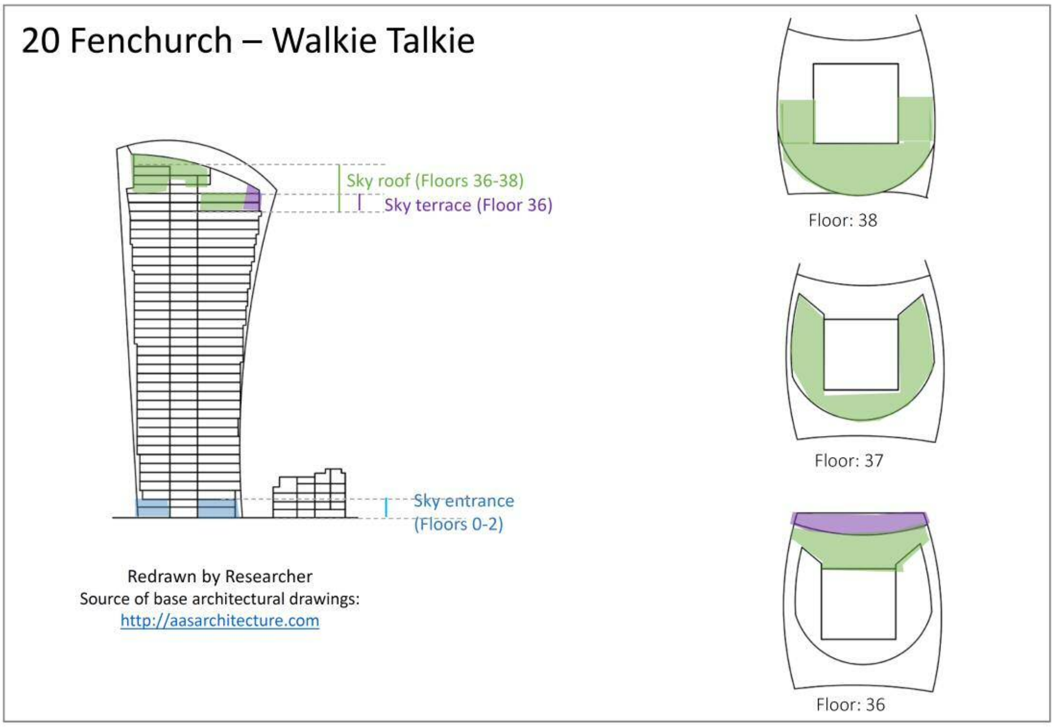




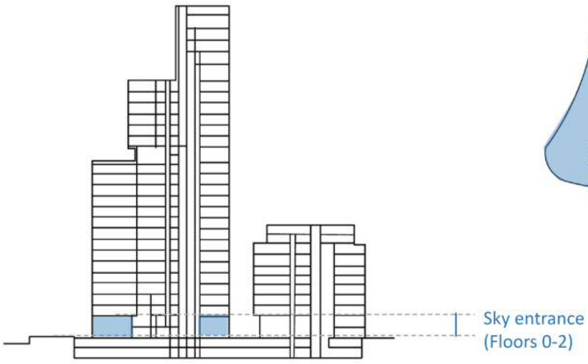

Leadenhall Tower
Sky court (Floors 48-52)
Sky roof (Floor 48)
Sky court
(Floors 46-47)
Sky
entrance
(Floors 0-4)
Floors: 48-52
Floors: 46-47
Floor: 48
Floor: 2
Floor: 3
Floor: 4
Redrawn by Researcher
Source of base architectural drawing:
http://www.skyscrapernews.com

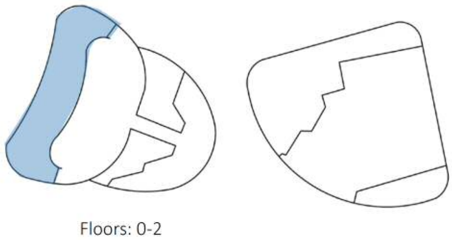

The 30 St Mary Axe
Sky court -restaurant (Floor 40)
Sky court-dome (Floors 38-40)
Sky terrace (Floors 31-36)
Sky terrace (Floors 25-30)
Sky terrace (Floors 19-24)
Sky terrace (Floors 11-18)
Sky terrace (Floors 5-10)
Sky entrance (Floors 0-1)
Floor: 40
Floors: 5-36
Floors: 0-1
Redrawn by Researcher
Source of base architectural drawing:
www.ctbuh.org/TallBuildings/


Broadgate
Sky roof (Floor 35)
Sky court-view
(Floors 34-35)
Sky entrance
(Floors 0-7)
Redrawn by Researcher
Source of base architectural drawings:
https://www.ongreening.com
Floor: 35
Floors: 34-35
Floors: 0-7


20 Fenchurch – Walkie Talkie
Sky roof (Floors 36-38)
Sky terrace (Floor 36)
Sky entrance
(Floors 0-2)
Redrawn by Researcher
Source of base architectural drawings:
http://aasarchitecture.com
Floor: 38
Floor: 37
Floor: 36

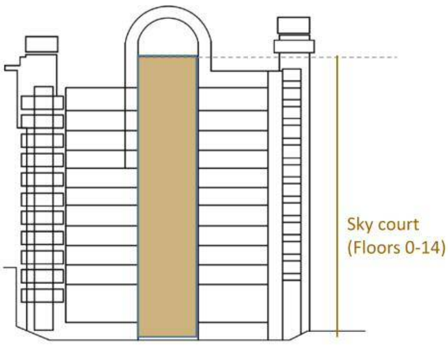
51 Lime Street



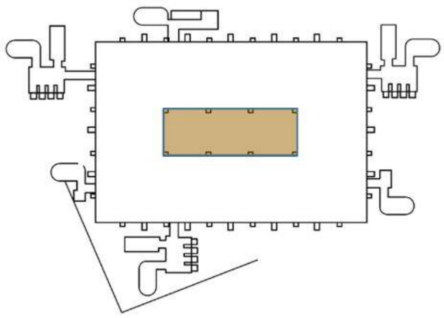


Redrawn by Researcher
Source of base architectural drawings:
https://www.fosterandpartners.com

The Lloyds Building

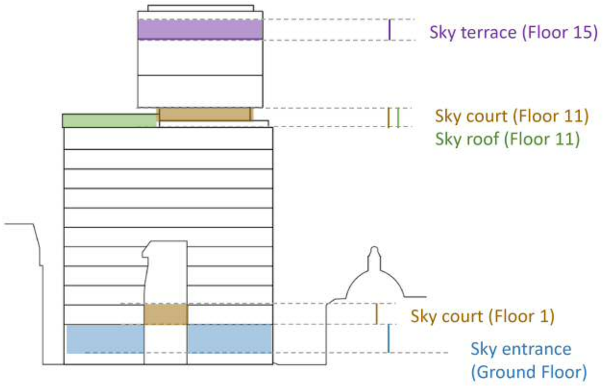


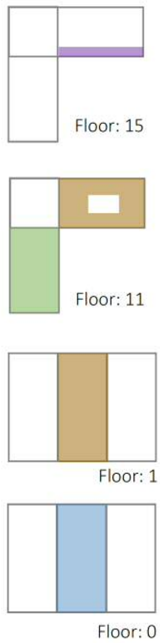
Redrawn by Researcher
Source of base architectural drawing:
https://www.thoughtco.com/



Redrawn by Researcher
Source of base architectural drawing:
https://www.designingbuildings.co.uk

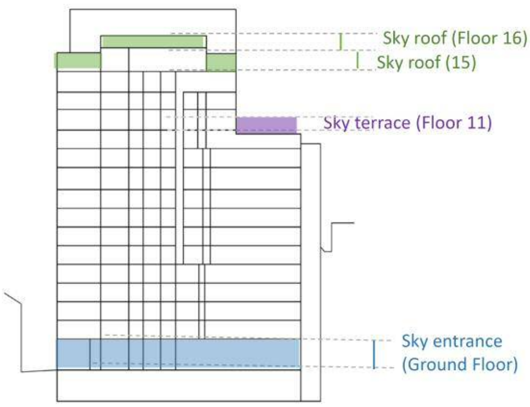
Rothschild Bank

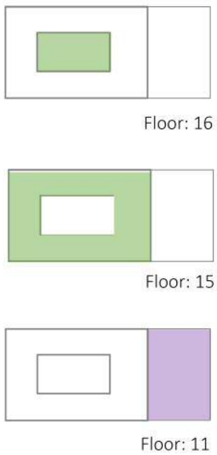




Redrawn by Researcher
Source of base architectural drawing:
https://www.bdonline.co.uk/

6 Bevis Marks





Redrawn by Researcher
Source of base architectural drawing:
https://www.steelconstruction.info/6_Bevis_Marks,_London

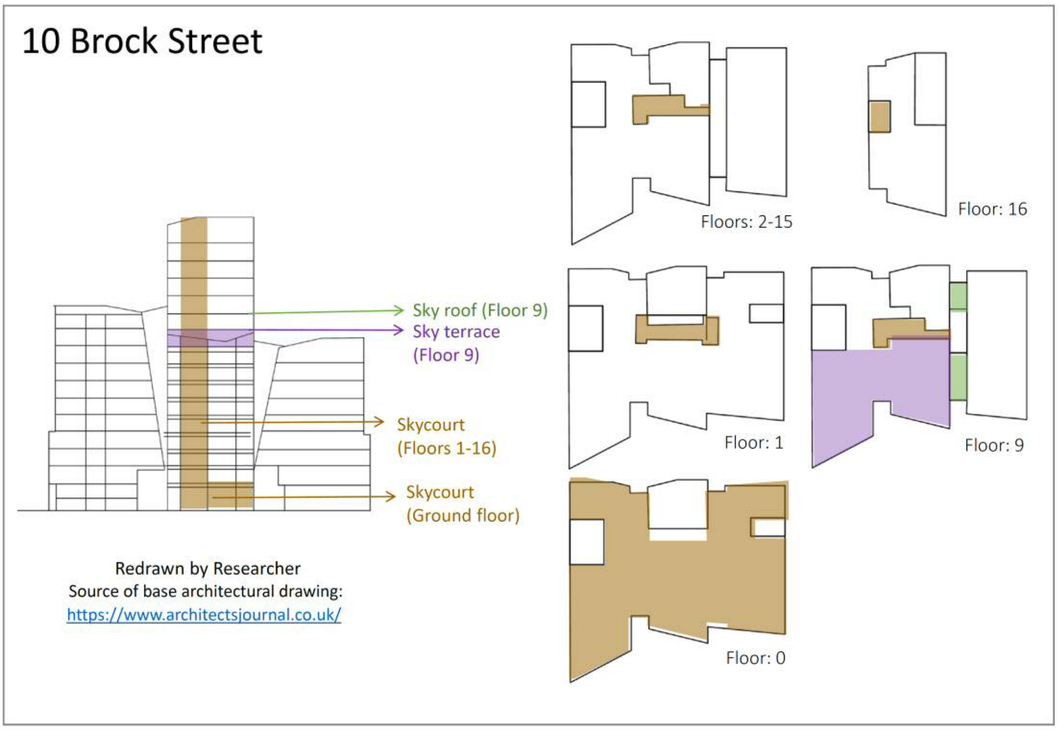
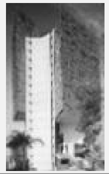

10 Brock Street
Sky roof (Floor 9)
Sky terrace
(Floor 9)
Skycourt
(Floors 1-16)
Skycourt
(Ground floor)
Redrawn by Researcher
Source of base architectural drawing:
https://www.architectsjournal.co.uk/
Floors: 2-15
Floor: 16
Floor: 1
Floor: 9
Floor: 0

Table B-2. Examples of high-rise office buildings with skycourt

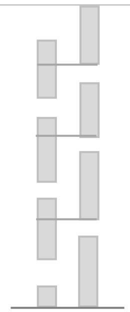
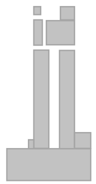
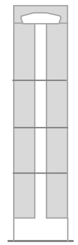
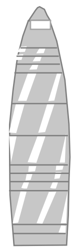
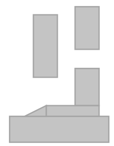
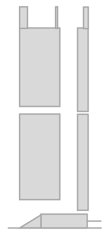
Building	**Commerzbank,** Frankfurt, Germany	**Liberty tower of Meiji university,** Tokyo, Japan	**Post tower,** Bonn, Germany	**30 St. Mary Axe** ''Gherkin / Swiss Re''	**Torre Cube,** Guadalajara, Mexico	**1 Bligh street**, Sydney, Australia
						
Completion Year	1997	1998	2002	2004	2005	2011
Use	Offices	Educational	Offices	Offices	Offices	Offices
Architect	Foster + partners	Nikken Sekkei Ltd.	Murphy/Jahn Architects	Foster + partners	Estudio Carme Pinos	Ingenhoven architects
Height (m)	259	119	163	180 m	60 m	139 m
No. of Floors	56	23	42	42	17	30
Gross Area (sq m)	85500 m^2	53068 m^2	65323 m^2	64470 m^2	17000 m^2	55000 m^2
Plan Depth	16.5 m (from central void)	20 m (from core)	12 m (from central void)	6.4-13.1 m (from central core)	9-12 m (from central void)	23.5 m (from void)
Design strategies	- Double-skin façade - Stepping sky gardens connected to segmented central atrium - Small aerofoil sections above/below ventilation slots in facade	- Ventilation ''wind core'' (central escalator void) - ''Wind floor'' = sky garden floor over central void - Innovative window openings in lecture rooms	- Double-skin façade - Full height central atrium divided into 9-storey sky gardens - Wing wall - Aerodynamic external form	- Double-skin façade - Stepping atria which tempers air before being distributed to offices	- Rain screen/brise-soleil façade - Central (open) atrium - Sky gardens - Funnel-shaped office spaces	- Naturally ventilated atrium, lobby and break-out areas

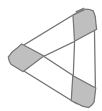
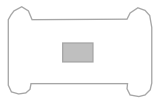
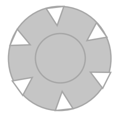
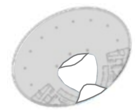
Building	**Commerzbank,** Frankfurt, Germany	**Liberty tower of Meiji university,** Tokyo, Japan	**Post tower,** Bonn, Germany	**30 St. Mary Axe** ''Gherkin / Swiss Re''	**Torre Cube,** Guadalajara, Mexico	**1 Bligh street**, Sydney, Australia
Internal spaces strategy	Connected internal spaces	Connected internal spaces	Connected internal spaces	Connected internal spaces	Connected internal spaces	Isolated internal spaces (only in atrium, lobby, break-out areas)
Ventilation Type	Mixed-mode Complementary-changeover	Mixed-mode Complementary-changeover	Mixed-mode: zoned / Complementary-changeover -skycourt :fully naturally ventilated -conference & meeting rooms: mechanically -offices: natural & mechanical	Mixed-mode Complementary-Concurrent	Natural ventilation (no mechanical)	Mixed-mode : zoned
Natural Ventilation Driving Force (stack, cross, both)	Cross and stack ventilation	Cross and stack ventilation	Cross and stack ventilation	Cross and stack ventilation	Cross and stack ventilation)	- Cross and stack ventilation (only in atrium, lobby, break-out areas) - Office spaces can be upgraded to natural ventilation
Control of Openings	Automatically & Manually (occupants)	Automatically controlled	Automatically & Manually (occupants)	Automatically & Manually (occupants)	Manually (occupants)	Not applicable
Night-time Ventilation	Yes	Yes	Yes	None	None	None
Percentage of Annual Usage of Natural Ventilation	80%	29%		40%	100%	100% (only in atrium, lobby and sky garden areas)
Percentage of Annual Energy Saving for Heating & Cooling	63%	55%	79%	20%	100%	63%
Typical Annual Energy Consumption for Heating & Cooling	117 kWh/m^2	166 kWh/m^2	75 kWh/m^2	-	0 kWh/m^2	-

Table B-3. Comparative analysis of skycourt in selected high-rise office buildings

Skycourt Characteristics		**Commerzbank,** Frankfurt, Germany	**Liberty tower of Meiji university,** Tokyo, Japan	**Post tower,** Bonn, Germany	**30 St. Mary Axe,** London, UK	**Torre Cube,** Guadalajara, Mexico	**1 Bligh street**, Sydney, Austria
Description	Description of Skycourt	- three 4-storey stepped sky gardens at each segment	- wind floor (one 1-storey sky garden at floor no.18 with openings on the four sides and three V-shaped glass screens (wind fences) to prevent outdoor air from disrupting	- three 9-storey sky garden at each segment and one 11-storey sky gardens at the upper segment	- three 2-storey sky gardens , stepped, spiraling - four 6-storey sky gardens, stepped, spiraling	- one 4-storey - two 3-storey stepped sky gardens	- one 1-storey sky garden floor at floor no. 15/ mid-height of the atrium - one 10m height at the top
	Total number	12	1	4	7	3	2
Type /style	Sky-roof/garden						1 (top floor/ 10m
	Sky- terrace/balcony				7 (stepped 5° respect to the one below) 6 fingers each floor		
	Sky-court/floor	3 each village/segment	1	Three 9-storey & one 11-sorey		1 each office wing (3 wings)	1 (floor no. 15)
	Sky-entrance						
Location	Level (Floor No.)		Floor 18	(1-9), (10-18) (19-27), (28-38)	(1-6), (7-8), (9-10), (11-12), (13-18), (19-24), (25-30)	(1-4), (5-7), (8-10)	Floor (30) Floor (15)
	Orientation	3 eastwards, 3 southwards, 3 westwards	Long axis: southeast	East-west	Rotated clockwise along with the prevailing southwest wind	1 each wing – irrespective	Long axis: southwest & northeast
Function	Social space	√ yes		√ yes	√ yes	√ yes	√ yes
	Psycho-physiological/well-being (thermal comfort+ visual) enhancer	√ yes					
	Transitional space	√ yes	√ yes	√ yes	√ yes	√ yes	√ yes
	Environmental filter (greenery)	√ yes					
	Bio-diversity enhancer						
	Passive design element (means for reducing the energy consumption)	√ yes	√ yes	√ yes	√ yes	√ yes	√ yes
	Productivity enhancer	√ yes					

Skycourt Characteristics		**Commerzbank,** Frankfurt, Germany	**Liberty tower of Meiji university,** Tokyo, Japan	**Post tower,** Bonn, Germany	**30 St. Mary Axe,** London, UK	**Torre Cube,** Guadalajara, Mexico	**1 Bligh street**, Sydney, Austria
Spatial Morphology	Infill space			√ yes			
	Stepped terrace space	√ yes			√ yes		
	Interstitial space		√ yes				
	Hollowed-out space	√ yes			√ yes	√ yes	√ yes
Environmental Benefits	used for air intake, air extraction or combination of the two	√ (Both air intake & exhaust)	√ (Both air intake & exhaust)	√ (Both air intake & exhaust)	√ yes (Both air intake & exhaust)	√ (only air intake)	√ (only air intake)
	used to induce ventilation in inward facing offices	√ yes			√ yes		
	Stack ventilation			√ yes			
	Lighting	Daylight (atrium & skycourts)	Daylight (atrium & skycourts)	Daylight (atrium & skycourts)	Daylight (skycourts)	Daylight (atrium & skycourts)	Daylight (atrium)
	Acoustics	.double skin facade provide acoustical insulation					
	Thermal buffer zone, to mediate temperature between exterior and interior	√ yes			√ yes	√ yes	√ yes
Geometry	Shape	Semi-triangular	Rectangular	Rectangular with curvilinear ends of the long axis	Triangular (allow for rectangular offices in between)	Semi triangular (open to air and to atrium)	Elliptical Long axis: southwest & northwest
	Form	Open-sided (two-sided)	Open (four-sided)	open-sided (Linear)	Open-sided (two-sided)	Open-sided (two-sided)	open-sided (Linear)
	Central/sided	Sided	Central	Sided Linear	Sided	Sided	Sided Linear
	Open/closed (enclosure 1,2 or 3 walls)	2 walls closed /open to the atrium and external façade (operable windows)	Core/centralised /Open from 4 sides	2 walls closed/ open from two sides (operable windows)	2 walls closed/ open from external façade (operable windows)	2 walls closed/ open from external façade and to the atrium	Centralised/ open from perimeter (operable windows)

	Skycourt Characteristics		**Commerzbank,** Frankfurt, Germany	**Liberty tower of Meiji university,** Tokyo, Japan	**Post tower,** Bonn, Germany	**30 St. Mary Axe,** London, UK	**Torre Cube,** Guadalajara, Mexico	**1 Bligh street**, Sydney, Austria
Geometry	Dimensions	Depth (D) m	16.5 m		7.2 m			
		Length (L) m			64.8 m			
		Height (H) m (floor to ceiling)	Twelve 4-storey 14m	One floor	Three 9-storeys One 11-storeys	Three 2-storeys Four 6-storeys	One bottom 4-storeys Two top 3-storeys	The top: 10 m The mid: 1-storey
	Section analysis	Void / Solid						

Skycourt Characteristics		**Commerzbank,** Frankfurt, Germany	**Liberty tower of Meiji university,** Tokyo, Japan	**Post tower,** Bonn, Germany	**30 St. Mary Axe,** London, UK	**Torre Cube,** Guadalajara, Mexico	**1 Bligh street**, Sydney, Austria
Supported features	Aerodynamic building form and elements	√ Yes Triangular  - Equilateral 60 m, convex sides, rounded corners - Corners used for elevators and services - Two sides of the plan for offices, one side for skygarden	X No Rectangular with four semi-cylindrical structures at each corner  - Wind core floors (1-17): this is a void space for escalators, enhances natural ventilation by stack-effect	√ Yes Two offsets elliptical segments separated by atrium, connected internally by bridges (aerodynamic)  - Two wing walls: at the east of north façade & at west of south façade - These enhance cross ventilation by creating pressure differential at each façade	√ Yes Cylindrical , aerodynamic curved  - This enhances natural ventilation by increasing wind velocity and pressure differences between windward and leeward sides)	√ Yes Three funnel-shaped timber-clad offices wings cantilevered & form three concrete cores 	√ Yes Elliptical building 

	Skycourt Characteristics	**Commerzbank,** Frankfurt, Germany	**Liberty tower of Meiji university,** Tokyo, Japan	**Post tower,** Bonn, Germany	**30 St. Mary Axe,** London, UK	**Torre Cube,** Guadalajara, Mexico	**1 Bligh street**, Sydney, Austria
	Use of vertical Segmentation and Function	Yes - Four 12-storey segmentation Function: .for fire security as a smoke barrier. .encourages fresh air by supporting shorter air circulation	No - The building is divided into two parts divided by the wind floor (no.17): the upper 6 floors and the lower 16 floors and the	Yes - Three 9-storey segmentations for the lower floors - One 11-storey the upper segmentation Function: .prevent extreme stack effect that cause draft & high pressure	Yes - Four 6-storey segmentation - Three 2-storey segmentation Function: - Prevent extreme stack effect - Allow for fire compartmentalized zone	No	No
	Use of Atrium and Function	Yes - Central atrium /segmented /full height of the tower separated by skylight (steel and glass diaphragms) every 12 floors Function: - Enhance visual communication and daylight - Enhance natural ventilation by stack effect	Yes - Central escalator core (core)/not segmented - Floors (1-17) .atrium not segmented - Floors (19-23) Function: - Natural light - Enhance natural ventilation by stack effect - Exhaust warm air through openings at the top of atrium	- No atrium - Skycourt height as an atrium Function: - Enhance natural ventilation by stack effect - Add fresh air through low-level vents to assist the natural flow - Exhaust warm air through operable windows at the top of skycourt façade	- No atrium	Yes - Central atrium/not segmented/full height of the tower (60m) Function: - Natural light - Enhance natural ventilation by stack effect - Exhaust warm air as it completely open at top - Connected to exterior sides by skygardens	Yes - Central atrium/not segmented/full height of the tower (120m) Function: - Enhance natural ventilation by stack effect - Exhaust air at the top through openings in the glass roof - Enhance visual communication and daylight - Vertical circulation
	Use of Landscape greenery feature	Yes	No	No	No	No	Yes

Skycourt Characteristics		Commerzbank, Frankfurt, Germany	Liberty tower of Meiji university, Tokyo, Japan	Post tower, Bonn, Germany	30 St. Mary Axe, London, UK	Torre Cube, Guadalajara, Mexico	1 Bligh street, Sydney, Austria
Façade /thermal mass		Yes /double-skin facade - Cavity depth = 200 mm - Horizontal continuity = 1.5 m - Vertical continuity = 2.4 m	No	Yes /double-skin facade - Cavity depth = 1.7 m (south façade), 1.2 m (north façade) - Horizontal continuity: fully continuous - Vertical continuity = 32 m (height of sky gardens)	Yes /double-skin facade - Cavity depth = 1-1.4 m - Horizontal continuity = varies (between diagonal structural frame members) - Vertical continuity = 4.15 m (floor-to-floor)	No	Yes /double-skin facade - Cavity depth = 600 mm - Horizontal continuity = fully continuous (around entire perimeter) - Vertical continuity = 3.85 m (floor-to-floor)
Use of Shading techniques		- Skycourt recessed				√ (Wooden brise-soleil)	
Use of Solar chimney		No	No	Yes – Skycourt	No	No	No
Use of Wind tower		No	No	No	No	No	No
Use of Night ventilation		√ yes	√ yes	√ yes	No	No	No
Offices' layout	Cellular plan	√ yes	√ yes	√ yes			
	Open plan					√ yes	√ yes
	Combination				√ yes		

<table>
<tr><th>Skycourt Characteristics</th><th>Commerzbank, Frankfurt, Germany</th><th>Liberty tower of Meiji university, Tokyo, Japan</th><th>Post tower, Bonn, Germany</th><th>30 St. Mary Axe, London, UK</th><th>Torre Cube, Guadalajara, Mexico</th><th>1 Bligh street, Sydney, Austria</th></tr>
<tr>
<td>Building Management System (BMS)</td>
<td>√ yes
<u>Principles:</u>
- Control of internal climate
- Determine level of control occupants have
<table>
<tr><td></td><td>Mechanical</td><td>Natural</td></tr>
<tr><td>C °</td><td>.external: <26 C °</td><td>.internal/ summer: <26 C °</td></tr>
<tr><td></td><td>Internal: > 18 C °</td><td>.internal/ winter: >17 C °</td></tr>
<tr><td>m/s</td><td>>15 m/s</td><td><15 m/s</td></tr>
</table></td>
<td>√ yes
<u>Principles</u>:
- Natural ventilation during shoulder seasons (autumn & spring)
<table>
<tr><td></td><td>Natural</td></tr>
<tr><td>C °</td><td>external/day: 15 - 22 C °</td></tr>
<tr><td></td><td>External/night 20 - 24 C °</td></tr>
<tr><td>m /s</td><td><10 m/s</td></tr>
</table></td>
<td>√ yes
<u>Principles:</u>
- Control of vents of outer façade
- Control radiation of concrete slab
- Control sun-shade in double skin
- It keeps temperature:
- at offices (22 C° summer & 26 C° winter)
- at skycourt (18 C° summer & 28 C° winter)</td>
<td>√ yes
<u>Principles</u>:
- Operation of openings of blinds in façade cavity:
- Closed
- One-third open
- Two-third open
- Horizontal
- Blinds/sun angle:
- Cut direct sun angle above 22° & eliminate 85% of solar heat gain & admit 50% of natural light
<table>
<tr><td></td><td>Mechanical</td><td>Natural</td></tr>
<tr><td>C °</td><td>.external: >28 C ° <5 C °</td><td>.external: 5 - 28 C °</td></tr>
<tr><td></td><td>Internal: > 24 C °</td><td>Internal: 20 - 24 C °</td></tr>
<tr><td>RH</td><td>>60%</td><td><60%</td></tr>
<tr><td>m/s</td><td>>10 m/s</td><td><10 m/s</td></tr>
</table></td>
<td>X No</td>
<td>X No</td>
</tr>
</table>

Skycourt Characteristics		Commerzbank, Frankfurt, Germany	Liberty tower of Meiji university, Tokyo, Japan	Post tower, Bonn, Germany	30 St. Mary Axe, London, UK	Torre Cube, Guadalajara, Mexico	1 Bligh street, Sydney, Austria
Considerations (problems)		- Orientation of the building should be toward prevailing wind - The bottom-hung windows in the outward-facing offices may not be sufficient to enter air to offices - The area occupied by atria and sky gardens is not economically efficient - Atrium height (12 floors) is too much	- Attention to use wind floor & wind core together may cause high airflow rate	- 9-storey sky garden is too much, it is better to be less height	- Combination of central core & spiralling atria is not spatially efficient economically - This building is 63% net-to-gross floor area - When building does not use natural ventilation, the lost floor area serves less purpose - No operable windows in offices spaces/ it is good to give occupants some control	- Problem of control - The 3-storey sky gardens within offices' wings may reduce the effectiveness of the central atrium as an exhaust device (stack-effect)	- For temperate climate, there should be natural ventilation in more spaces

Appendix C: Simulation Files

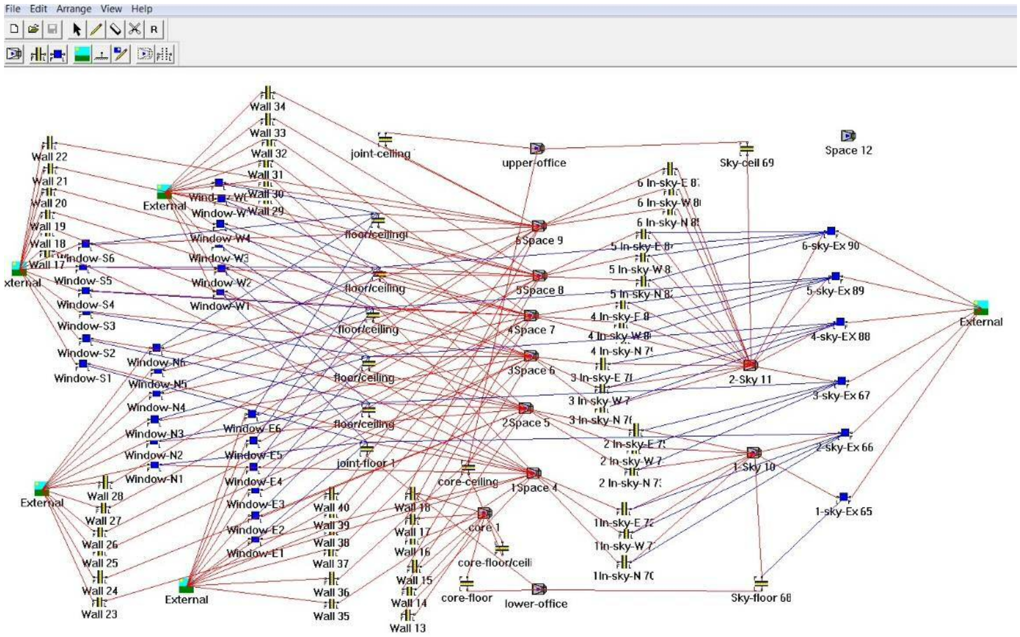


Figure C-1. Schematic model sample for building-skycourt prototype (A) in HTB2

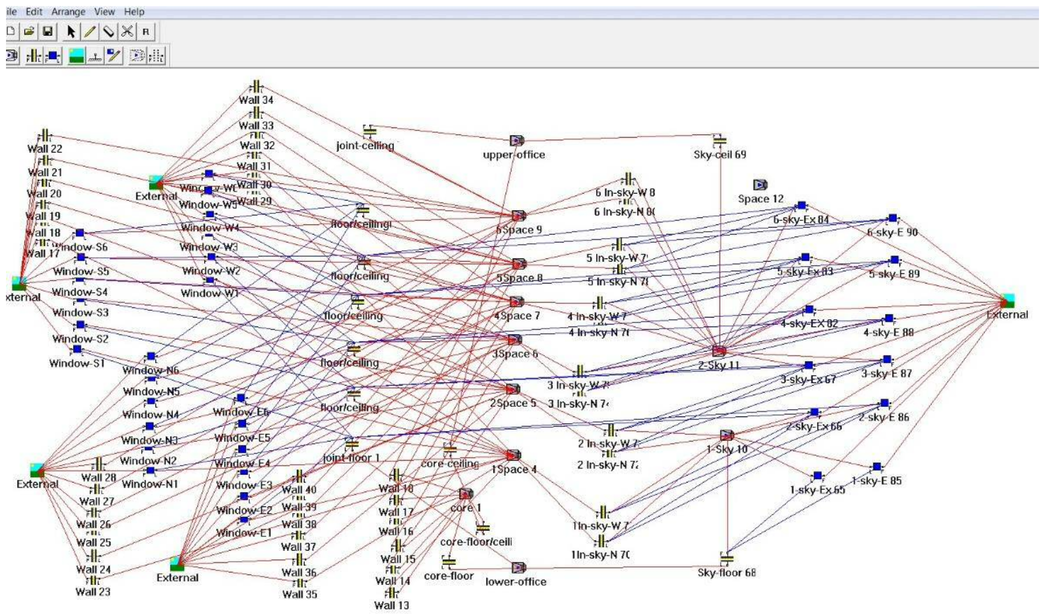


Figure C-2. Schematic model sample for building-skycourt prototype (B) in HTB2

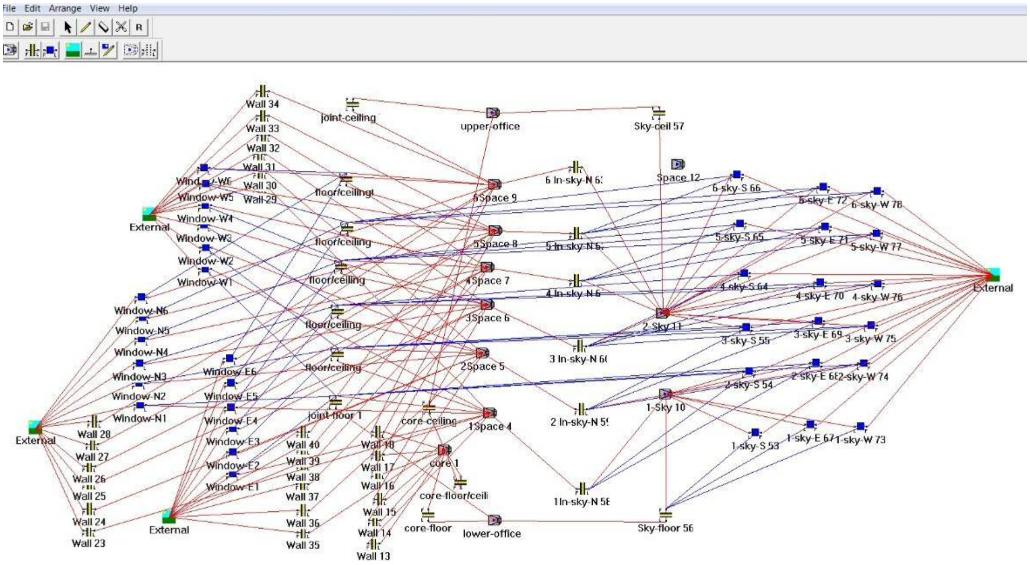
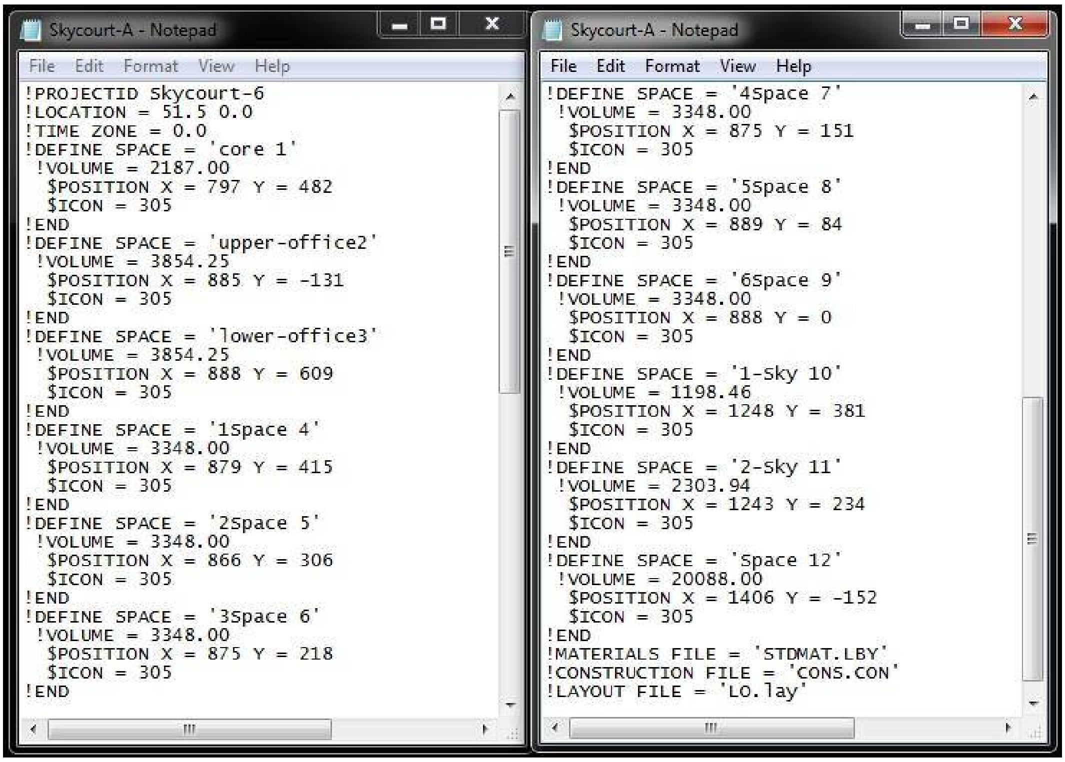


Figure C-3. Schematic model sample for building-skycourt prototype (C) in HTB2



Skycourt-A - Notepad

File Edit Format View Help

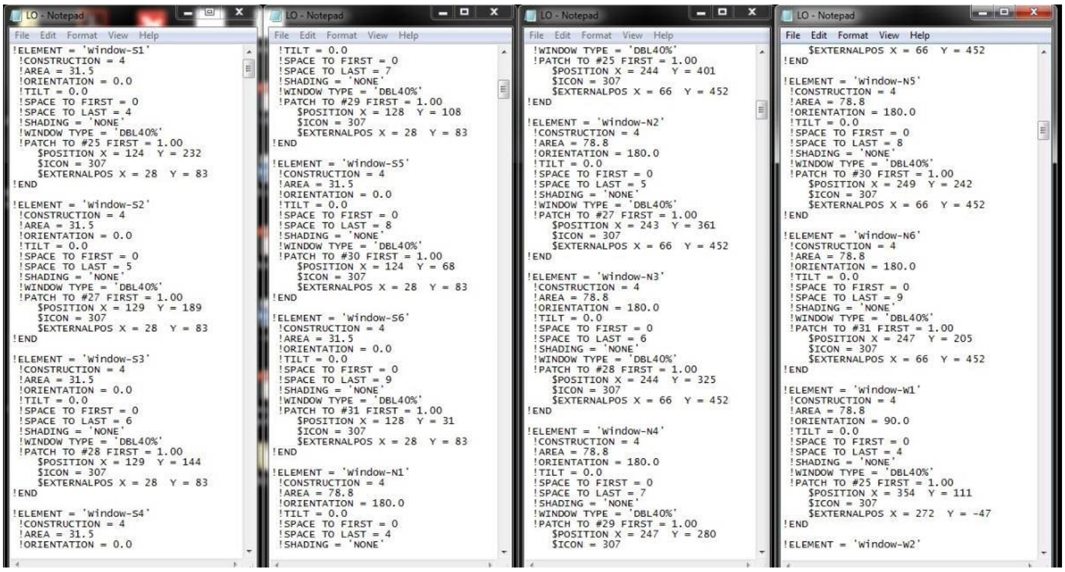
```
!PROJECTID Skycourt-6
!LOCATION = 51.5 0.0
!TIME ZONE = 0.0
!DEFINE SPACE = 'core 1'
 !VOLUME = 2187.00
  $POSITION X = 797 Y = 482
  $ICON = 305
!END
!DEFINE SPACE = 'upper-office2'
 !VOLUME = 3854.25
  $POSITION X = 885 Y = -131
  $ICON = 305
!END
!DEFINE SPACE = 'lower-office3'
 !VOLUME = 3854.25
  $POSITION X = 888 Y = 609
  $ICON = 305
!END
!DEFINE SPACE = '1Space 4'
 !VOLUME = 3348.00
  $POSITION X = 879 Y = 415
  $ICON = 305
!END
!DEFINE SPACE = '2Space 5'
 !VOLUME = 3348.00
  $POSITION X = 866 Y = 306
  $ICON = 305
!END
!DEFINE SPACE = '3Space 6'
 !VOLUME = 3348.00
  $POSITION X = 875 Y = 218
  $ICON = 305
!END
```

Skycourt-A - Notepad

File Edit Format View Help

```
!DEFINE SPACE = '4Space 7'
 !VOLUME = 3348.00
  $POSITION X = 875 Y = 151
  $ICON = 305
!END
!DEFINE SPACE = '5Space 8'
 !VOLUME = 3348.00
  $POSITION X = 889 Y = 84
  $ICON = 305
!END
!DEFINE SPACE = '6Space 9'
 !VOLUME = 3348.00
  $POSITION X = 888 Y = 0
  $ICON = 305
!END
!DEFINE SPACE = '1-Sky 10'
 !VOLUME = 1198.46
  $POSITION X = 1248 Y = 381
  $ICON = 305
!END
!DEFINE SPACE = '2-Sky 11'
 !VOLUME = 2303.94
  $POSITION X = 1243 Y = 234
  $ICON = 305
!END
!DEFINE SPACE = 'Space 12'
 !VOLUME = 20088.00
  $POSITION X = 1406 Y = -152
  $ICON = 305
!END
!MATERIALS FILE = 'STDMAT.LBY'
!CONSTRUCTION FILE = 'CONS.CON'
!LAYOUT FILE = 'LO.lay'
```

Figure C-4. Building file sample for building-skycourt prototype (A) in HTB2



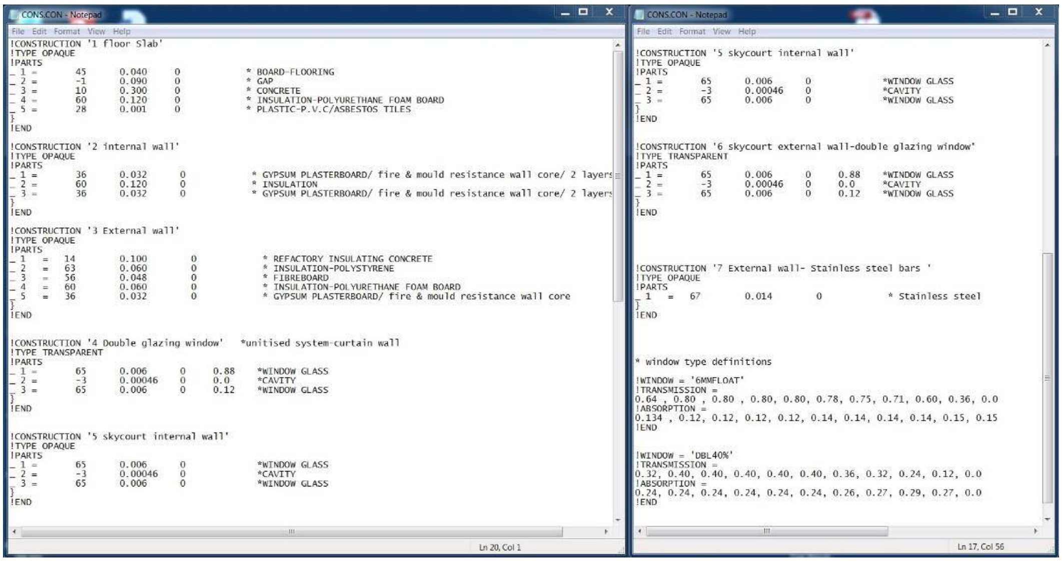
```
!ELEMENT = 'Window-S1'
 !CONSTRUCTION = 4
 !AREA = 31.5
 !ORIENTATION = 0.0
 !TILT = 0.0
 !SPACE TO FIRST = 0
 !SPACE TO LAST = 4
 !SHADING = 'NONE'
 !WINDOW TYPE = 'DBL40%'
 !PATCH TO #25 FIRST = 1.00
    $POSITION X = 124  Y = 232
    $ICON = 307
    $EXTERNALPOS X = 28  Y = 83
!END

!ELEMENT = 'Window-S2'
 !CONSTRUCTION = 4
 !AREA = 31.5
 !ORIENTATION = 0.0
 !TILT = 0.0
 !SPACE TO FIRST = 0
 !SPACE TO LAST = 5
 !SHADING = 'NONE'
 !WINDOW TYPE = 'DBL40%'
 !PATCH TO #27 FIRST = 1.00
    $POSITION X = 129  Y = 189
    $ICON = 307
    $EXTERNALPOS X = 28  Y = 83
!END

!ELEMENT = 'Window-S3'
 !CONSTRUCTION = 4
 !AREA = 31.5
 !ORIENTATION = 0.0
 !TILT = 0.0
 !SPACE TO FIRST = 0
 !SPACE TO LAST = 6
 !SHADING = 'NONE'
 !WINDOW TYPE = 'DBL40%'
 !PATCH TO #28 FIRST = 1.00
    $POSITION X = 129  Y = 144
    $ICON = 307
    $EXTERNALPOS X = 28  Y = 83
!END

!ELEMENT = 'Window-S4'
 !CONSTRUCTION = 4
 !AREA = 31.5
 !ORIENTATION = 0.0
```

```
 !TILT = 0.0
 !SPACE TO FIRST = 0
 !SPACE TO LAST = 7
 !SHADING = 'NONE'
 !WINDOW TYPE = 'DBL40%'
 !PATCH TO #29 FIRST = 1.00
    $POSITION X = 128  Y = 108
    $ICON = 307
    $EXTERNALPOS X = 28  Y = 83
!END

!ELEMENT = 'Window-S5'
 !CONSTRUCTION = 4
 !AREA = 31.5
 !ORIENTATION = 0.0
 !TILT = 0.0
 !SPACE TO FIRST = 0
 !SPACE TO LAST = 8
 !SHADING = 'NONE'
 !WINDOW TYPE = 'DBL40%'
 !PATCH TO #30 FIRST = 1.00
    $POSITION X = 124  Y = 68
    $ICON = 307
    $EXTERNALPOS X = 28  Y = 83
!END

!ELEMENT = 'Window-S6'
 !CONSTRUCTION = 4
 !AREA = 31.5
 !ORIENTATION = 0.0
 !TILT = 0.0
 !SPACE TO FIRST = 0
 !SPACE TO LAST = 9
 !SHADING = 'NONE'
 !WINDOW TYPE = 'DBL40%'
 !PATCH TO #31 FIRST = 1.00
    $POSITION X = 128  Y = 31
    $ICON = 307
    $EXTERNALPOS X = 28  Y = 83
!END

!ELEMENT = 'Window-N1'
 !CONSTRUCTION = 4
 !AREA = 78.8
 !ORIENTATION = 180.0
 !TILT = 0.0
 !SPACE TO FIRST = 0
 !SPACE TO LAST = 4
 !SHADING = 'NONE'
```

```
 !WINDOW TYPE = 'DBL40%'
 !PATCH TO #25 FIRST = 1.00
    $POSITION X = 244  Y = 401
    $ICON = 307
    $EXTERNALPOS X = 66  Y = 452
!END

!ELEMENT = 'Window-N2'
 !CONSTRUCTION = 4
 !AREA = 78.8
 !ORIENTATION = 180.0
 !TILT = 0.0
 !SPACE TO FIRST = 0
 !SPACE TO LAST = 5
 !SHADING = 'NONE'
 !WINDOW TYPE = 'DBL40%'
 !PATCH TO #27 FIRST = 1.00
    $POSITION X = 243  Y = 361
    $ICON = 307
    $EXTERNALPOS X = 66  Y = 452
!END

!ELEMENT = 'Window-N3'
 !CONSTRUCTION = 4
 !AREA = 78.8
 !ORIENTATION = 180.0
 !TILT = 0.0
 !SPACE TO FIRST = 0
 !SPACE TO LAST = 6
 !SHADING = 'NONE'
 !WINDOW TYPE = 'DBL40%'
 !PATCH TO #28 FIRST = 1.00
    $POSITION X = 244  Y = 325
    $ICON = 307
    $EXTERNALPOS X = 66  Y = 452
!END

!ELEMENT = 'Window-N4'
 !CONSTRUCTION = 4
 !AREA = 78.8
 !ORIENTATION = 180.0
 !TILT = 0.0
 !SPACE TO FIRST = 0
 !SPACE TO LAST = 7
 !SHADING = 'NONE'
 !WINDOW TYPE = 'DBL40%'
 !PATCH TO #29 FIRST = 1.00
    $POSITION X = 247  Y = 280
    $ICON = 307
```

```
    $EXTERNALPOS X = 66  Y = 452
!END

!ELEMENT = 'Window-N5'
 !CONSTRUCTION = 4
 !AREA = 78.8
 !ORIENTATION = 180.0
 !TILT = 0.0
 !SPACE TO FIRST = 0
 !SPACE TO LAST = 8
 !SHADING = 'NONE'
 !WINDOW TYPE = 'DBL40%'
 !PATCH TO #30 FIRST = 1.00
    $POSITION X = 249  Y = 242
    $ICON = 307
    $EXTERNALPOS X = 66  Y = 452
!END

!ELEMENT = 'Window-N6'
 !CONSTRUCTION = 4
 !AREA = 78.8
 !ORIENTATION = 180.0
 !TILT = 0.0
 !SPACE TO FIRST = 0
 !SPACE TO LAST = 9
 !SHADING = 'NONE'
 !WINDOW TYPE = 'DBL40%'
 !PATCH TO #31 FIRST = 1.00
    $POSITION X = 247  Y = 205
    $ICON = 307
    $EXTERNALPOS X = 66  Y = 452
!END

!ELEMENT = 'Window-W1'
 !CONSTRUCTION = 4
 !AREA = 78.8
 !ORIENTATION = 90.0
 !TILT = 0.0
 !SPACE TO FIRST = 0
 !SPACE TO LAST = 4
 !SHADING = 'NONE'
 !WINDOW TYPE = 'DBL40%'
 !PATCH TO #25 FIRST = 1.00
    $POSITION X = 354  Y = 111
    $ICON = 307
    $EXTERNALPOS X = 272  Y = -47
!END

!ELEMENT = 'Window-W2'
```

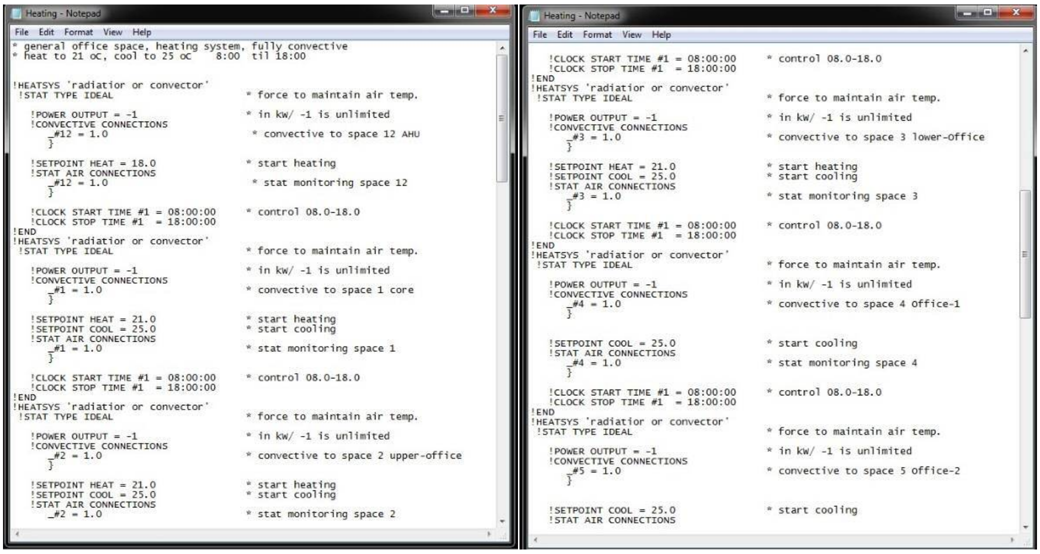
Figure C-5. Layout file sample for building-skycourt prototype (A) in HTB2



```
!CONSTRUCTION '1 floor Slab'
!TYPE OPAQUE
!PARTS
_ 1 =      45     0.040    0          * BOARD-FLOORING
_ 2 =      -1     0.090    0          * GAP
_ 3 =      10     0.300    0          * CONCRETE
_ 4 =      60     0.120    0          * INSULATION-POLYURETHANE FOAM BOARD
_ 5 =      28     0.001    0          * PLASTIC-P.V.C/ASBESTOS TILES
}
!END

!CONSTRUCTION '2 internal wall'
!TYPE OPAQUE
!PARTS
_ 1 =      36     0.032    0          * GYPSUM PLASTERBOARD/ fire & mould resistance wall core/ 2 layers
_ 2 =      60     0.120    0          * INSULATION
_ 3 =      36     0.032    0          * GYPSUM PLASTERBOARD/ fire & mould resistance wall core/ 2 layers
}
!END

!CONSTRUCTION '3 External wall'
!TYPE OPAQUE
!PARTS
_ 1   =   14      0.100      0          * REFACTORY INSULATING CONCRETE
_ 2   =   63      0.060      0          * INSULATION-POLYSTYRENE
_ 3   =   56      0.048      0          * FIBREBOARD
_ 4   =   60      0.060      0          * INSULATION-POLYURETHANE FOAM BOARD
_ 5   =   36      0.032      0          * GYPSUM PLASTERBOARD/ fire & mould resistance wall core
}
!END

!CONSTRUCTION '4 Double glazing window'   *unitised system-curtain wall
!TYPE TRANSPARENT
!PARTS
_ 1 =      65     0.006     0    0.88    *WINDOW GLASS
_ 2 =      -3     0.00046   0    0.0     *CAVITY
_ 3 =      65     0.006     0    0.12    *WINDOW GLASS
}
!END

!CONSTRUCTION '5 skycourt internal wall'
!TYPE OPAQUE
!PARTS
_ 1 =      65     0.006     0            *WINDOW GLASS
_ 2 =      -3     0.00046   0            *CAVITY
_ 3 =      65     0.006     0            *WINDOW GLASS
}
!END
```

```
!CONSTRUCTION '5 skycourt internal wall'
!TYPE OPAQUE
!PARTS
_ 1 =      65     0.006     0            *WINDOW GLASS
_ 2 =      -3     0.00046   0            *CAVITY
_ 3 =      65     0.006     0            *WINDOW GLASS
}
!END

!CONSTRUCTION '6 skycourt external wall-double glazing window'
!TYPE TRANSPARENT
!PARTS
_ 1 =      65     0.006     0    0.88    *WINDOW GLASS
_ 2 =      -3     0.00046   0    0.0     *CAVITY
_ 3 =      65     0.006     0    0.12    *WINDOW GLASS
}
!END

!CONSTRUCTION '7 External wall- Stainless steel bars '
!TYPE OPAQUE
!PARTS
_ 1   =   67      0.014       0          * Stainless steel
}
!END

* window type definitions

!WINDOW = '6MMFLOAT'
!TRANSMISSION =
0.64 , 0.80 , 0.80 , 0.80, 0.80, 0.78, 0.75, 0.71, 0.60, 0.36, 0.0
!ABSORPTION =
0.134 , 0.12, 0.12, 0.12, 0.12, 0.14, 0.14, 0.14, 0.14, 0.15, 0.15
!END

!WINDOW = 'DBL40%'
!TRANSMISSION =
0.32, 0.40, 0.40, 0.40, 0.40, 0.40, 0.36, 0.32, 0.24, 0.12, 0.0
!ABSORPTION =
0.24, 0.24, 0.24, 0.24, 0.24, 0.24, 0.26, 0.27, 0.29, 0.27, 0.0
!END
```

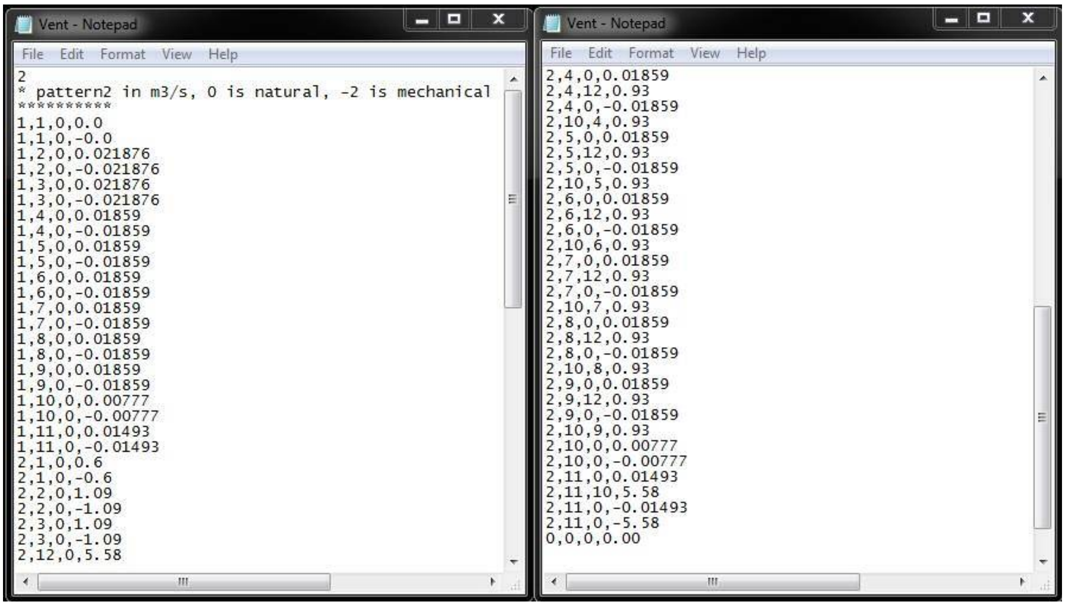
Figure C-6. Construction file sample for building-skycourt prototype (A) in HTB2



```
Heating - Notepad
File Edit Format View Help
* general office space, heating system, fully convective
* heat to 21 oC, cool to 25 oC    8:00  til 18:00

!HEATSYS 'radiatior or convector'
 !STAT TYPE IDEAL                     * force to maintain air temp.

   !POWER OUTPUT = -1                 * in kW/ -1 is unlimited
   !CONVECTIVE CONNECTIONS
      _#12 = 1.0                       * convective to space 12 AHU
      }

   !SETPOINT HEAT = 18.0              * start heating
   !STAT AIR CONNECTIONS
      _#12 = 1.0                       * stat monitoring space 12
      }

   !CLOCK START TIME #1 = 08:00:00    * control 08.0-18.0
   !CLOCK STOP TIME #1  = 18:00:00
!END
!HEATSYS 'radiatior or convector'
 !STAT TYPE IDEAL                     * force to maintain air temp.

   !POWER OUTPUT = -1                 * in kW/ -1 is unlimited
   !CONVECTIVE CONNECTIONS
      _#1 = 1.0                       * convective to space 1 core
      }

   !SETPOINT HEAT = 21.0              * start heating
   !SETPOINT COOL = 25.0              * start cooling
   !STAT AIR CONNECTIONS
      _#1 = 1.0                       * stat monitoring space 1
      }

   !CLOCK START TIME #1 = 08:00:00    * control 08.0-18.0
   !CLOCK STOP TIME #1  = 18:00:00
!END
!HEATSYS 'radiatior or convector'
 !STAT TYPE IDEAL                     * force to maintain air temp.

   !POWER OUTPUT = -1                 * in kW/ -1 is unlimited
   !CONVECTIVE CONNECTIONS
      _#2 = 1.0                       * convective to space 2 upper-office
      }

   !SETPOINT HEAT = 21.0              * start heating
   !SETPOINT COOL = 25.0              * start cooling
   !STAT AIR CONNECTIONS
      _#2 = 1.0                       * stat monitoring space 2
```

```
Heating - Notepad
File Edit Format View Help
   !CLOCK START TIME #1 = 08:00:00    * control 08.0-18.0
   !CLOCK STOP TIME #1  = 18:00:00
!END
!HEATSYS 'radiatior or convector'
 !STAT TYPE IDEAL                     * force to maintain air temp.

   !POWER OUTPUT = -1                 * in kW/ -1 is unlimited
   !CONVECTIVE CONNECTIONS
      _#3 = 1.0                       * convective to space 3 lower-office
      }

   !SETPOINT HEAT = 21.0              * start heating
   !SETPOINT COOL = 25.0              * start cooling
   !STAT AIR CONNECTIONS
      _#3 = 1.0                       * stat monitoring space 3
      }

   !CLOCK START TIME #1 = 08:00:00    * control 08.0-18.0
   !CLOCK STOP TIME #1  = 18:00:00
!END
!HEATSYS 'radiatior or convector'
 !STAT TYPE IDEAL                     * force to maintain air temp.

   !POWER OUTPUT = -1                 * in kW/ -1 is unlimited
   !CONVECTIVE CONNECTIONS
      _#4 = 1.0                       * convective to space 4 office-1
      }


   !SETPOINT COOL = 25.0              * start cooling
   !STAT AIR CONNECTIONS
      _#4 = 1.0                       * stat monitoring space 4
      }

   !CLOCK START TIME #1 = 08:00:00    * control 08.0-18.0
   !CLOCK STOP TIME #1  = 18:00:00
!END
!HEATSYS 'radiatior or convector'
 !STAT TYPE IDEAL                     * force to maintain air temp.

   !POWER OUTPUT = -1                 * in kW/ -1 is unlimited
   !CONVECTIVE CONNECTIONS
      _#5 = 1.0                       * convective to space 5 office-2
      }


   !SETPOINT COOL = 25.0              * start cooling
   !STAT AIR CONNECTIONS
```

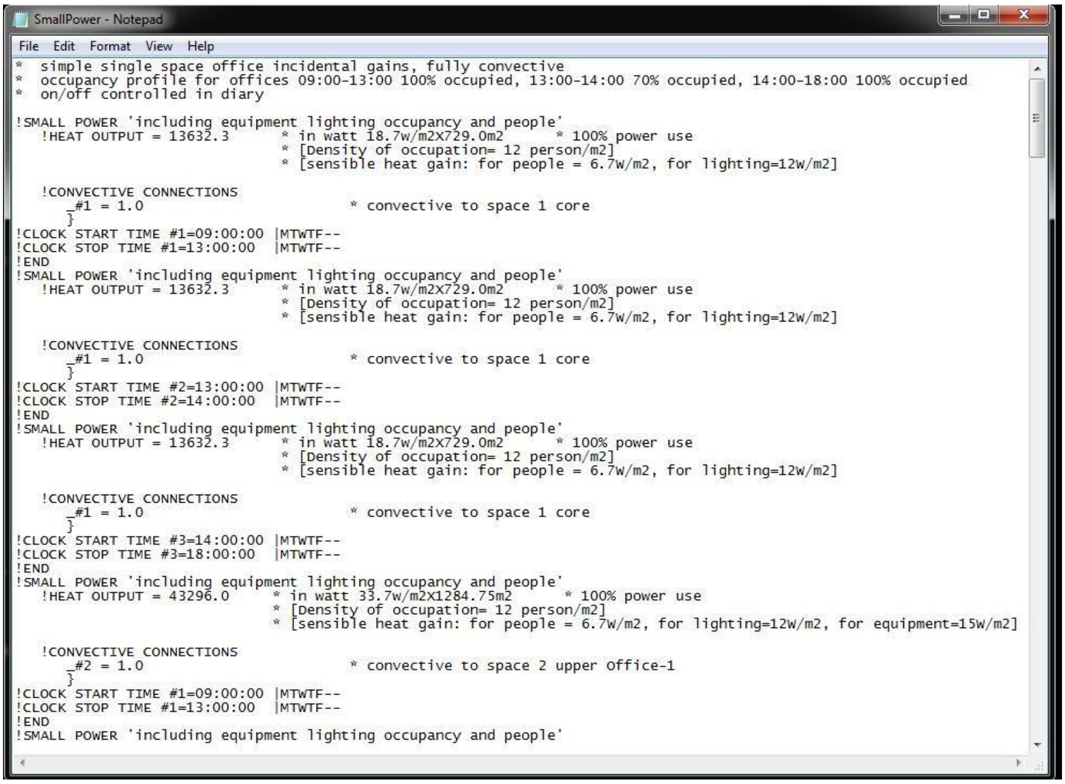
Figure C-7. Heating file sample for building-skycourt prototype (A) in HTB2



```
Vent - Notepad
File Edit Format View Help
2
* pattern2 in m3/s, 0 is natural, -2 is mechanical
**********
1,1,0,0.0
1,1,0,-0.0
1,2,0,0.021876
1,2,0,-0.021876
1,3,0,0.021876
1,3,0,-0.021876
1,4,0,0.01859
1,4,0,-0.01859
1,5,0,0.01859
1,5,0,-0.01859
1,6,0,0.01859
1,6,0,-0.01859
1,7,0,0.01859
1,7,0,-0.01859
1,8,0,0.01859
1,8,0,-0.01859
1,9,0,0.01859
1,9,0,-0.01859
1,10,0,0.00777
1,10,0,-0.00777
1,11,0,0.01493
1,11,0,-0.01493
2,1,0,0.6
2,1,0,-0.6
2,2,0,1.09
2,2,0,-1.09
2,3,0,1.09
2,3,0,-1.09
2,12,0,5.58
```

```
Vent - Notepad
File Edit Format View Help
2,4,0,0.01859
2,4,12,0.93
2,4,0,-0.01859
2,10,4,0.93
2,5,0,0.01859
2,5,12,0.93
2,5,0,-0.01859
2,10,5,0.93
2,6,0,0.01859
2,6,12,0.93
2,6,0,-0.01859
2,10,6,0.93
2,7,0,0.01859
2,7,12,0.93
2,7,0,-0.01859
2,10,7,0.93
2,8,0,0.01859
2,8,12,0.93
2,8,0,-0.01859
2,10,8,0.93
2,9,0,0.01859
2,9,12,0.93
2,9,0,-0.01859
2,10,9,0.93
2,10,0,0.00777
2,10,0,-0.00777
2,11,0,0.01493
2,11,10,5.58
2,11,0,-0.01493
2,11,0,-5.58
0,0,0,0.00
```

Figure C-8. Ventilation file sample for building-skycourt prototype (A) in HTB2



```
*  simple single space office incidental gains, fully convective
*  occupancy profile for offices 09:00-13:00 100% occupied, 13:00-14:00 70% occupied, 14:00-18:00 100% occupied
*  on/off controlled in diary

!SMALL POWER 'including equipment lighting occupancy and people'
   !HEAT OUTPUT = 13632.3       * in watt 18.7w/m2X729.0m2       * 100% power use
                                * [Density of occupation= 12 person/m2]
                                * [sensible heat gain: for people = 6.7w/m2, for lighting=12w/m2]

   !CONVECTIVE CONNECTIONS
      _#1 = 1.0                         * convective to space 1 core
      }
!CLOCK START TIME #1=09:00:00  |MTWTF--
!CLOCK STOP TIME #1=13:00:00   |MTWTF--
!END
!SMALL POWER 'including equipment lighting occupancy and people'
   !HEAT OUTPUT = 13632.3       * in watt 18.7w/m2X729.0m2       * 100% power use
                                * [Density of occupation= 12 person/m2]
                                * [sensible heat gain: for people = 6.7w/m2, for lighting=12w/m2]

   !CONVECTIVE CONNECTIONS
      _#1 = 1.0                         * convective to space 1 core
      }
!CLOCK START TIME #2=13:00:00  |MTWTF--
!CLOCK STOP TIME #2=14:00:00   |MTWTF--
!END
!SMALL POWER 'including equipment lighting occupancy and people'
   !HEAT OUTPUT = 13632.3       * in watt 18.7w/m2X729.0m2       * 100% power use
                                * [Density of occupation= 12 person/m2]
                                * [sensible heat gain: for people = 6.7w/m2, for lighting=12w/m2]

   !CONVECTIVE CONNECTIONS
      _#1 = 1.0                         * convective to space 1 core
      }
!CLOCK START TIME #3=14:00:00  |MTWTF--
!CLOCK STOP TIME #3=18:00:00   |MTWTF--
!END
!SMALL POWER 'including equipment lighting occupancy and people'
   !HEAT OUTPUT = 43296.0      * in watt 33.7w/m2x1284.75m2       * 100% power use
                               * [Density of occupation= 12 person/m2]
                               * [sensible heat gain: for people = 6.7w/m2, for lighting=12w/m2, for equipment=15w/m2]

   !CONVECTIVE CONNECTIONS
      _#2 = 1.0                         * convective to space 2 upper office-1
      }
!CLOCK START TIME #1=09:00:00  |MTWTF--
!CLOCK STOP TIME #1=13:00:00   |MTWTF--
!END
!SMALL POWER 'including equipment lighting occupancy and people'
```

Figure C-9. Small power file sample for building-skycourt prototype (A) in HTB2

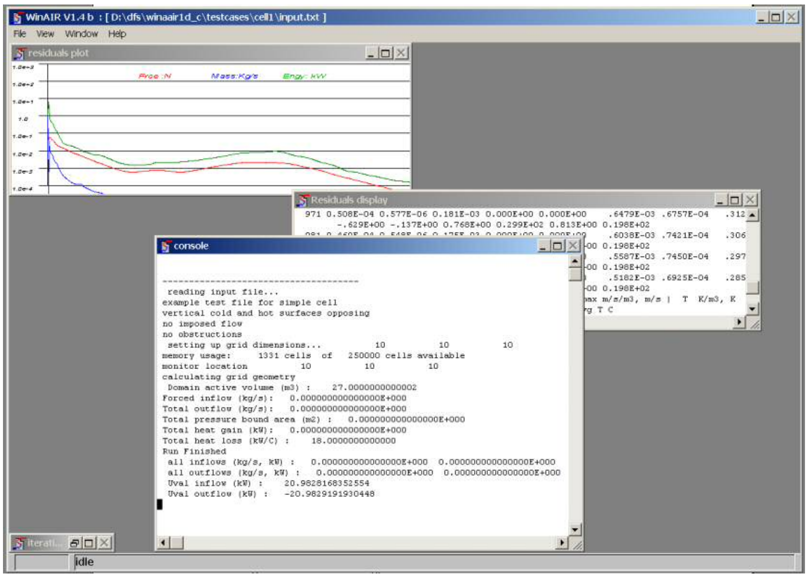


Figure C-10. Interface screen for WinAir

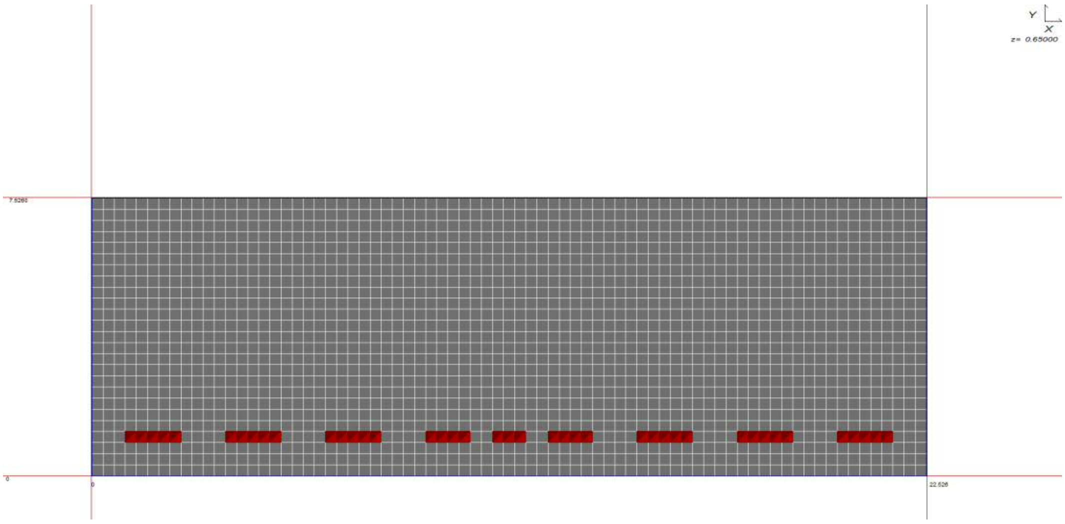


Figure C-11. Grid model sample for skycourt prototype (A) in WinAir showing horizontal section

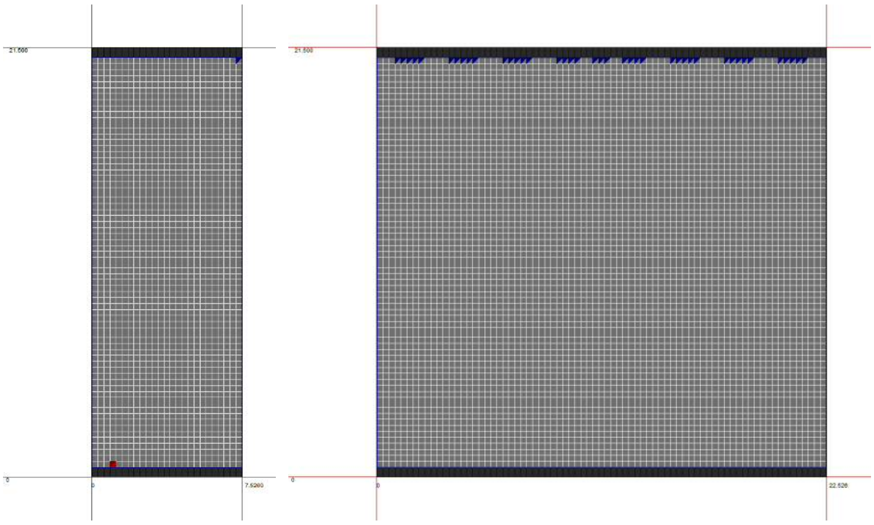


Figure C-12. Grid model sample for skycourt prototype (A) in WinAir showing vertical section input-summer-A-V2 - Notepad

```
A test run of WinAir4
Case 1: Prototype A/ Summer
--------------- domain sizes, ni nj nk
77, 27, 67
--------------- monitor i,j,k
33, 12, 30
--------------- gravity (m/s2)
0, 0, -9.81
--------------- external temp (C), external contanimant, rh(%)
28.3, 0.0,  42.0
--------------- fluid density (kg/m3), viscosity
1.2, 0.000018
--------------- initial domain temp (c), conc, rh
27.0, 0.0, 0.0
--------------- x grid  i1 i2 distance (m)
2, 2, 0.013
3, 77, 0.3
78, 78, 0.013
0, 0,  0
--------------- y grid
2, 2, 0.013
3, 27, 0.3
28, 28, 0.013
0, 0,  0
--------------- z grid
2, 2, 0.5
3, 12, 0.3
13, 13, 0.5
14, 23, 0.3
24, 24, 0.5
25, 34, 0.3
35, 35, 0.5
36, 45, 0.3
46, 46, 0.5
47, 56, 0.3
57, 57, 0.5
58, 67, 0.3
68, 68, 0.5
0, 0,  0
--------------- cell blockages i1, i2, j1, j2, k1, k2, value
1, 77, 1, 1, 1, 67, 0.0
1, 77, 27, 27, 1, 67, 0.0
1, 1, 1, 27, 1, 67, 0.0
77, 77, 1, 27, 1, 67, 0.0
1, 77, 1, 27, 1, 1, 0.0
1, 77, 1, 27, 67, 67, 0.0
0, 0, 0, 0, 0, 0, 0.0
--------------- face blockages i1, i2, j1, j2, k1, k2, fu, fv, fw
0, 0, 0, 0, 0, 0, 0.0, 0.0, 0.0
```

input-summer-A-V2 - Notepad

```
-------------------- inflow i1, i2, j1, j2, k1, k2, flow(m3/s), u,v,w(m/s) temp(c
5, 5, 5, 5, 2, 2, 0.1361, 0.0, 0.0, 1.512, 25.0, 0.0, 0.0
6, 6, 5, 5, 2, 2, 0.1361, 0.0, 0.0, 1.512, 25.0, 0.0, 0.0
7, 7, 5, 5, 2, 2, 0.1361, 0.0, 0.0, 1.512, 25.0, 0.0, 0.0
8, 8, 5, 5, 2, 2, 0.1361, 0.0, 0.0, 1.512, 25.0, 0.0, 0.0
9, 9, 5, 5, 2, 2, 0.1361, 0.0, 0.0, 1.512, 25.0, 0.0, 0.0
14, 14, 5, 5, 2, 2, 0.1361, 0.0, 0.0, 1.512, 25.0, 0.0, 0.0
15, 15, 5, 5, 2, 2, 0.1361, 0.0, 0.0, 1.512, 25.0, 0.0, 0.0
16, 16, 5, 5, 2, 2, 0.1361, 0.0, 0.0, 1.512, 25.0, 0.0, 0.0
17, 17, 5, 5, 2, 2, 0.1361, 0.0, 0.0, 1.512, 25.0, 0.0, 0.0
18, 18, 5, 5, 2, 2, 0.1361, 0.0, 0.0, 1.512, 25.0, 0.0, 0.0
23, 23, 5, 5, 2, 2, 0.1361, 0.0, 0.0, 1.512, 25.0, 0.0, 0.0
24, 24, 5, 5, 2, 2, 0.1361, 0.0, 0.0, 1.512, 25.0, 0.0, 0.0
25, 25, 5, 5, 2, 2, 0.1361, 0.0, 0.0, 1.512, 25.0, 0.0, 0.0
26, 26, 5, 5, 2, 2, 0.1361, 0.0, 0.0, 1.512, 25.0, 0.0, 0.0
27, 27, 5, 5, 2, 2, 0.1361, 0.0, 0.0, 1.512, 25.0, 0.0, 0.0
32, 32, 5, 5, 2, 2, 0.1361, 0.0, 0.0, 1.512, 25.0, 0.0, 0.0
33, 33, 5, 5, 2, 2, 0.1361, 0.0, 0.0, 1.512, 25.0, 0.0, 0.0
34, 34, 5, 5, 2, 2, 0.1361, 0.0, 0.0, 1.512, 25.0, 0.0, 0.0
35, 35, 5, 5, 2, 2, 0.1361, 0.0, 0.0, 1.512, 25.0, 0.0, 0.0
38, 38, 5, 5, 2, 2, 0.1361, 0.0, 0.0, 1.512, 25.0, 0.0, 0.0
39, 39, 5, 5, 2, 2, 0.1361, 0.0, 0.0, 1.512, 25.0, 0.0, 0.0
40, 40, 5, 5, 2, 2, 0.1361, 0.0, 0.0, 1.512, 25.0, 0.0, 0.0
43, 43, 5, 5, 2, 2, 0.1361, 0.0, 0.0, 1.512, 25.0, 0.0, 0.0
44, 44, 5, 5, 2, 2, 0.1361, 0.0, 0.0, 1.512, 25.0, 0.0, 0.0
45, 45, 5, 5, 2, 2, 0.1361, 0.0, 0.0, 1.512, 25.0, 0.0, 0.0
46, 46, 5, 5, 2, 2, 0.1361, 0.0, 0.0, 1.512, 25.0, 0.0, 0.0
51, 51, 5, 5, 2, 2, 0.1361, 0.0, 0.0, 1.512, 25.0, 0.0, 0.0
52, 52, 5, 5, 2, 2, 0.1361, 0.0, 0.0, 1.512, 25.0, 0.0, 0.0
53, 53, 5, 5, 2, 2, 0.1361, 0.0, 0.0, 1.512, 25.0, 0.0, 0.0
54, 54, 5, 5, 2, 2, 0.1361, 0.0, 0.0, 1.512, 25.0, 0.0, 0.0
55, 55, 5, 5, 2, 2, 0.1361, 0.0, 0.0, 1.512, 25.0, 0.0, 0.0
60, 60, 5, 5, 2, 2, 0.1361, 0.0, 0.0, 1.512, 25.0, 0.0, 0.0
61, 61, 5, 5, 2, 2, 0.1361, 0.0, 0.0, 1.512, 25.0, 0.0, 0.0
62, 62, 5, 5, 2, 2, 0.1361, 0.0, 0.0, 1.512, 25.0, 0.0, 0.0
63, 63, 5, 5, 2, 2, 0.1361, 0.0, 0.0, 1.512, 25.0, 0.0, 0.0
64, 64, 5, 5, 2, 2, 0.1361, 0.0, 0.0, 1.512, 25.0, 0.0, 0.0
69, 69, 5, 5, 2, 2, 0.1361, 0.0, 0.0, 1.512, 25.0, 0.0, 0.0
70, 70, 5, 5, 2, 2, 0.1361, 0.0, 0.0, 1.512, 25.0, 0.0, 0.0
71, 71, 5, 5, 2, 2, 0.1361, 0.0, 0.0, 1.512, 25.0, 0.0, 0.0
72, 72, 5, 5, 2, 2, 0.1361, 0.0, 0.0, 1.512, 25.0, 0.0, 0.0
73, 73, 5, 5, 2, 2, 0.1361, 0.0, 0.0, 1.512, 25.0, 0.0, 0.0
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0
-------------------- outflow i1, i2, j1, j2, k1, k2, flow (m3/s)
5, 5, 26, 26, 66, 66, -0.1361
6, 6, 26, 26, 66, 66, -0.1361
7, 7, 26, 26, 66, 66, -0.1361
8, 8, 26, 26, 66, 66, -0.1361
9, 9, 26, 26, 66, 66, -0.1361
```

input-summer-A-V2 - Notepad

```
14, 14, 26, 26, 66, 66, -0.1361
15, 15, 26, 26, 66, 66, -0.1361
16, 16, 26, 26, 66, 66, -0.1361
17, 17, 26, 26, 66, 66, -0.1361
18, 18, 26, 26, 66, 66, -0.1361
23, 23, 26, 26, 66, 66, -0.1361
24, 24, 26, 26, 66, 66, -0.1361
25, 25, 26, 26, 66, 66, -0.1361
26, 26, 26, 26, 66, 66, -0.1361
27, 27, 26, 26, 66, 66, -0.1361
32, 32, 26, 26, 66, 66, -0.1361
33, 33, 26, 26, 66, 66, -0.1361
34, 34, 26, 26, 66, 66, -0.1361
35, 35, 26, 26, 66, 66, -0.1361
38, 38, 26, 26, 66, 66, -0.1361
39, 39, 26, 26, 66, 66, -0.1361
40, 40, 26, 26, 66, 66, -0.1361
43, 43, 26, 26, 66, 66, -0.1361
44, 44, 26, 26, 66, 66, -0.1361
45, 45, 26, 26, 66, 66, -0.1361
46, 46, 26, 26, 66, 66, -0.1361
51, 51, 26, 26, 66, 66, -0.1361
52, 52, 26, 26, 66, 66, -0.1361
53, 53, 26, 26, 66, 66, -0.1361
54, 54, 26, 26, 66, 66, -0.1361
55, 55, 26, 26, 66, 66, -0.1361
60, 60, 26, 26, 66, 66, -0.1361
61, 61, 26, 26, 66, 66, -0.1361
62, 62, 26, 26, 66, 66, -0.1361
63, 63, 26, 26, 66, 66, -0.1361
64, 64, 26, 26, 66, 66, -0.1361
69, 69, 26, 26, 66, 66, -0.1361
70, 70, 26, 26, 66, 66, -0.1361
71, 71, 26, 26, 66, 66, -0.1361
72, 72, 26, 26, 66, 66, -0.1361
73, 73, 26, 26, 66, 66, -0.1361
0, 0, 0, 0, 0, 0, -0
-------------------- pressure bounds i1, i2, j1, j2, k1, k2, face, cv, pext (Pa),
0, 0, 0, 0, 0, 0, 0, 0.0, 0.0, 0.0
-------------------- internal heat gains i1, i2, j1, j2, k1, k2, flux (kw, kw/m2
6, 19, 6, 12, 4, 4, 0.0027, 0, 0, 1
6, 19, 16, 22, 4, 4, 0.0027, 0, 0, 1
24, 37, 6, 12, 4, 4, 0.0027, 0, 0, 1
24, 37, 16, 22, 4, 4, 0.0027, 0, 0, 1
41, 54, 6, 12, 4, 4, 0.0027, 0, 0, 1
41, 54, 16, 22, 4, 4, 0.0027, 0, 0, 1
59, 72, 6, 12, 4, 4, 0.0027, 0, 0, 1
59, 72, 16, 22, 4, 4, 0.0027, 0, 0, 1
6, 19, 11, 12, 57, 57, 0.0045, 0, 0, 1
```

input-summer-A-V2 - Notepad

```
41, 54, 6, 12, 4, 4, 0.0027, 0, 0, 1
41, 54, 16, 22, 4, 4, 0.0027, 0, 0, 1
59, 72, 6, 12, 4, 4, 0.0027, 0, 0, 1
59, 72, 16, 22, 4, 4, 0.0027, 0, 0, 1
6, 19, 11, 12, 57, 57, 0.0045, 0, 0, 1
6, 19, 21, 22, 57, 57, 0.0045, 0, 0, 1
24, 37, 11, 12, 57, 57, 0.0045, 0, 0, 1
24, 37, 21, 22, 57, 57, 0.0045, 0, 0, 1
41, 54, 11, 12, 57, 57, 0.0045, 0, 0, 1
41, 54, 21, 22, 57, 57, 0.0045, 0, 0, 1
59, 72, 11, 12, 57, 57, 0.0045, 0, 0, 1
59, 72, 21, 22, 57, 57, 0.0045, 0, 0, 1
0, 0, 0, 0, 0, 0, 0.0, 0, 0, 0
-------------------- temperature/uval i1, i2, j1, j2, k1, k2, face (1:6), uval (k
1, 77, 2, 2, 2, 12, 3, 0.003, 37.4
1, 77, 2, 2, 13, 23, 3, 0.003, 37.4
1, 77, 2, 2, 24, 34, 3, 0.003, 38.5
1, 77, 2, 2, 35, 45, 3, 0.003, 38.5
1, 77, 2, 2, 46, 56, 3, 0.003, 38.5
1, 77, 2, 2, 57, 66, 3, 0.003, 38.5
1, 77, 1, 27, 2, 2, 5, 0.003, 38.5
1, 77, 1, 27, 66, 66, 6, 0.003, 37.1
1, 77, 26, 26, 2, 12, 4, 0.003, 36.5
2, 2, 2, 26, 2, 12, 1, 0.003, 36.5
76, 76, 2, 26, 2, 12, 2, 0.003, 36.5
1, 77, 26, 26, 13, 23, 4, 0.003, 36.5
2, 2, 2, 26, 13, 23, 1, 0.003, 36.5
76, 76, 2, 26, 13, 23, 2, 0.003, 36.5
1, 77, 26, 26, 24, 34, 4, 0.003, 37.7
2, 2, 2, 26, 24, 34, 1, 0.003, 37.7
76, 76, 2, 26, 24, 34, 2, 0.003, 37.7
1, 77, 26, 26, 35, 45, 4, 0.003, 37.7
2, 2, 2, 26, 35, 45, 1, 0.003, 37.7
76, 76, 2, 26, 35, 45, 2, 0.003, 37.7
1, 77, 26, 26, 46, 56, 4, 0.003, 37.4
2, 2, 2, 26, 46, 56, 1, 0.003, 37.4
76, 76, 2, 26, 46, 56, 2, 0.003, 37.4
1, 77, 26, 26, 57, 66, 4, 0.003, 36.2
2, 2, 2, 26, 57, 66, 1, 0.003, 36.2
76, 76, 2, 26, 57, 66, 2, 0.003, 36.2
0, 0, 0, 0, 0, 0, 0, 0.0, 0.0
-------------------- contaminant gains i1, i2, j1, j2, k1, k2, flux (g/s, g/s/m2
0, 0, 0, 0, 0, 0, 0.0, 0, 0, 0
-------------------- contaminant2 (water) gains i1, i2, j1, j2, k1, k2, flux (g/s
0, 0, 0, 0, 0, 0, 0.0, 0, 0, 0
--------------- buoyancy zones i1, i2, j1, j2, k1, k2, zone
0, 0, 0, 0, 0, 0, 0
```

Figure C-13. Input file sample for skycourt prototype (A) in WinAir

control - Notepad

```
example air4 control parameter file
------------- turbulence model (1 mult, 2 zeroeqn) , multiplier, prandtl number
1 200.0  0.9
------------- convergence criteria momentum, mass, energy, concentration
0.1 0.1 0.1 0.3
------------- number sweeps
8
------------- solve for temperature (1) number sweeps
1 4
------------- solve for concentration (1) number sweeps
0 0
------------- transient (1), timestep (s)
0 0
------------- relaxation factors; momentum, temperature, pressure, mass, conc.
0.2  0.5  1.0  1.0  1.0
------------- print residuals
0
------------- time at end
1.0
```

Figure C-14. Control file sample for skycourt prototype (A) in WinAir

Appendix D: Results Data

Table D-1. Results of the models energy performance under the isolated ventilation strategy (air-conditioned skycourt)

Case	Energy Demand (Kwh/m².yr)	Heating Gain (Kwh/m².yr)	Cooling Gain (Kwh/m².yr)
No-skycourt model	90.97	18.76	72.21
Skycourt prototype A	220.46	29.29	191.17
Skycourt prototype B	245.09	32.89	212.19
Skycourt prototype C	329.64	40.66	288.98

Table D-2. Results of the skycourts air temperature and airspeed at occupancy level under the isolated ventilation strategy (air-conditioned skycourt)

Case	Summer (Hottest hour)		Winter (Coldest hour)		Transitional (Typical hour)	
	Skycourt air-temp. (°C)	Skycourt air-speed (m/s)	Skycourt air-temp. (°C)	Skycourt air-speed (m/s)	Skycourt air-temp. (°C)	Skycourt air-speed (m/s)
Skycourt prototype A	18.2-27.5	0.077	17.3-24.1	0.310	20.0-22.2	0.061
Skycourt prototype B	18.2-27.5	0.092	16.8-23.9	0.320	19.3-21.5	0.056
Skycourt prototype C	18.2-28.0	0.084	16.3-23.6	0.340	20.3-21.2	0.046

Table D-3. Results of the models energy performance and the skycourts air temperature and airspeed at occupancy level under the combined ventilation strategies

	Case	Strategy one (V1)	Strategy two (V2)	Strategy three (V3)	Strategy four (V4)	Strategy five (V5)
Skycourt prototype A	**Summer (Hottest hour)**					
	Occupancy level air-temp. (°C)	48.7-50.4	25.0-28.5	25.0-29.5	27.5-30.1	27.6-31.5
	Mean air-temp. (°C)	49.3	26.7	27.3	28.7	29.6
	Occupancy level air-speed (m/s)	0.236	0.225	0.145	0.226	0.141
	Winter (Coldest hour)					
	Occupancy level air-temp. (°C)	7.5-8.8	14.2-19.9	12.8-19.7	13.4-17.9	11.9-17.7
	Mean air-temp. (°C)	8.0	15.6	14.2	14.6	13.4
	Occupancy level air-speed (m/s)	0.271	0.332	0.360	0.280	0.324
	Transitional/ Mid- season (Typical hour)					
	Occupancy level air-temp. (°C)	22.5-23.7	22.0-22.5	21.9-22.0	18.0-19.6	18.0-19.6
	Mean air-temp. (°C)	22.7	22.1	22.0	19.0	18.8
	Occupancy level air-speed (m/s)	0.064	0.175	0.099	0.183	0.124
	Cooling & heating energy demand (Kwh/m^2.year)	94.33	91.96	93.21	110.05	98.30
Skycourt prototype B	**Summer (Hottest hour)**					
	Occupancy level air-temp. (°C)	52.6-54.7	25.0-28.7	25.1-30.0	27.5-30.9	27.6-32.1
	Mean air-temp. (°C)	53.2	26.8	27.6	29.1	29.7
	Occupancy level airspeed (m/s)	0.322	0.206	0.150	0.219	0.145
	Winter (Coldest hour)					
	Occupancy level air-temp. (°C)	4.9-6.5	13.1-19.9	10.7-19.4	11.9-17.9	10.4-17.5
	Mean air-temp. (°C)	5.5	14.5	12.6	13.2	11.7
	Occupancy level air-speed (m/s)	0.282	0.377	0.347	0.360	0.361
	Transitional/ Mid- season (Typical hour)					
	Occupancy level air-temp. (°C)	22.8-23.7	22.0-22.7	22.0-22.8	18.0-19.4	18.0-19.7
	Mean air-temp. (°C)	23.0	22.3	22.2	18.7	18.8
	Occupancy level air-speed (m/s)	0.090	0.156	0.108	0.163	0.125
	Cooling & heating energy demand (Kwh/m^2.year)	93.75	91.52	92.70	98.89	98.03
Skycourt prototype C	**Summer (Hottest hour)**					
	Occupancy level air-temp. (°C)	55.9-58.1	25.1-29.0	25.1-31.4	27.6-32.1	27.6-33.4
	Mean air-temp. (°C)	56.4	27.6	28.5	29.9	30.7
	Occupancy level air-speed (m/s)	0.179	0.179	0.126	0.190	0.124
	Winter (Coldest hour)					
	Occupancy level air-temp. (°C)	3.4-4.7	11.4-19.8	9.4-19.0	10.0-17.9	7.9-17.4
	Mean air-temp. (°C)	3.9	13.1	10.8	11.7	9.7
	Occupancy level air-speed (m/s)	0.222	0.391	0.315	0.296	0.284
	Transitional/ Mid- season (Typical hour)					
	Occupancy level air-temp. (°C)	22.6-23.5	22.1-23.0	22.1-23.0	18.0-19.9	18.0-20.0
	Mean air-temp. (°C)	22.9	22.5	22.6	19.0	19.1
	Occupancy level air-speed (m/s)	0.043	0.131	0.084	0.154	0.094
	Cooling & heating energy demand (Kwh/m^2.year)	93.35	90.9	92.10	100.57	99.05

Table D-4. Results of the models energy performance and the skycourts air temperature and airspeed at occupancy level under different orientations of skycourt

	Case	South (S)	North (N)	West (W)	East (E)
Skycourt prototype A	**Summer (Hottest hour)**				
	Occupancy level air-temp. (°C)	25.0-28.5	25.0-27.0	25.0-27.4	25.0-27.0
	Mean air-temp. (°C)	26.7	26.0	26.3	26.0
	Occupancy level air-speed (m/s)	0.225	0.216	0.208	0.214
	Winter (Coldest hour)				
	Occupancy level air-temp. (°C)	14.2-19.9	14.2-19.9	14.2-19.9	14.6-19.9
	Mean air-temp. (°C)	15.6	15.4	15.9	15.7
	Occupancy level air-speed (m/s)	0.332	0.321	0.322	0.356
	Transitional/ Mid- season (Typical hour)				
	Occupancy level air-temp. (°C)	22.0-22.5	22.0-22.3	22.0-22.7	22.0-22.7
	Mean air-temp. (°C)	22.1	22.0	22.3	22.3
	Occupancy level air-speed (m/s)	0.175	0.172	0.184	0.137
	Cooling & heating energy demand (Kwh/m^2.year)	91.96	92.07	92.03	92.09
	Case	**South- East (S-E)**	**North- West (N-W)**	**West- South (W-S)**	**East- North (E-N)**
Skycourt prototype B	**Summer (Hottest hour)**				
	Occupancy level air-temp. (°C)	25.0-28.7	25.0-27.3	25.0-28.0	25.0-27.5
	Mean air-temp. (°C)	26.8	26.2	26.6	26.2
	Occupancy level air-speed (m/s)	0.206	0.221	0.209	0.215
	Winter (Coldest hour)				
	Occupancy level air-temp. (°C)	13.1-19.9	13.4-19.8	13.0-19.9	13.0-19.9
	Mean air-temp. (°C)	14.6	14.5	14.4	14.4
	Occupancy level air-speed (m/s)	0.377	0.359	0.375	0.373
	Transitional/ Mid- season (Typical hour)				
	Occupancy level air-temp. (°C)	22.0-22.7	22.0-22.5	22.0-22.6	22.0-22.6
	Mean air-temp. (°C)	22.3	22.1	22.2	22.2
	Occupancy level air-speed (m/s)	0.156	0.168	0.128	0.135
	Cooling & heating energy demand (Kwh/m^2.year)	91.52	91.79	91.58	91.75
	Case	**South- East West (E-EW)**	**North- East West (N-EW)**	**West- South North (W-SN)**	**East- South North (E-SN)**
Skycourt prototype C	**Summer (Hottest hour)**				
	Occupancy level air-temp. (°C)	25.1-29.0	25.1-27.7	25.1-28.8	25.1-28.2
	Mean air-temp. (°C)	27.6	26.4	27.0	26.6
	Occupancy level air-speed (m/s)	0.179	0.155	0.167	0.158
	Winter (Coldest hour)				
	Occupancy level air-temp. (°C)	11.4-19.8	10.3-19.9	11.3-19.9	11.1-19.8
	Mean air-temp. (°C)	13.1	12.5	13.0	12.5
	Occupancy level air-speed (m/s)	0.391	0.363	0.381	0.414
	Transitional/ Mid- season (Typical hour)				
	Occupancy level air-temp. (°C)	22.1-23.0	22.1-22.7	22.1-23.0	22.1-22.5
	Mean air-temp. (°C)	22.5	22.3	22.5	22.2
	Occupancy level air-speed (m/s)	0.131	0.084	0.105	0.093
	Cooling & heating energy demand (Kwh/m^2.year)	90.9	91.41	91.13	91.24

Table D-5. Results of the models energy performance and the skycourts air temperature and airspeed at occupancy level under different heights of skycourt

	Case	Six-floor height	Three-floor height	Nine-floor height
Skycourt prototype A	**Summer (Hottest hour)**			
	Occupancy level air-temp. (°C)	25.0-28.5	25.0-29.1	25.0-27.8
	Mean air-temp. (°C)	26.7	27.3	26.1
	Occupancy level air-speed (m/s)	0.225	0.172	0.272
	Winter (Coldest hour)			
	Occupancy level air-temp. (°C)	14.2-19.9	14.5-19.9	15.7-19.9
	Mean air-temp. (°C)	15.6	14.6	17.2
	Occupancy level air-speed (m/s)	0.332	0.260	0.381
	Transitional/ Mid- season (Typical hour)			
	Occupancy level air-temp. (°C)	22.0-22.5	22.0-22.3	22.3-22.8
	Mean air-temp. (°C)	22.1	22.0	22.7
	Occupancy level air-speed (m/s)	0.175	0.151	0.246
	Cooling & heating energy demand (Kwh/m^2.year)	91.96	91.96	91.60
Skycourt prototype B	**Summer (Hottest hour)**			
	Occupancy level air-temp. (°C)	25.0-28.7	25.0-29.2	25.0-28.10
	Mean air-temp. (°C)	26.8	27.4	26.1
	Occupancy level airspeed (m/s)	0.206	0.171	0.321
	Winter (Coldest hour)			
	Occupancy level air-temp. (°C)	13.1-19.9	12.8-19.9	13.9-19.9
	Mean air-temp. (°C)	14.5	13.9	15.1
	Occupancy level air-speed (m/s)	0.377	0.341	0.433
	Transitional/ Mid- season (Typical hour)			
	Occupancy level air-temp. (°C)	22.0-22.7	22.0-22.5	22.0-23.0
	Mean air-temp. (°C)	22.3	22.2	22.6
	Occupancy level air-speed (m/s)	0.156	0.15	0.233
	Cooling & heating energy demand (Kwh/m^2.year)	91.52	91.70	91.04
Skycourt prototype C	**Summer (Hottest hour)**			
	Occupancy level air-temp. (°C)	25.1-29.0	25.1-29.4	25.1-28.6
	Mean air-temp. (°C)	27.6	27.9	27.1
	Occupancy level air-speed (m/s)	0.179	0.154	0.211
	Winter (Coldest hour)			
	Occupancy level air-temp. (°C)	11.4-19.8	11.0-19.8	11.4-19.9
	Mean air-temp. (°C)	13.1	12.2	13.3
	Occupancy level air-speed (m/s)	0.391	0.391	0.450
	Transitional/ Mid- season (Typical hour)			
	Occupancy level air-temp. (°C)	22.1-23.0	22.1-22.9	22.2-23.3
	Mean air-temp. (°C)	22.5	22.4	22.8
	Occupancy level air-speed (m/s)	0.131	0.101	0.15
	Cooling & heating energy demand (Kwh/m^2.year)	90.9	91.3	90.11

Table D-6. Results of the models energy performance and the skycourts air temperature and airspeed at occupancy level under different areas of skycourt

	Case	(12%) GIA	(8%) GIA	(4%) GIA
Skycourt prototype A	**Summer (Hottest hour)**			
	Occupancy level air-temp. (°C)	25.0-28.5	25.0-27.9	25.0-27.0
	Mean air-temp. (°C)	26.7	26.2	26.0
	Occupancy level air-speed (m/s)	0.225	0.238	0.402
	Winter (Coldest hour)			
	Occupancy level air-temp. (°C)	14.2-19.9	16.0-19.8	17.1-19.9
	Mean air-temp. (°C)	15.6	16.7	17.8
	Occupancy level air-speed (m/s)	0.332	0.393	0.400
	Transitional/ Mid- season (Typical hour)			
	Occupancy level air-temp. (°C)	22.0-22.5	22.0-22.6	22.0-22.4
	Mean air-temp. (°C)	22.1	22.1	22.2
	Occupancy level air-speed (m/s)	0.175	0.183	0.395
	Cooling & heating energy demand (Kwh/m^2.year)	91.96	91.18	90.53
	Case	**(12%) GIA**	**(8%) GIA**	**(4%) GIA**
Skycourt prototype B	**Summer (Hottest hour)**			
	Occupancy level air-temp. (°C)	25.0-28.7	25.0-28.2	25.0-29.3
	Mean air-temp. (°C)	26.8	26.4	27.1
	Occupancy level air-speed (m/s)	0.206	0.232	0.366
	Winter (Coldest hour)			
	Occupancy level air-temp. (°C)	13.1-19.9	13.8-19.9	15.4-19.9
	Mean air-temp. (°C)	14.5	15.4	16.8
	Occupancy level air-speed (m/s)	0.377	0.417	0.404
	Transitional/ Mid- season (Typical hour)			
	Occupancy level air-temp. (°C)	22.0-22.7	22.0-22.6	22.0-22.7
	Mean air-temp. (°C)	22.3	22.2	22.2
	Occupancy level air-speed (m/s)	0.156	0.166	0.320
	Cooling & heating energy demand (Kwh/m^2.year)	91.52	90.79	90.22
	Case	**(12%) GIA**	**(8%) GIA**	
Skycourt prototype C	**Summer (Hottest hour)**			
	Occupancy level air-temp. (°C)	25.1-29.0	25.1-29.5	
	Mean air-temp. (°C)	27.6	27.4	
	Occupancy level air-speed (m/s)	0.179	0.184	
	Winter (Coldest hour)			
	Occupancy level air-temp. (°C)	11.4-19.8	11.0-20.0	
	Mean air-temp. (°C)	13.1	13.3	
	Occupancy level air-speed (m/s)	0.391	0.384	
	Transitional/ Mid- season (Typical hour)			
	Occupancy level air-temp. (°C)	22.1-23.0	22.1-23.0	
	Mean air-temp. (°C)	22.5	22.6	
	Occupancy level air-speed (m/s)	0.131	0.122	
	Cooling & heating energy demand (Kwh/m^2.year)	90.9	90.13	

Table D-7. Results of the models energy performance and the skycourts air temperature and airspeed at occupancy level under different lengths and depths of skycourt

	Case	22.5 m × 7.5 m	15 m × 7.5 m	7.5 m × 15 m	7.5 m × 7.5 m
Skycourt prototype A	**Summer (Hottest hour)**				
	Occupancy level air-temp. (°C)	25.0-28.5	25.0-27.9	25.0-26.9	25.0-27.0
	Mean air-temp. (°C)	26.7	26.2	25.9	26.0
	Occupancy level air-speed (m/s)	0.225	0.238	0.231	0.402
	Winter (Coldest hour)				
	Occupancy level air-temp. (°C)	14.2-19.9	16.0-19.8	16.8-19.9	17.1-19.9
	Mean air-temp. (°C)	15.6	16.7	17.6	17.8
	Occupancy level air-speed (m/s)	0.332	0.393	0.330	0.400
	Transitional/ Mid- season (Typical hour)				
	Occupancy level air-temp. (°C)	22.0-22.5	22.0-22.6	22.0-22.4	22.0-22.4
	Mean air-temp. (°C)	22.1	22.1	22.2	22.1
	Occupancy level air-speed (m/s)	0.175	0.183	0.210	0.395
	Cooling & heating energy demand (Kwh/m^2.year)	91.96	91.18	91.42	90.53
	Case	**22.5 m × 7.5 m**	**15 m × 7.5 m**	**7.5 m × 15 m**	**7.5 m × 7.5 m**
Skycourt prototype B	**Summer (Hottest hour)**				
	Occupancy level air-temp. (°C)	25.0-28.7	25.0-28.2	25.0-27.5	25.0-29.3
	Mean air-temp. (°C)	26.8	26.4	25.9	27.1
	Occupancy level air-speed (m/s)	0.206	0.232	0.230	0.366
	Winter (Coldest hour)				
	Occupancy level air-temp. (°C)	13.1-19.9	13.8-19.9	13.8-19.8	15.4-19.9
	Mean air-temp. (°C)	14.6	15.4	15.6	16.8
	Occupancy level air-speed (m/s)	0.377	0.417	0.442	0.404
	Transitional/ Mid- season (Typical hour)				
	Occupancy level air-temp. (°C)	22.0-22.7	22.0-22.6	22.0-22.6	22.0-22.7
	Mean air-temp. (°C)	22.3	22.2	22.2	22.2
	Occupancy level air-speed (m/s)	0.156	0.166	0.181	0.320
	Cooling & heating energy demand (Kwh/m^2.year)	91.52	90.79	90.87	90.22
	Case	**37.5 m × 4.5 m**	**37.5 m × 3 m**		
Skycourt prototype C	**Summer (Hottest hour)**				
	Occupancy level air-temp. (°C)	25.1-29.0	25.1-29.5		
	Mean air-temp. (°C)	27.6	27.4		
	Occupancy level air-speed (m/s)	0.179	0.184		
	Winter (Coldest hour)				
	Occupancy level air-temp. (°C)	11.4-19.8	11.0-20.0		
	Mean air-temp. (°C)	13.1	13.3		
	Occupancy level air-speed (m/s)	0.391	0.384		
	Transitional/ Mid- season (Typical hour)				
	Occupancy level air-temp. (°C)	22.1-23.0	22.1-23.0		
	Mean air-temp. (°C)	22.5	22.6		
	Occupancy level air-speed (m/s)	0.131	0.122		
	Cooling & heating energy demand (Kwh/m^2.year)	90.9	90.13		

Table D-8. Results of the models energy performance and the skycourts air temperature and airspeed at occupancy level under different air inlet & outlet openings locations in skycourt

	Case	Air Loc. a	Air Loc. b	Air Loc. c	Air Loc. d	Air Loc. e
Skycourt prototype A	**Summer (Hottest hour)**					
	Occupancy level air-temp. (°C)	25.0-28.5	25.0-30.0	25.0-28.7	25.0-29.4	25.0-29.6
	Mean air-temp. (°C)	26.7	27.7	26.9	27.3	27.9
	Occupancy level air-speed (m/s)	0.225	0.178	0.235	0.145	0.218
	Winter (Coldest hour)					
	Occupancy level air-temp. (°C)	14.2-19.9	14.0-19.5	14.4-19.8	13.7-19.6	14.2-19.3
	Mean air-temp. (°C)	15.6	15.1	15.9	15.0	15.3
	Occupancy level air-speed (m/s)	0.332	0.212	0.324	0.247	0.260
	Transitional/ Mid- season (Typical hour)					
	Occupancy level air-temp. (°C)	22.0-22.5	22.0-22.5	22.0-22.5	22.0-22.6	21.9-22.5
	Mean air-temp. (°C)	22.1	22.3	22.2	22.2	22.2
	Occupancy level air-speed (m/s)	0.175	0.105	0.207	0.107	0.133
	Cooling & heating energy demand (Kwh/m^2.year)	91.96	91.96	91.96	91.96	91.96
Skycourt prototype B	**Summer (Hottest hour)**					
	Occupancy level air-temp. (°C)	25.0-28.7	25.0-29.1	25.0-28.9	25.0-29.5	25.0-30.1
	Mean air-temp. (°C)	26.3	27.0	26.9	27.3	28.2
	Occupancy level airspeed (m/s)	0.206	0.162	0.232	0.144	0.218
	Winter (Coldest hour)					
	Occupancy level air-temp. (°C)	13.1-19.9	12.6-19.4	13.0-19.9	12.3-19.7	12.7-19.3
	Mean air-temp. (°C)	14.5	14.0	14.6	13.9	14.2
	Occupancy level air-speed (m/s)	0.377	0.291	0.364	0.275	0.307
	Transitional/ Mid- season (Typical hour)					
	Occupancy level air-temp. (°C)	22.0-22.7	22.0-22.7	22.0-22.6	22.0-22.7	22.0-22.7
	Mean air-temp. (°C)	22.3	22.3	22.2	22.3	22.2
	Occupancy level air-speed (m/s)	0.156	0.097	0.150	0.079	0.131
	Cooling & heating energy demand (Kwh/m^2.year)	91.52	91.52	91.52	91.52	91.52
Skycourt prototype C	**Summer (Hottest hour)**					
	Occupancy level air-temp. (°C)	25.1-29.0	25.1-33.2	25.1-30.0	25.1-30.7	25.1-30.5
	Mean air-temp. (°C)	27.6	29.1	27.9	28.2	28.2
	Occupancy level air-speed (m/s)	0.179	0.133	0.178	0.125	0.174
	Winter (Coldest hour)					
	Occupancy level air-temp. (°C)	11.4-19.8	10.7-19.5	9.6-19.7	10.5-19.3	9.6-19.7
	Mean air-temp. (°C)	13.1	12.7	12.7	12.3	12.5
	Occupancy level air-speed (m/s)	0.391	0.291	0.351	0.275	0.217
	Transitional/ Mid- season (Typical hour)					
	Occupancy level air-temp. (°C)	22.1-23.0	22.1-22.9	22.1-22.8	22.1-22.9	22.1-22.6
	Mean air-temp. (°C)	22.5	22.5	22.4	22.5	22.3
	Occupancy level air-speed (m/s)	0.131	0.083	0.103	0.065	0.098
	Cooling & heating energy demand (Kwh/m^2.year)	90.9	90.09	90.09	90.09	90.09

Table D-9. Results of the models energy performance and the skycourts air temperature and airspeed at occupancy level under different air inlet & outlet openings positions in skycourt

	Case	Air Pos. a	Air Pos. b	Air Pos. c	Air Pos. d
Skycourt prototype A	**Summer (Hottest hour)**				
	Occupancy level air-temp. (°C)	25.0-28.5	25.0-29.3	25.0-28.5	25.0-28.8
	Mean air-temp. (°C)	26.7	27.0	26.8	27.0
	Occupancy level air-speed (m/s)	0.225	0.250	0.201	0.239
	Winter (Coldest hour)				
	Occupancy level air-temp. (°C)	14.2-19.9	14.0-19.9	14.7-19.9	14.5-19.8
	Mean air-temp. (°C)	15.6	15.2	15.6	15.2
	Occupancy level air-speed (m/s)	0.332	0..371	0.390	0.393
	Transitional/ Mid- season (Typical hour)				
	Occupancy level air-temp. (°C)	22.0-22.5	22.0-22.6	22.0-22.6	22.0-22.7
	Mean air-temp. (°C)	22.1	22.2	22.3	22.3
	Occupancy level air-speed (m/s)	0.175	0.167	0.119	0.150
	Cooling & heating energy demand (Kwh/m^2.year)	91.96	91.96	91.96	91.96
Skycourt prototype B	**Summer (Hottest hour)**				
	Occupancy level air-temp. (°C)	25.0-28.7	25.0-28.8	25.0-28.7	25.0-29.0
	Mean air-temp. (°C)	26.8	27.0	26.8	27.1
	Occupancy level airspeed (m/s)	0.206	0.260	0.205	0.238
	Winter (Coldest hour)				
	Occupancy level air-temp. (°C)	13.1-19.9	13.0-19.8	12.9-19.9	13.0-19.9
	Mean air-temp. (°C)	14.5	14.2	14.4	14.3
	Occupancy level air-speed (m/s)	0.377	0.376	0.415	0.411
	Transitional/ Mid- season (Typical hour)				
	Occupancy level air-temp. (°C)	22.0-22.7	22.0-22.7	22.0-22.7	22.0-22.7
	Mean air-temp. (°C)	22.3	22.3	22.2	22.3
	Occupancy level air-speed (m/s)	0.156	0.109	0.130	0.098
	Cooling & heating energy demand (Kwh/m^2.year)	91.52	91.52	91.52	91.52
Skycourt prototype C	**Summer (Hottest hour)**				
	Occupancy level air-temp. (°C)	25.1-29.0	25.1-30.2	25.1-29.9	25.1-30.5
	Mean air-temp. (°C)	27.6	27.6	27.7	17.6
	Occupancy level air-speed (m/s)	0.179	0.196	0.193	0.188
	Winter (Coldest hour)				
	Occupancy level air-temp. (°C)	11.4-19.8	11.2-19.7	9.5-19.7	11.6-19.8
	Mean air-temp. (°C)	13.1	12.8	12.5	12.9
	Occupancy level air-speed (m/s)	0.391	0.321	0.354	0.383
	Transitional/ Mid- season (Typical hour)				
	Occupancy level air-temp. (°C)	22.1-23.0	22.1-22.9	22.1-23.0	22.1-22.9
	Mean air-temp. (°C)	22.5	22.5	22.5	22.5
	Occupancy level air-speed (m/s)	0.131	0.106	0.143	0.083
	Cooling & heating energy demand (Kwh/m^2.year)	90.9	90.9	90.9	90.9

Table D-10. Results of the models energy performance and the skycourts air temperature and airspeed at occupancy level for the improved configuration alternatives of skycourts

	Case	A1: Skycourt-A alternative one	A2: Skycourt-A alternative two	A3: Skycourt-A alternative three	A4: Skycourt-A alternative four
Skycourt prototype A	**Summer (Hottest hour)**				
	Occupancy level air-temp. (°C)	25.0-27.9	25.0-26.4	25.0-26.9	25.0-26.0
	Mean air-temp. (°C)	26.2	25.7	25.9	25.4
	Occupancy level air-speed (m/s)	0.238	0.236	0.231	0.183
	Winter (Coldest hour)				
	Occupancy level air-temp. (°C)	16.0-19.8	15.5-19.9	16.8-19.9	16.5-19.9
	Mean air-temp. (°C)	16.7	16.4	17.6	17.7
	Occupancy level air-speed (m/s)	0.393	0.384	0.290	0.295
	Transitional/ Mid- season (Typical hour)				
	Occupancy level air-temp. (°C)	22.0-22.6	22.0-22.4	22.0-22.4	21.9-22.4
	Mean air-temp. (°C)	22.1	22.2	22.2	22.1
	Occupancy level air-speed (m/s)	0.183	0.214	0.210	0.190
	Cooling & heating energy demand (Kwh/m^2.year)	91.18	91.23	91.42	91.37
	Case	**B1: Skycourt-B alternative one**	**B2: Skycourt-B alternative two**	**B3: Skycourt-B alternative three**	**B4: Skycourt-B alternative four**
Skycourt prototype B	**Summer (Hottest hour)**				
	Occupancy level air-temp. (°C)	25.0-28.2	25.0-27.3	25.0-27.5	25.0-27.3
	Mean air-temp. (°C)	26.4	25.9	25.9	26.1
	Occupancy level air-speed (m/s)	0.232	0.276	0.260	0.273
	Winter (Coldest hour)				
	Occupancy level air-temp. (°C)	13.8-19.9	12.1-19.6	13.8-19.8	13.7-19.8
	Mean air-temp. (°C)	15.4	14.3	15.6	15.5
	Occupancy level air-speed (m/s)	0.417	0.383	0.442	0.442
	Transitional/ Mid- season (Typical hour)				
	Occupancy level air-temp. (°C)	22.0-22.6	22.1-22.5	22.0-22.6	22.0-22.5
	Mean air-temp. (°C)	22.2	22.2	22.2	22.2
	Occupancy level air-speed (m/s)	0.166	0.160	0.181	0.196
	Cooling & heating energy demand (Kwh/m^2.year)	90.79	90.98	90.87	90.93
	Case	**C1: Skycourt-C alternative one**	**C2: Skycourt-C alternative two**	**C3: Skycourt-C alternative three**	**C4: Skycourt-C alternative four**
Skycourt prototype C	**Summer (Hottest hour)**				
	Occupancy level air-temp. (°C)	25.1-29.0	25.1-27.7	25.1-29.5	25.0-27.5
	Mean air-temp. (°C)	27.6	26.4	27.4	26.3
	Occupancy level airspeed (m/s)	0.179	0.155	0.184	0.152
	Winter (Coldest hour)				
	Occupancy level air-temp. (°C)	11.4-19.8	10.3-19.9	11.0-20.0	11.8-19.9
	Mean air-temp. (°C)	13.1	12.5	13.3	13.6
	Occupancy level air-speed (m/s)	0.391	0.363	0.384	0.294
	Transitional/ Mid- season (Typical hour)				
	Occupancy level air-temp. (°C)	22.1-23.0	22.1-22.7	22.1-23.0	22.1-22.9
	Mean air-temp. (°C)	22.5	22.3	22.6	22.5
	Occupancy level air-speed (m/s)	0.131	0.084	0.122	0.122
	Cooling & heating energy demand (Kwh/m^2.year)	90.9	91.41	90.13	90.51

Table D-11. Comparison for results of energy performance for the reference model, base case and optimal case among the simulation cases

	Case	Reference skycourt	Base case skycourt	Optimal skycourt
Skycourt prototype A	Heating Demand (Kwh/m^2.yr)	29.29	19.13	18.25
	Annual Heating Demand Reduction (%)	-	34.7 %	37.7 %
	Cooling Demand (Kwh/m^2.yr)	191.17	72.83	72.25
	Annual Cooling Demand Reduction (%)	-	61.9 %	62.2 %
	Total Heating & Cooling Demand (Kwh/m^2.yr)	220.46	91.96	91.18
	Annual Heating & Cooling Demand Reduction (%)	-	58.29 %	58.64 %
Skycourt prototype B	Heating Demand (Kwh/m^2.yr)	32.89	18.93	18.74
	Annual Heating Demand Reduction (%)	-	42.4 %	43.0 %
	Cooling Demand (Kwh/m^2.yr)	212.19	72.59	72.05
	Annual Cooling Demand Reduction (%)	-	65.8 %	66.0 %
	Total Heating & Cooling Demand (Kwh/m^2.yr)	245.08	91.52	90.79
	Annual Heating & Cooling Demand Reduction (%)	-	62.66 %	62.95 %
Skycourt prototype C	Heating Demand (Kwh/m^2.yr)	40.66	18.61	18.41
	Annual Heating Demand Reduction (%)	-	54.2 %	54.7 %
	Cooling Demand (Kwh/m^2.yr)	288.98	72.29	71.72
	Annual Cooling Demand Reduction (%)	-	74.9 %	75.2 %
	Total Heating & Cooling Demand (Kwh/m^2.yr)	329.64	90.90	90.13
	Annual Heating & Cooling Demand Reduction (%)	-	72.42 %	72.66 %

Table D-12. Comparison for results of the skycourts air temperature and airspeed at occupancy level for the reference model, base case and optimal case among the simulation cases

	Case	Reference skycourt	Base case skycourt	Optimal skycourt
Skycourt prototype A	**Summer (Hottest hour)**			
	Skycourt air-temp. (°C)	18.2-27.5	25.0-28.5	25.0-27.9
	Mean air-temp. (°C)	25.0	26.7	26.2
	Skycourt air-speed (m/s)	0.077	0.225	0.238
	Winter (Coldest hour)			
	Skycourt air-temp. (°C)	17.3-24.1	14.2-19.9	16.0-19.8
	Mean air-temp. (°C)	19.1	15.6	16.7
	Skycourt air-speed (m/s)	0.31	0.332	0.404
	Transitional/ Mid- season (Typical hour)			
	Skycourt air-temp. (°C)	20.0-22.0	22.0-22.5	22.0-22.6
	Mean air-temp. (°C)	21.1	22.1	22.1
	Skycourt air-speed (m/s)	0.061	0.175	0.183
Skycourt prototype B	**Summer (Hottest hour)**			
	Skycourt air-temp. (°C)	18.2-27.5	25.0-28.7	25.0-28.2
	Mean air-temp. (°C)	25.0	26.8	26.4
	Skycourt air-speed (m/s)	0.092	0.206	0.259
	Winter (Coldest hour)			
	Skycourt air-temp. (°C)	16.8-23.9	13.1-19.9	13.8-19.9
	Mean air-temp. (°C)	19.0	14.5	15.4
	Skycourt air-speed (m/s)	0.33	0.377	0.447
	Transitional/ Mid- season (Typical hour)			
	Skycourt air-temp. (°C)	19.3-21.5	22.0-22.7	22.0-22.6
	Mean air-temp. (°C)	21.2	22.3	22.2
	Skycourt air-speed (m/s)	0.056	0.156	0.166
Skycourt prototype C	**Summer (Hottest hour)**			
	Skycourt air-temp. (°C)	18.2-28.0	25.1-29.0	25.1-29.5
	Mean air-temp. (°C)	25.1	27.6	27.4
	Skycourt air-speed (m/s)	0.084	0.179	0.184
	Winter (Coldest hour)			
	Skycourt air-temp. (°C)	16.3-23.6	11.4-19.8	11.0-20.0
	Mean air-temp. (°C)	18.8	13.1	13.3
	Skycourt air-speed (m/s)	0.34	0.311	0.304
	Transitional/ Mid- season (Typical hour)			
	Skycourt air-temp. (°C)	20.3-21.2	22.1-23.0	22.1-23.0
	Mean air-temp. (°C)	20.6	22.5	22.6
	Skycourt air-speed (m/s)	0.03	0.131	0.122

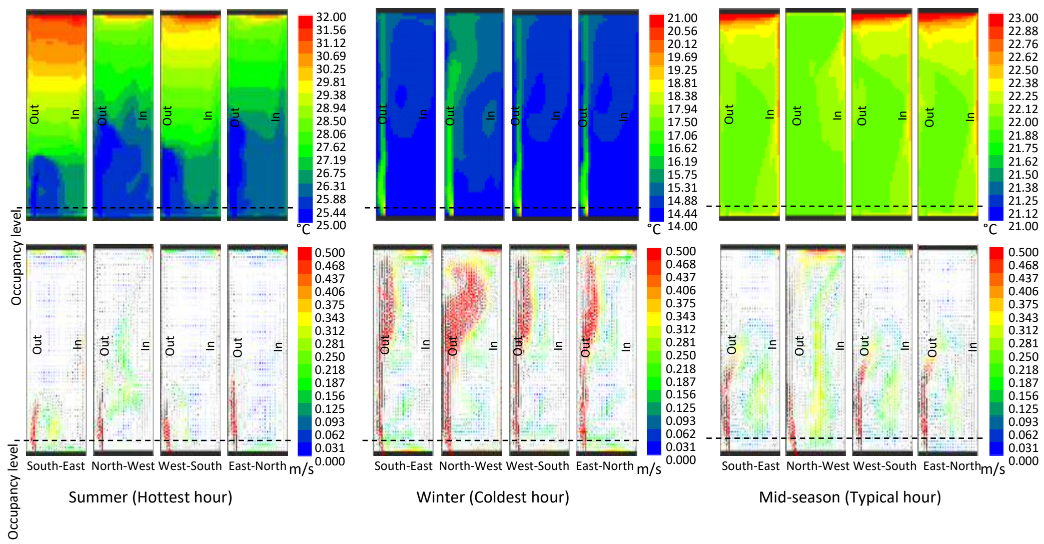


Figure D-1. Thermal conditions in skycourt (B) at the hottest hour in summer, the coldest hour in winter and typical hour in mid-season: orientation

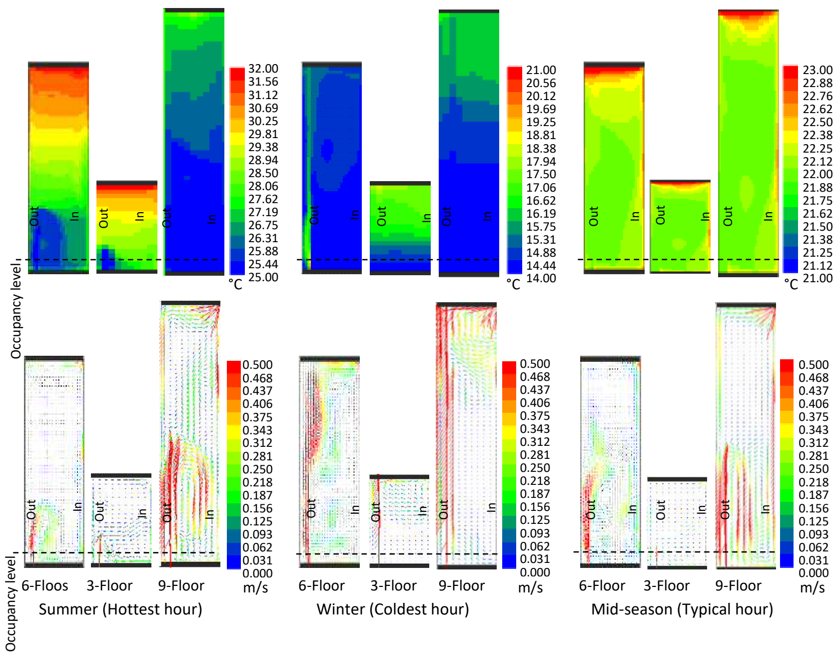


Figure D-2. Thermal conditions in skycourt (B) at the hottest hour in summer, the coldest hour in winter and typical hour in mid-season: height

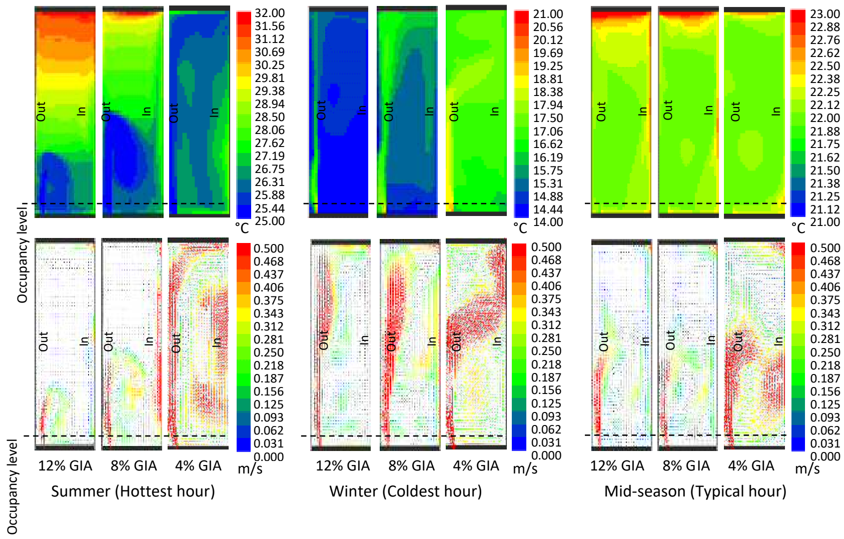


Figure D-3. Thermal conditions in skycourt (B) at the hottest hour in summer, the coldest hour in winter and typical hour in mid-season: area to GIA

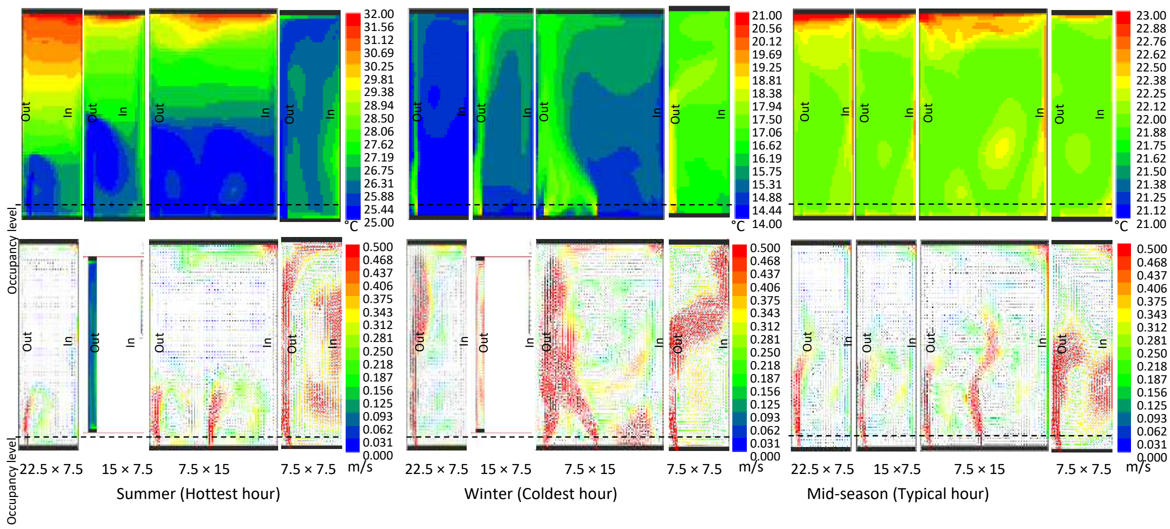


Figure D-4. Thermal conditions in skycourt (B) at the hottest hour in summer, the coldest hour in winter and typical hour in mid-season: length and depth

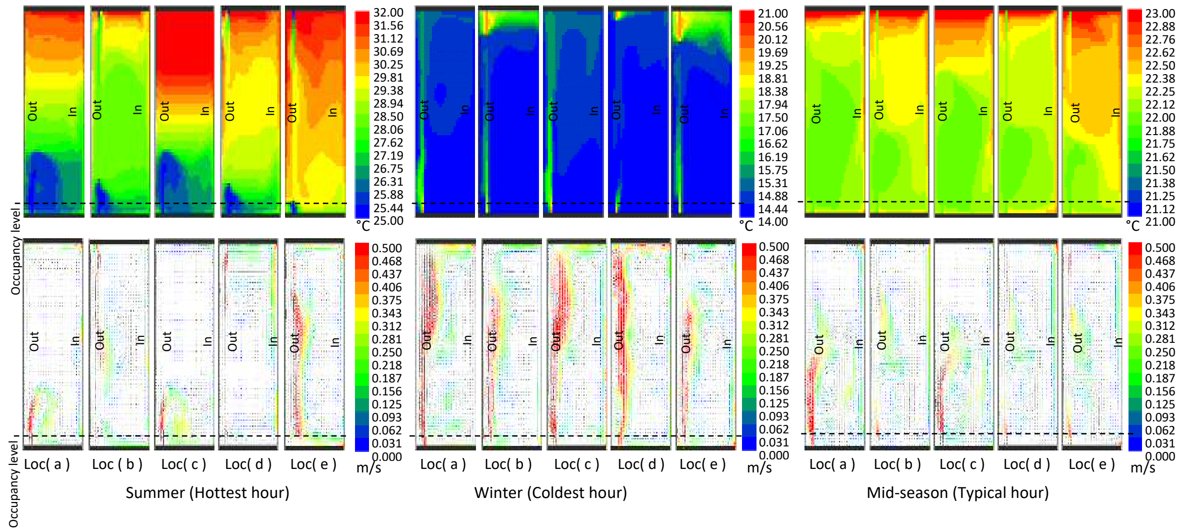


Figure D-5. Thermal conditions in skycourt (B) at the hottest hour in summer, the coldest hour in winter and typical hour in mid-season: air inlet and outlet openings vertical distribution

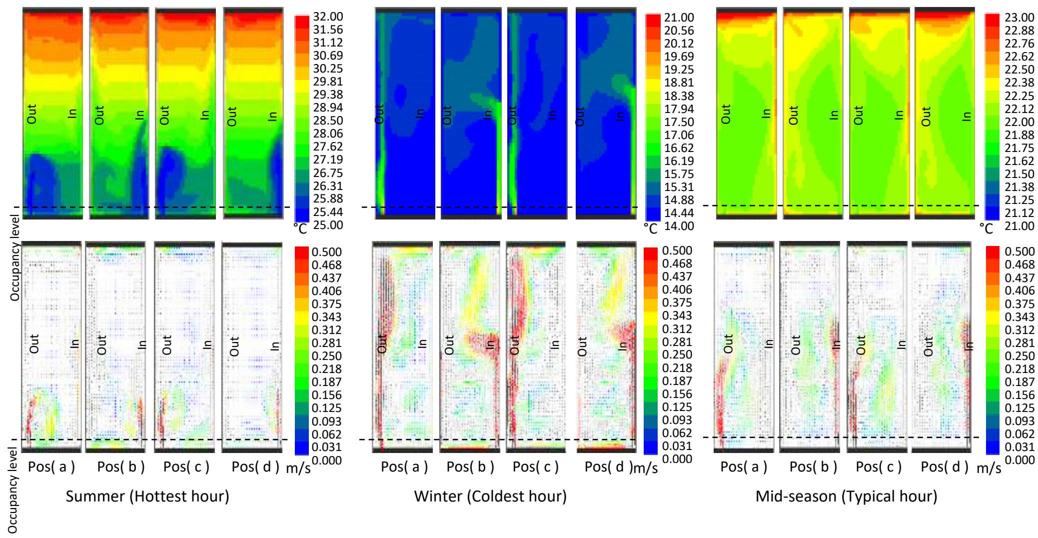


Figure D-6. Thermal conditions in skycourt (B) at the hottest hour in summer, the coldest hour in winter and typical hour in mid-season: air inlet and outlet openings horizontal positions

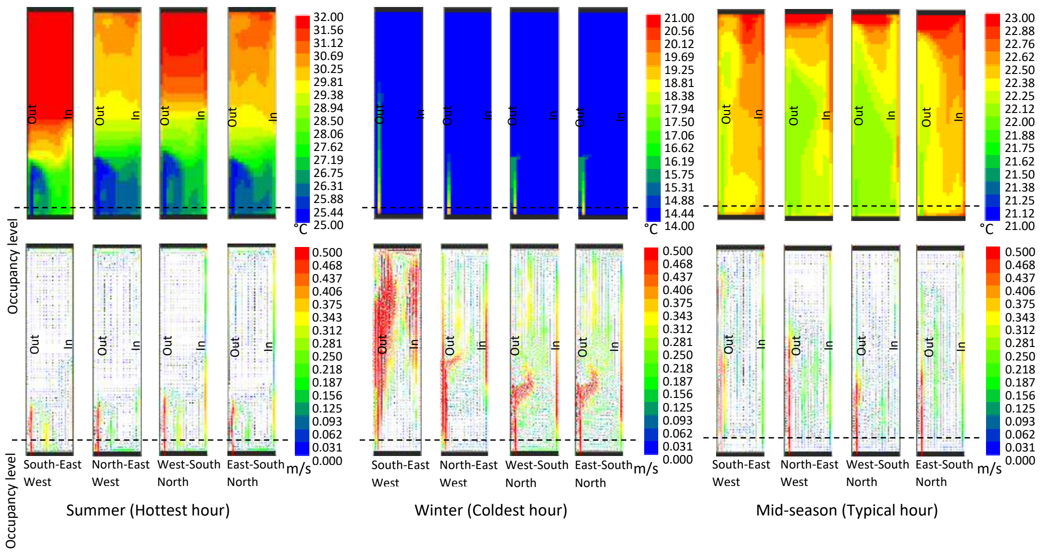


Figure D-7. Thermal conditions in skycourt (C) at the hottest hour in summer, the coldest hour in winter and typical hour in mid-season: orientation

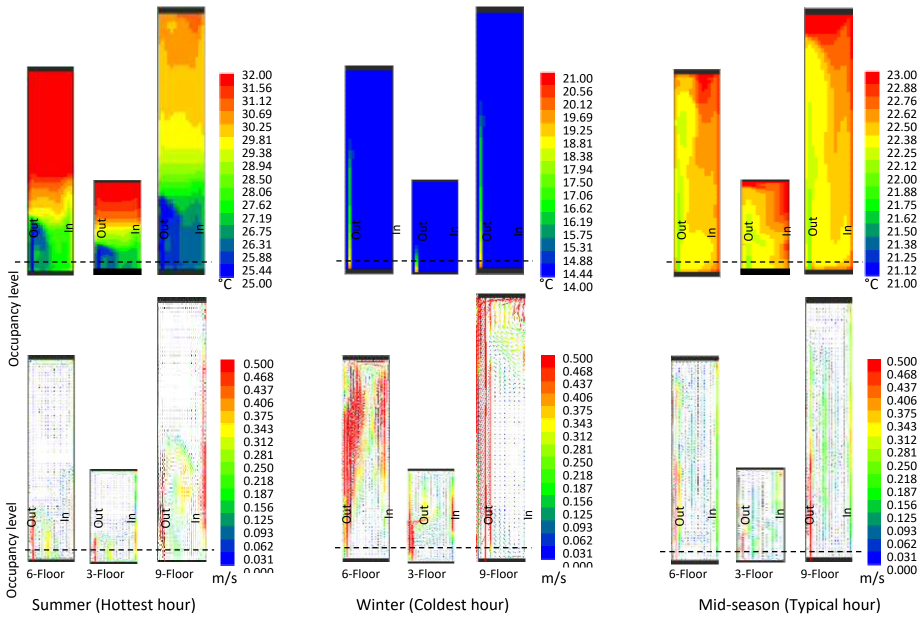


Figure D-8. Thermal conditions in skycourt (C) at the hottest hour in summer, the coldest hour in winter and typical hour in mid-season: height

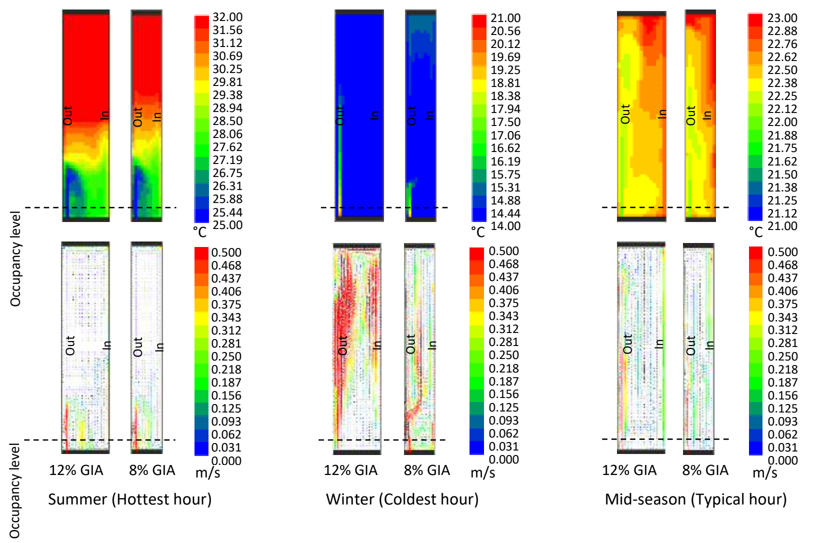


Figure D-9. Thermal conditions in skycourt (C) at the hottest hour in summer, the coldest hour in winter and typical hour in mid-season: area to GIA

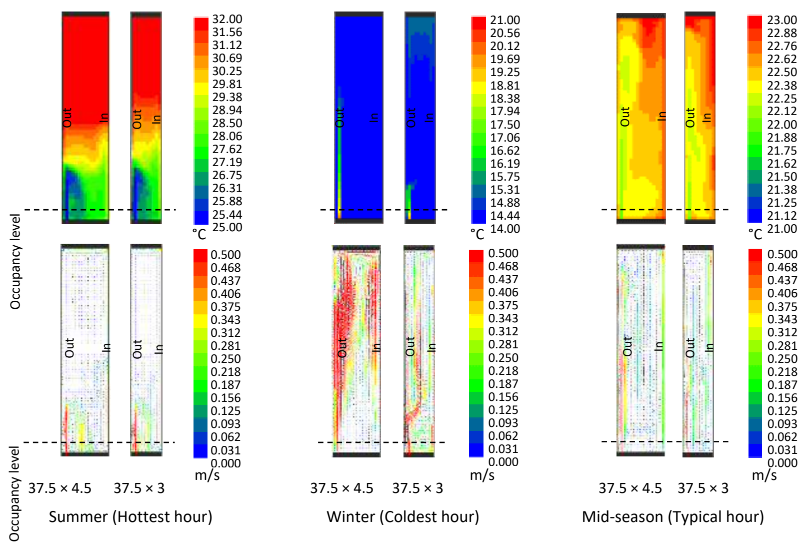


Figure D-10. Thermal conditions in skycourt (C) at the hottest hour in summer, the coldest hour in winter and typical hour in mid-season: length and depth

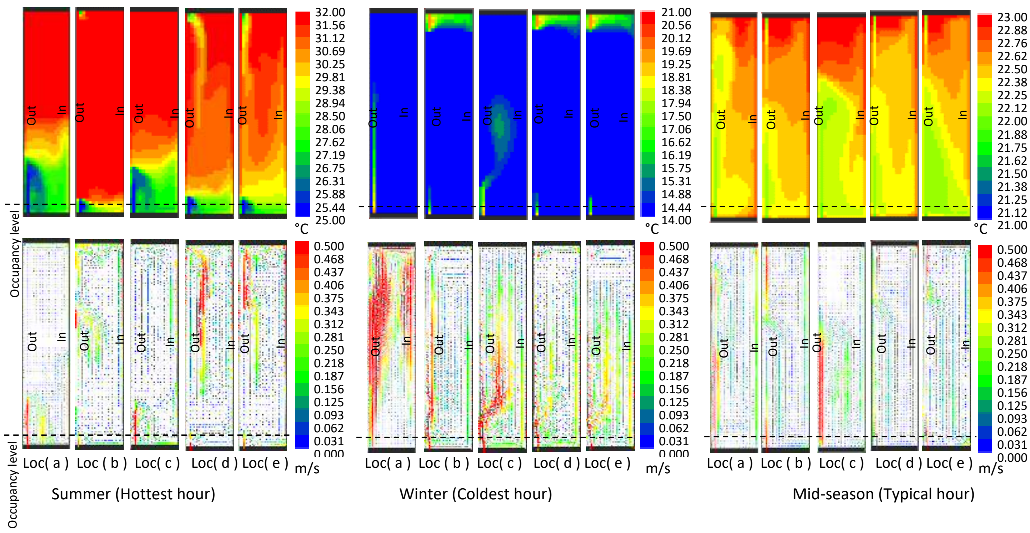


Figure D-11. Thermal conditions in skycourt (C) at the hottest hour in summer, the coldest hour in winter and typical hour in mid-season: air inlet and outlet openings vertical distribution

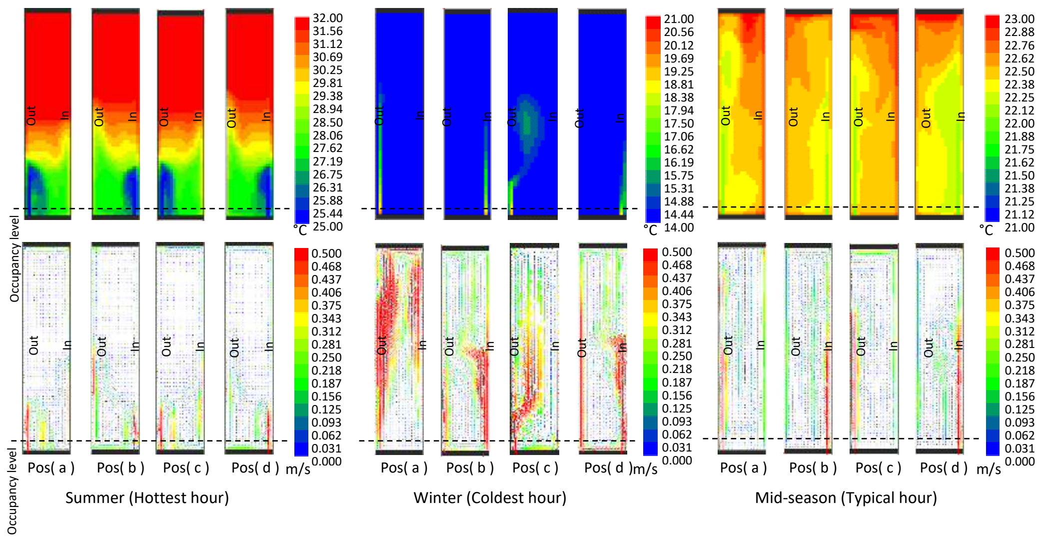


Figure D-12. Thermal conditions in skycourt (C) at the hottest hour in summer, the coldest hour of winter and typical hour in mid-season: air inlet and outlet openings horizontal positions

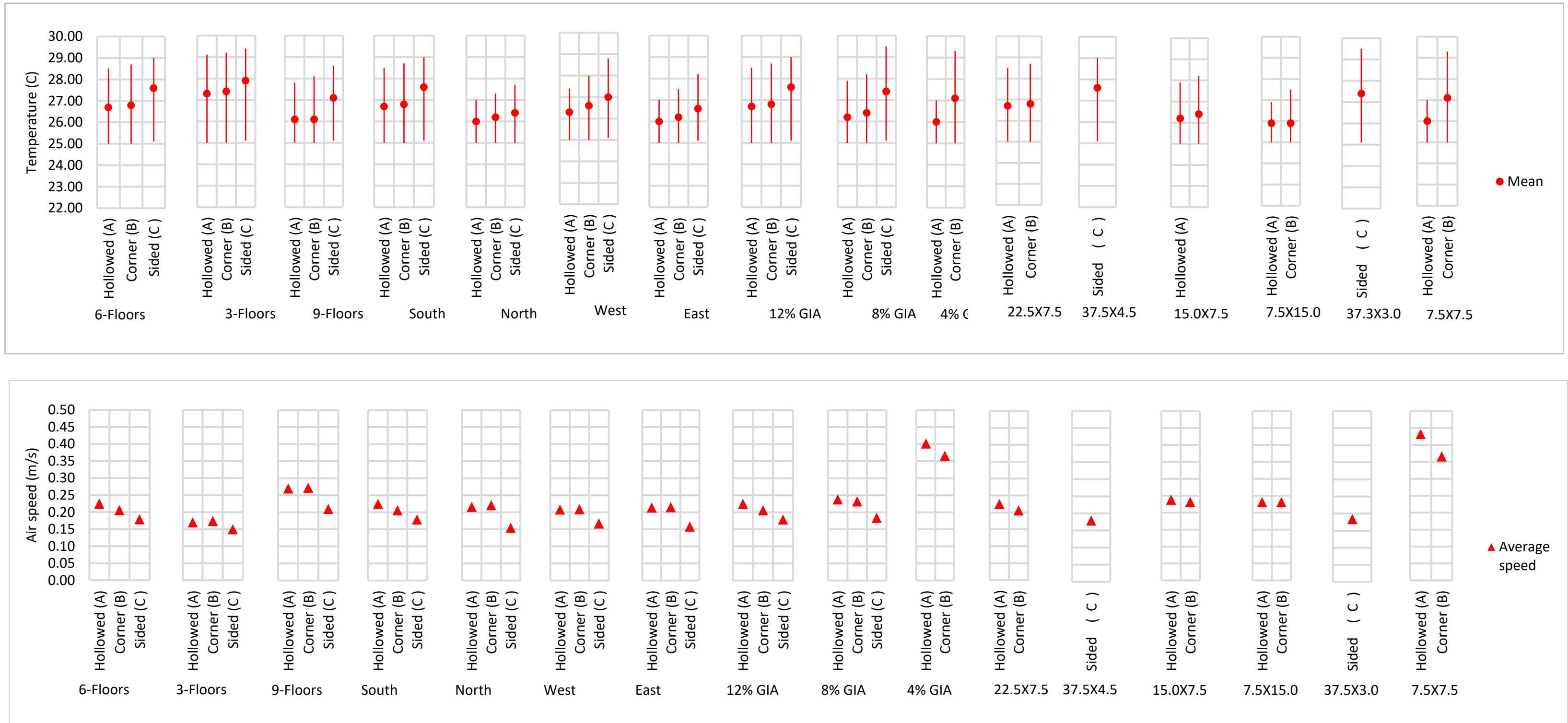


Figure D-13. Thermal conditions comparison at occupancy level of the (A) hollowed-out, (B) corner and (C) sided ventilated skycourts in summer case: geometric configurations

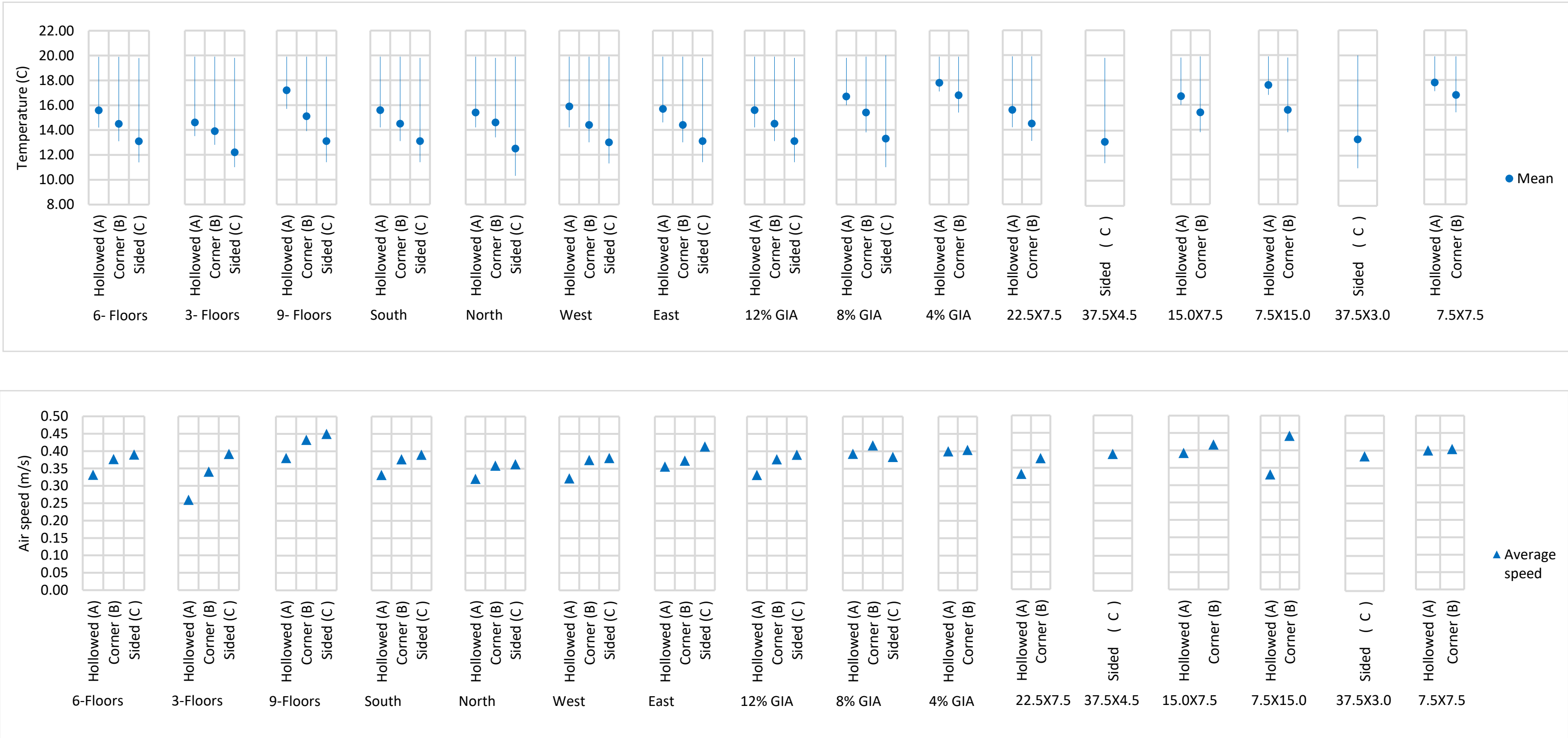


Figure D-14. Thermal conditions at the occupancy level of the (A) hollowed-out, (B) corner and (C) sided ventilated skycourts in winter case: geometric configurations

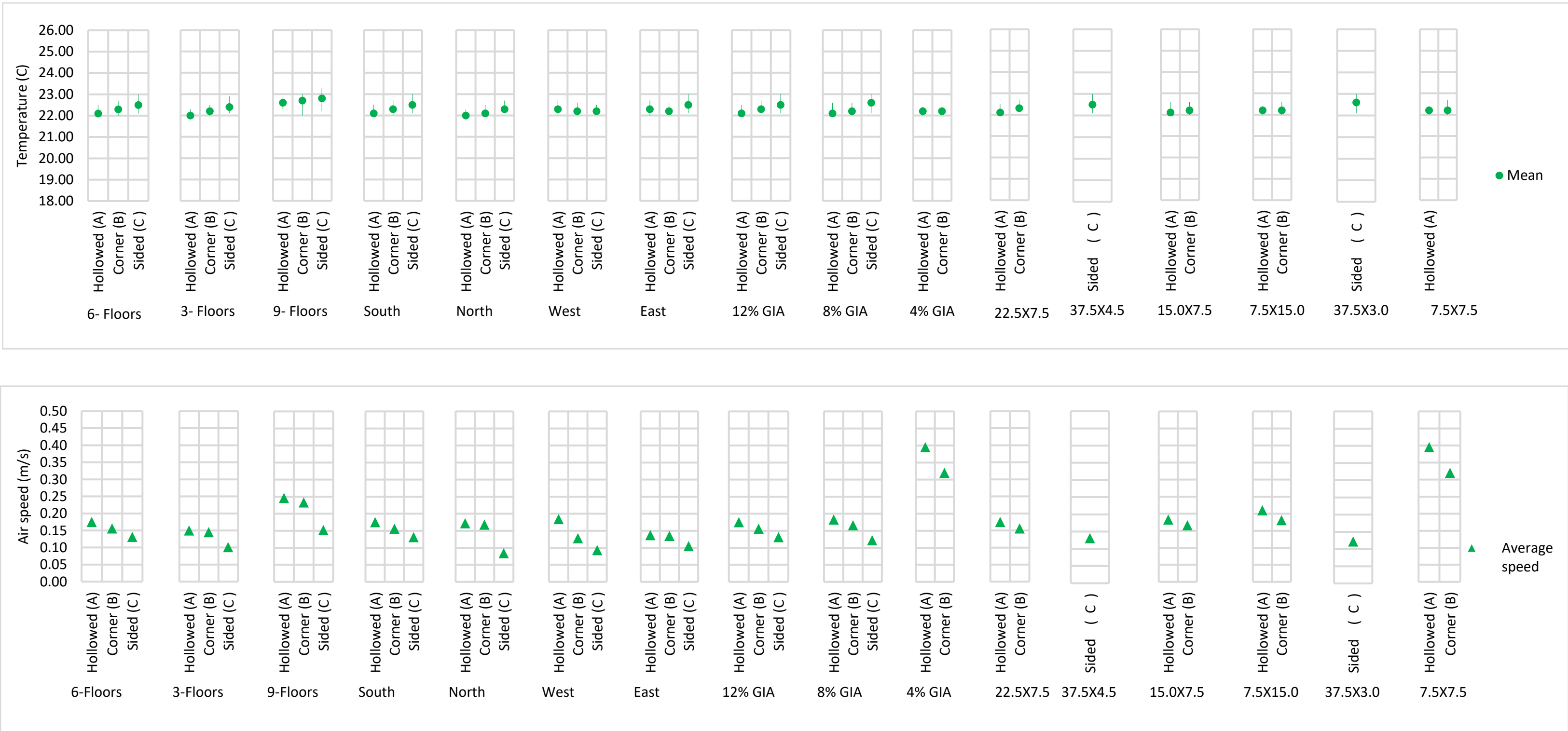


Figure D-15. Thermal conditions at the occupancy level of the (A) hollowed-out, (B) corner and (C) sided ventilated skycourts in mid-seasons cases: geometric configuration

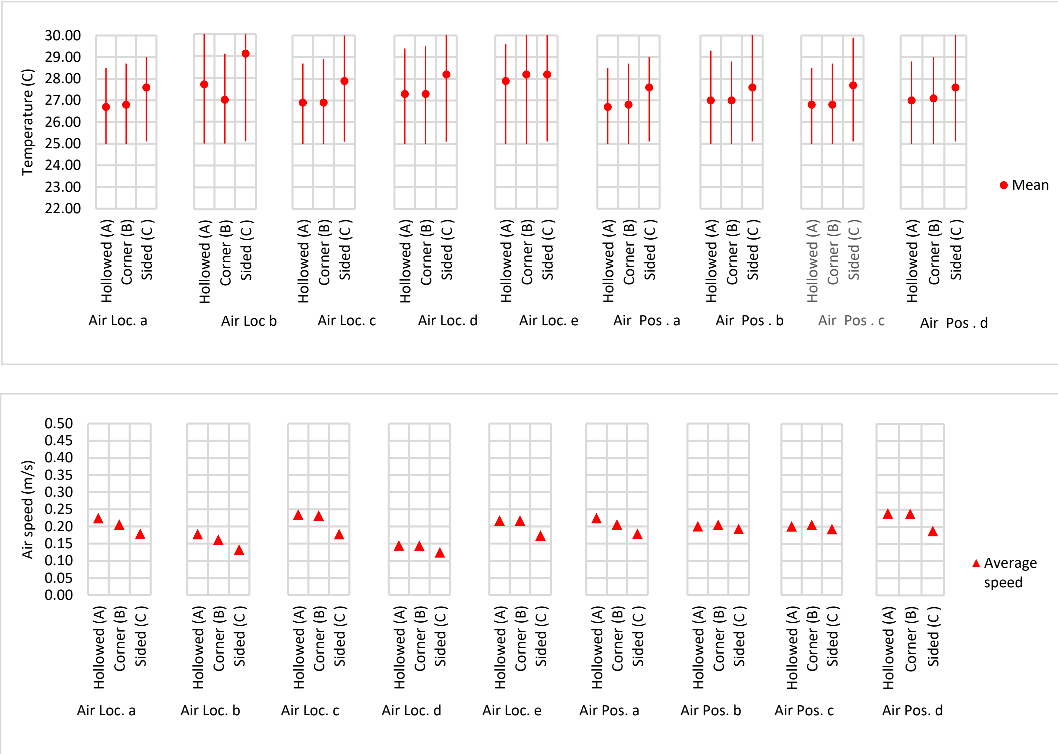


Figure D-16. Thermal conditions comparison at occupancy level of the (A) hollowed-out, (B) corner and (C) sided ventilated skycourts in summer case: air inlet and outlet openings

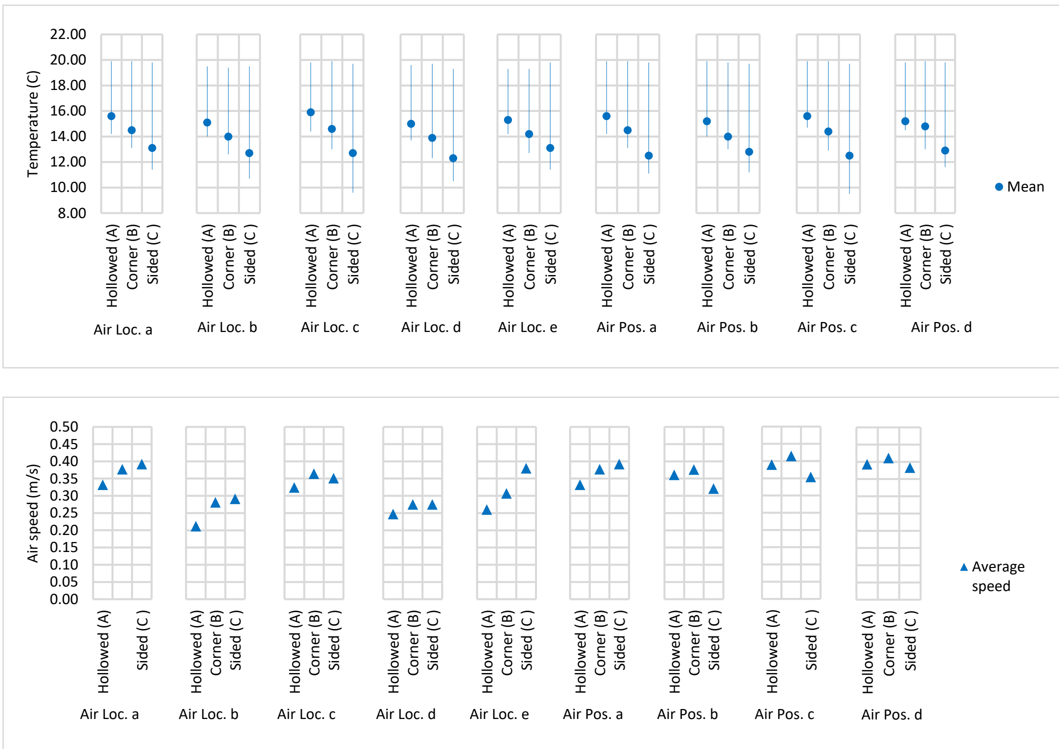


Figure D-17. Thermal conditions at the occupancy level of the (A) hollowed-out, (B) corner and (C) sided ventilated skycourts in winter cases: air inlet and outlet openings

Figure D-18. Thermal conditions at the occupancy level of the (A) hollowed-out, (B) corner and (C) sided ventilated skycourts in mid-seasons cases: air inlet and outlet openings

Table D-13. Results of the skycourts energy performance in (Kwh/m^2.yr) under the isolated ventilation strategy

Case	Energy Demand	Heating	Cooling	Power	Solar	Ventilation	Fabric
Skycourt prototype A	1085.84	10.41	117.17	28.09	496.76	30.65	462.95
Skycourt prototype B	1372.04	14.02	138.48	28.09	636.05	34.02	521.38
Skycourt prototype C	2109.72	22.03	215.73	28.09	996.56	40.25	806.48

Table D-14. Results of the skycourts energy performance in (Kwh/m^2.yr) under the combined ventilation strategies

	Case	Energy Demand	Heating	Cooling	Power	Solar	Ventilation	Fabric
Skycourt prototype A	**Strategy One (V1)**	1065.42	0	0	28.09	496.76	017.94	522.63
	Strategy Two (V2)	1065.42	0	0	28.09	496.76	138.83	401.73
	Strategy Three (V3)	1065.42	0	0	28.09	496.76	117.00	423.56
	Strategy Four (V4)	1065.42	0	0	28.09	496.76	216.37	324.19
	Strategy Five (V5)	1065.42	0	0	28.09	496.76	227.03	313.53
Skycourt prototype B	**Strategy One (V1)**	1344.00	0	0	28.09	636.05	023.15	656.71
	Strategy Two (V2)	1344.00	0	0	28.09	636.05	163.14	516.72
	Strategy Three (V3)	1344.00	0	0	28.09	636.05	137.49	542.37
	Strategy Four (V4)	1344.00	0	0	28.09	636.05	294.36	385.50
	Strategy Five (V5)	1344.00	0	0	28.09	636.05	249.76	430.10
Skycourt prototype C	**Strategy One (V1)**	2065.04	0	0	28.09	996.56	035.35	1005.03
	Strategy Two (V2)	2065.04	0	0	28.09	996.56	233.72	806.66
	Strategy Three (V3)	2065.04	0	0	28.09	996.56	187.87	852.51
	Strategy Four (V4)	2065.04	0	0	28.09	996.56	400.82	639.56
	Strategy Five (V5)	2065.04	0	0	28.09	996.56	325.59	714.79

Table D-15. Results of the skycourts energy performance in (Kwh/m².yr) under different orientations of skycourt

	Case	Energy Demand	Heating	Cooling	Power	Solar	Ventilation	Fabric
Skycourt prototype A	South (S)	1065.42	0	0	28.09	496.76	138.83	401.73
	North (N)	776.10	0	0	28.09	352.10	058.13	337.77
	West (W)	935.76	0	0	28.09	431.93	095.93	379.81
	East (E)	908.53	0	0	28.09	418.32	093.49	368.62
Skycourt prototype B	South- East (S-E)	1344.00	0	0	28.09	636.05	163.14	516.72
	North- West (N-W)	1063.76	0	0	28.09	495.93	083.72	456.02
	West- South (W-S)	1266.59	0	0	28.09	597.34	135.56	505.79
	East- North (E-N)	1143.02	0	0	28.09	535.56	106.34	473.03
Skycourt prototype C	South- East West (E-EW)	2065.04	0	0	28.09	996.56	233.72	806.66
	North- East West (N-EW)	1582.73	0	0	28.09	755.41	110.61	688.62
	West- South North (W-SN)	1851.86	0	0	28.09	889.98	169.41	764.39
	East- South North (E-SN)	1806.45	0	0	28.09	867.27	166.19	744.90

Table D-16. Results of the skycourts energy performance in (Kwh/m².yr) under different areas of skycourt

	Case	Energy Demand	Heating	Cooling	Power	Solar	Ventilation	Fabric
Skycourt prototype A	(12%) GIA	1065.42	0	0	28.09	496.76	138.83	401.73
	(8%) GIA	1065.95	0	0	28.09	497.03	146.81	394.02
	(4%) GIA	1064.22	0	0	28.09	496.22	154.53	385.48
Skycourt prototype B	(12%) GIA	1344.00	0	0	28.09	636.05	163.14	516.72
	(8%) GIA	1483.82	0	0	28.09	705.96	185.57	564.20
	(4%) GIA	1900.08	0	0	28.09	914.09	237.60	720.30
Skycourt prototype C	(12%) GIA	2065.04	0	0	28.09	996.56	233.72	806.66
	(8%) GIA	2894.06	0	0	28.09	1411.07	337.85	1117.05

Table D-17. Results of the skycourts energy performance in (Kwh/m^2.yr) under different lengths and depths of skycourt

	Case	Energy Demand	Heating	Cooling	Power	Solar	Ventilation	Fabric
Skycourt prototype A	**22.5 m × 7.5 m**	1065.42	0	0	28.09	496.76	138.83	401.73
	15 m × 7.5 m	1065.95	0	0	28.09	497.03	146.81	394.02
	7.5 m × 15 m	0568.10	0	0	28.09	248.11	082.39	209.51
	7.5 m × 7.5 m	1064.22	0	0	28.09	496.22	154.53	385.48
Skycourt prototype B	**22.5 m × 7.5 m**	1344.00	0	0	28.09	636.05	163.14	516.72
	15 m × 7.5 m	1483.82	0	0	28.09	705.96	185.57	564.20
	7.5 m × 15 m	1405.21	0	0	28.09	666.65	161.59	548.88
	7.5 m × 7.5 m	1900.08	0	0	28.09	914.09	237.60	720.30
Skycourt prototype C	**37.5 m × 4.5 m**	2065.04	0	0	28.09	996.56	233.72	806.66
	37.5 m × 3 m	2894.06	0	0	28.09	1411.07	337.85	1117.05

Table D-18. Results of the skycourts energy performance in (Kwh/m^2.yr) under different inlet & outlet openings locations in skycourt

	Case	Energy Demand	Heating	Cooling	Power	Solar	Ventilation	Fabric
Skycourt prototype A	**Air Loc. a**	1065.42	0	0	28.09	496.76	138.83	401.73
	Air Loc. b	1065.42	0	0	28.09	496.76	138.83	401.73
	Air Loc. c	1065.42	0	0	28.09	496.76	138.83	401.73
	Air Loc. d	1065.42	0	0	28.09	496.76	138.83	401.73
	Air Loc. e	1065.42	0	0	28.09	496.76	138.83	401.73
Skycourt prototype B	**Air Loc. a**	1344.00	0	0	28.09	636.05	163.14	516.72
	Air Loc. b	1344.00	0	0	28.09	636.05	163.14	516.72
	Air Loc. c	1344.00	0	0	28.09	636.05	163.14	516.72
	Air Loc. d	1344.00	0	0	28.09	636.05	163.14	516.72
	Air Loc. e	1344.00	0	0	28.09	636.05	163.14	516.72
Skycourt prototype C	**Air Loc. a**	2065.04	0	0	28.09	996.56	233.72	806.66
	Air Loc. b	2065.04	0	0	28.09	996.56	233.72	806.66
	Air Loc. c	2065.04	0	0	28.09	996.56	233.72	806.66
	Air Loc. d	2065.04	0	0	28.09	996.56	233.72	806.66
	Air Loc. e	2065.04	0	0	28.09	996.56	233.72	806.66

Table D-19. Results of the skycourts energy performance in (Kwh/m^2.yr) under different inlet & outlet openings positions in skycourt

	Case	Energy Demand	Heating	Cooling	Power	Solar	Ventilation	Fabric
Skycourt prototype A	**Air Pos. a**	1065.42	0	0	28.09	496.76	138.83	401.73
	Air Pos. b	1065.42	0	0	28.09	496.76	138.83	401.73
	Air Pos. c	1065.42	0	0	28.09	496.76	138.83	401.73
	Air Pos. d	1065.42	0	0	28.09	496.76	138.83	401.73
Skycourt prototype B	**Air Pos. a**	1344.00	0	0	28.09	636.05	163.14	516.72
	Air Pos. b	1344.00	0	0	28.09	636.05	163.14	516.72
	Air Pos. c	1344.00	0	0	28.09	636.05	163.14	516.72
	Air Pos. d	1344.00	0	0	28.09	636.05	163.14	516.72
Skycourt prototype C	**Air Pos. a**	2065.04	0	0	28.09	996.56	233.72	806.66
	Air Pos. b	2065.04	0	0	28.09	996.56	233.72	806.66
	Air Pos. c	2065.04	0	0	28.09	996.56	233.72	806.66
	Air Pos. d	2065.04	0	0	28.09	996.56	233.72	806.66

Table D-20. Results of the skycourts energy performance in (Kwh/m^2.yr) for the improved configuration alternatives of skycourts

	Case	Energy Demand	Heating	Cooling	Power	Solar	Ventilation	Fabric
Skycourt prototype A	**A1: Skycourt-A alternative one**	1065.95	0	0	28.09	497.03	146.81	394.02
	A2: Skycourt-A alternative two	776.47	0	0	28.09	352.29	61.69	334.40
	A3: Skycourt-A alternative three	0568.10	0	0	28.09	248.11	082.39	209.51
	A4: Skycourt-A alternative four	423.60	0	0	28.09	175.86	39.70	179.94
Skycourt prototype B	**B1: Skycourt-B alternative one**	1483.82	0	0	28.09	705.96	185.57	564.20
	B2: Skycourt-B alternative two	1207.95	0	0	28.09	568.03	102.67	509.16
	B3: Skycourt-B alternative three	1405.21	0	0	28.09	666.65	161.59	548.88
	B4: Skycourt-B alternative four	1287.97	0	0	28.09	608.03	122.83	529.01
Skycourt prototype C	**C1: Skycourt-C alternative one**	2065.04	0	0	28.09	996.56	233.72	806.66
	C2: Skycourt-C alternative two	1582.73	0	0	28.09	755.41	110.61	688.62
	C3: Skycourt-C alternative three	2894.06	0	0	28.09	1411.07	337.85	1117.05
	C4: Skycourt-C alternative four	2170.60	0	0	28.09	1049.34	150.17	943.00