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# Ventilated Skycourts to Enhance Energy Savings in High-rise Office Buildings

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**ABSTRACT**

Heating and cooling in high-rise buildings devour about one-third of overall energy consumption. Skycourts is increasingly integrated in high-rise buildings, in particular offices. Skycourts are perceived as transitional and social nodes. This paper aims to investigate potentials of a skycourt when perform as a ventilated buffer zone in offices in a temperate climate. Using a hypothetical office building in London, a coupled approach of energy simulation and CFD was carried out for two ventilation modes; air-conditioned skycourt, and alternative models that incorporate combined ventilation strategies with the adjacent offices' zones of the skycourt. Furthermore, to determine the most critical ventilation conditions, different parameters were investigated. Overall, the results highlight that the incorporation of a ventilated skycourt potentially has a significant impact on the annual energy consumption. The optimized parameters enhance comfort temperature ranges of skycourts. Finally, the study developed guidelines to define the most effective configurations of ventilated skycourts.

**Keywords:** skycourt; ventilation; coupling simulation; energy efficiency; thermal comfort

## Introduction

Skycourts are increasingly incorporated in high-rise office buildings. These spaces act as social gathering areas and transitional spaces that could offer a diversity of social, environmental and economic benefits, and improve the overall performance of buildings (Pomeroy 2014). 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 2013). Skycourts in mid-rise and high-rise buildings could provide a contemporary alternative to courtyards by allowing natural light to penetrate deeper into interior spaces, and promoting ventilation while avoiding unwanted solar gain. Other advantages include the support of occupants' social networking by offering space for seating and relaxation for users while enjoying the outside views. Such potentials make the skycourt an important responsive element that facilitates the holistic sustainable environment and improves the performance of the building.

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). Influence of skycourt in ventilation is considered in relation to two main issues. The first concerns the potential of skycourts to improve the efficiency of airflow in buildings. Skycourts could 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. 2014), segmentation (Liu, Ford, and Etheridge 2012), smart facades and wing forms (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 achieving comfort requirements, thermally and acoustically (Strelitz 2011). This is 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. The second influence 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 recognized 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 and Saleh 2007). This is associated with higher energy costs in a temperate climate due to the excessive solar heat gain in summer and heat loss from large glazed surfaces. 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). In addition, the current HVAC system might not be enough to provide thermal comfort in areas of a large volume, particularly, when they act as buffer spaces, such areas suffer from excessive temperatures compared to other small spaces. Yet, there are limited studies addressing the influence of skycourts on the total performance of buildings (Katolicky, Julinek, and Jicha 2002). So, this study investigates the potential advantages of skycourts as transitional buffer spaces to improve ventilation.

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 about 55% of the total energy consumption in offices (Pérez-Lombard, Ortiz, and Pout 2008). A study (Yuana et al. 2016) analysed the overall level of energy consumption in office buildings that hold sustainable certificates such as LEED and BREEAM, and concluded that the HVAC system accounts 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. Previous studies showed that potentials for energy reduction in buildings could be enhanced by minimizing spaces that are consuming heating and cooling energy or by minimizing requirements for comfortable conditions. Utilizing such strategies in enclosed transitional spaces serving as buffer zones could achieve energy savings by lowering the demand for heating and cooling loads. In addition, accepted levels of thermal comfort could be achieved in these spaces.

Therefore, this study investigates the potential energy advantages of implementing ventilation strategies in skycourts with the absence of heating and cooling in these spaces, taking into consideration achieving accepted levels of thermal comfort in these spaces in office buildings in a temperate climate, such as London. To accomplish this aim, ventilation strategies to achieve thermal conditions of skycourts were investigated. Furthermore, several parameters, which include skycourt's orientation, area, length and depth, and air inlet and air outlet locations and positions within the skycourt, were examined to determine the most critical ventilation conditions. 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.

## Method and Procedures

### *Coupling simulation approach*

The study used a coupling simulation approach in which two models were integrated: Building Energy Simulation (BES) and Computational Fluid Dynamics (CFD). This method produces complementary information about energy consumption and indoor thermal conditions for buildings. Moreover, it predicts results that are more accurate, detailed and quick compared to the separate simulation (Barbason and Reiter 2014; Zhai and Chen 2005). 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 receive more exact and real-time internal thermal conditions and predict the dynamic indoor thermal conditions.

HTB2 and WinAir software were adopted in this study. HTB2 software (version 10) was used to provide information of thermal performance and energy efficiency, while WinAir (version 4) was adopted as the CFD simulation provide information on 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 can estimate the energy demands for buildings during both the preliminary design stage and occupancy period (Lewis and Alexander 1990). 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). WinAir has been developed for conducting ventilation research to predict airflow distribution, air temperature, air velocity and heat transfer. 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 ($\kappa$-$\varepsilon$) turbulence model for the prediction of the airflow.

In the present study, HTB2 and WinAir models were coupled to investigate the thermal conditions in the skycourt. Iteration between these two programs accomplishes graduating and accurate information of air temperature, air velocity and air concentration ( Jones and Kippenberg, 2000). 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 1 illustrates the HTB2 and WinAir coupling approach conducted in the study.

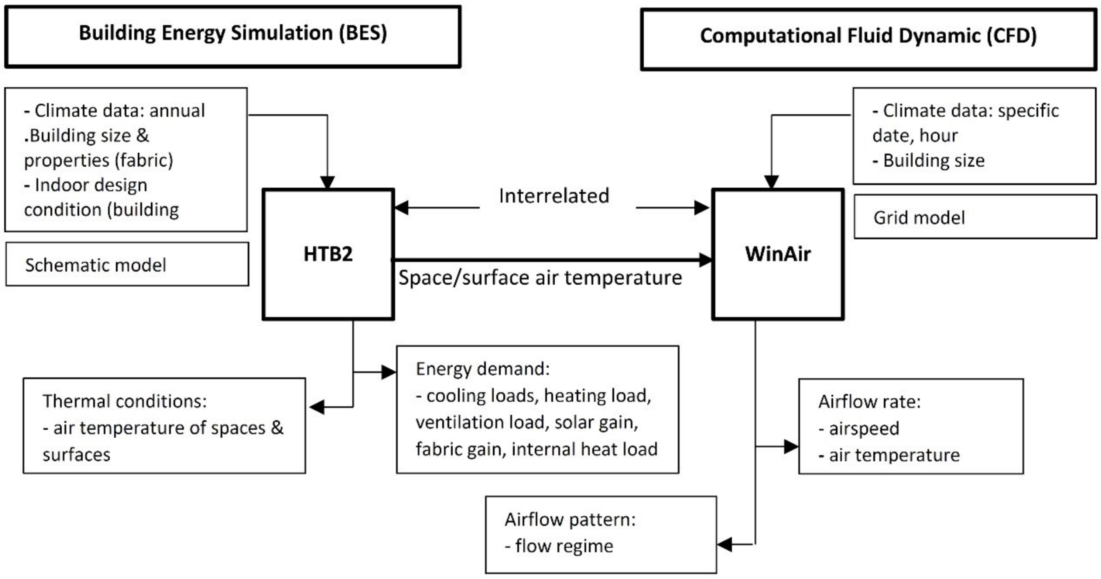


Figure 1. Coupling HTB2 and WinAir.

### *Hypothetical building and simulation settings*

A theoretical reference model was developed based on the design guidelines suggested by the British Council for Offices (BCO) in London (BCO Guide 2014). A spatial configuration (prototype) of skycourt was used. That was found to be widely constructed in the research context according to prototype analysis developed in conjunction with the present study by the authors. This prototype reveals 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), connected with the outdoors by a one-edged (hollowed-out) skycourt (Figure 2). However, to reduce the simulation time needed for each simulation run, the model was constructed to include the skycourt section.

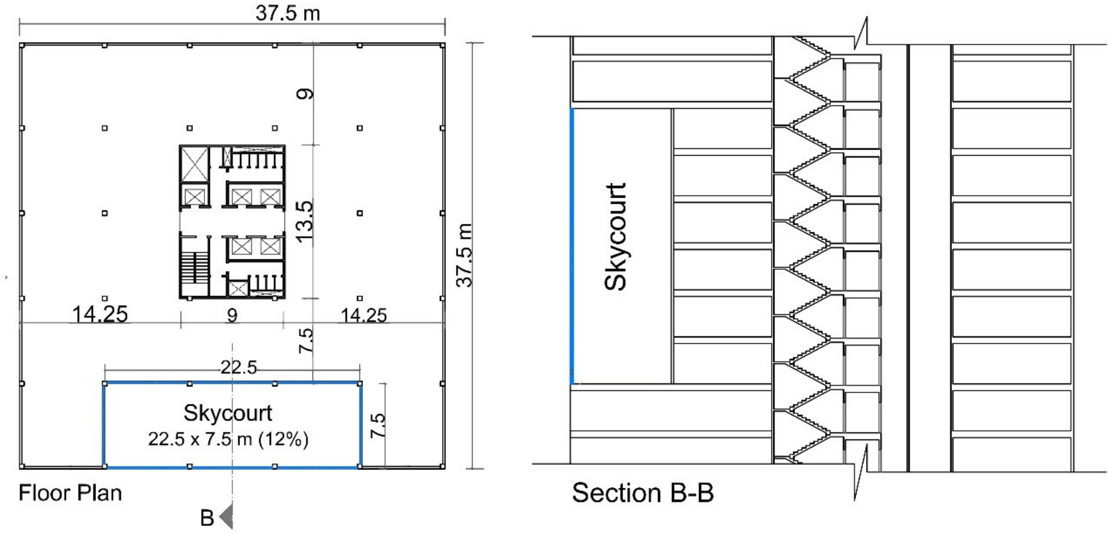


Figure 2. Spatial configuration of building model considered in the study: Floor plan and section.

All energy simulations were carried out hourly for one year period using the climate data of London. This city is classified as temperate oceanic climate (Cfb) according to Köppen-Geiger climate classification (Peel, Finlayson, and McMahon 2007). Gatwick statistics for London weather data was employed in the study, these applied 51° 9' N latitude and 0° 10' longitude. The weather forecast data are imported from the EnergyPlus weather format. However, CFD simulation was carried out on the peak hours of temperature: the hottest external air temperature in summer (28.3°C on June 28th at 14.00 pm), the coldest external temperature in winter (-5.0°C on December 7th at 9.00 am) and the typical temperature in mid-seasons (13.2°C on April 19th at 9.00 am) (Figure 3).

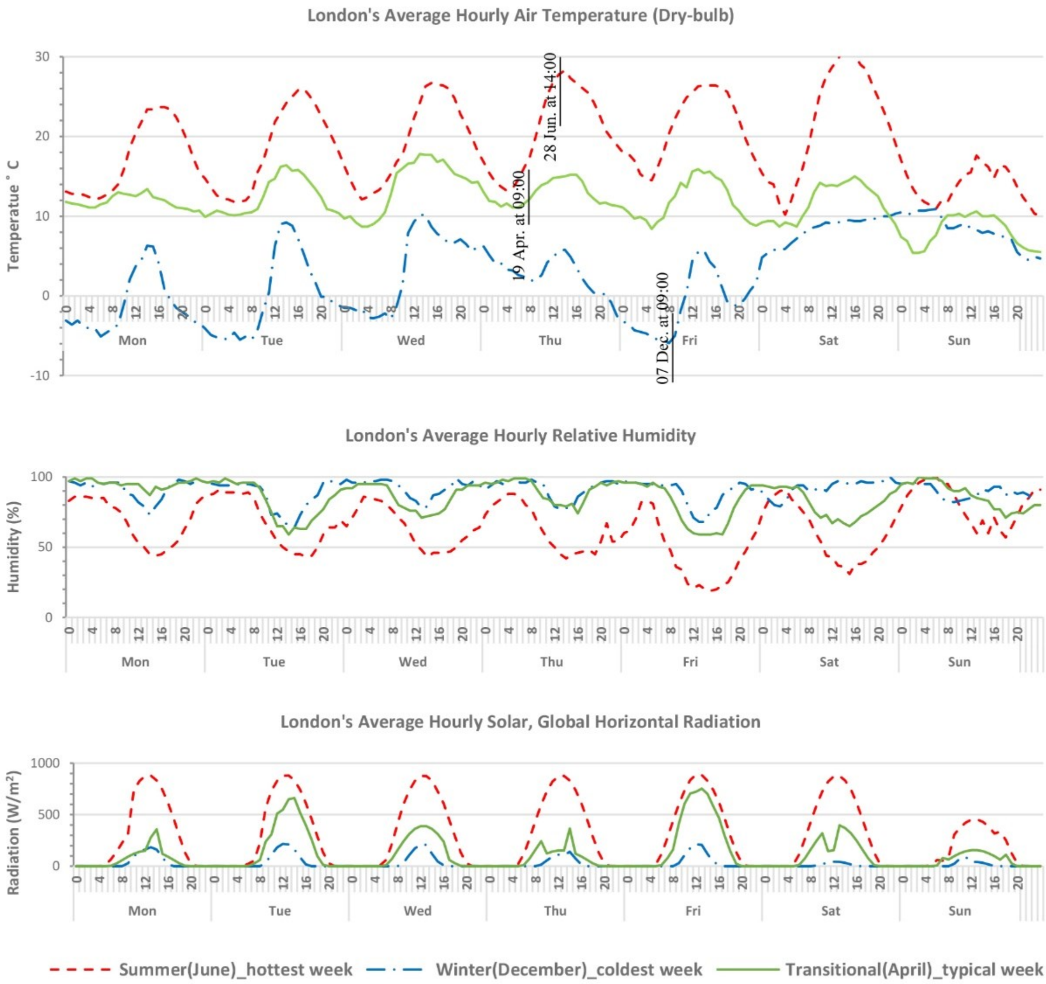


Figure 3. Weather data applied in the study.

The minimum ventilation rate to maintain an accepted air quality was determined based on the number of occupants, taking into consideration the envelope airtightness (infiltration) at the perimeter of the building. The heating set point was assumed to be 18.0 °C, and the cooling set point was 25.0 °C. Table 1 illustrates the main numerical settings and assumptions for the simulation process. Displacement ventilation is assumed to determine air distribution in the skycourt when air enters the skycourt. This system is widespread in office buildings due to ventilation effectiveness compared to the mixing system (Cao et al. 2014). Therefore, it is anticipated that this system can be an efficient alternative in the skycourt.

Table 1. Simulation settings for office spaces

| **Internal Heat Gain*** | | **Building Fabric** | | **Ventilation Setting** | |
|---|---|---|---|---|---|
| Workplace density | 12 m² /person | Glazing U-value<br>g-value | 1.5 (W/m$^2$.C)<br>0.4 | Infiltration rate | 3.5 m$^3$/(m$^2$.hr) at 50 Pa |
| People | 12 W/m$^2$ | Window to wall ratio | 70 % | Air supply rate | 10 L/s per person |
| Equipment | 15 W/m$^2$ | External wall U-value | 0.18 (W/m$^2$.C) | Heating set-point | 18 °C |
| Lighting | 12 W/m$^2$ | Internal wall U-value | 0.22 (W/m$^2$.C) | Cooling set- point | 25 °C |
| | | Floor/ceiling U-value | 0.20 (W/m$^2$.C) | Operating time | 08:00-18:00 |

*Occupancy profile: the building occupied five days a week, based on the following schedule, for offices 09:00-13:00 occupied 100%, 13:00-14:00 occupied 70%, 14:00-18:00 occupied 100%. For skycourt 09:00-18:00 occupied 100%

***Study stages***

The study involved three main stages. These are as follows:

*Ventilation strategy*

Energy and CFD simulations were carried out over two modes; an air-conditioned skycourt, and an unheated and uncooled skycourt. First, the reference case, which represents the current practice, considers an isolated mechanical heating, cooling and ventilation for the skycourt. This model was used as a reference to compare the energy and thermal performance when other ventilation strategies were applied (Figure 4).

| Heated and cooled skycourt: 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<br>- Inlet air volume rate for each office floor is 0.93 $m^3/s$ at 18°C<br>- Inlet air volume rate for the skycourt is 0.85 $m^3/s$ at 18°C |

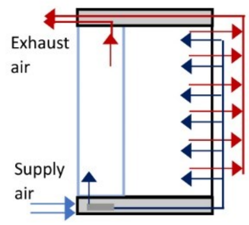


Figure 4. Proposed ventilation strategy for the reference case: Heated and cooled skycourt.

The second mode considers 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 ventilation scenarios. In the first scenario, the skycourt use infiltration only. In the second scenario, the air extracted from the offices is driven through the office outlets and pushed into the skycourt inlets. In the third scenario, the fresh air is supplied to the skycourt space, then it is forced to extract into the adjacent offices. Five ventilation strategies (Figure 5) under the previous scenarios were examined to identify the appropriate ventilation strategy for skycourts in summer, winter and mid-seasons, particularly, in the occupied area.

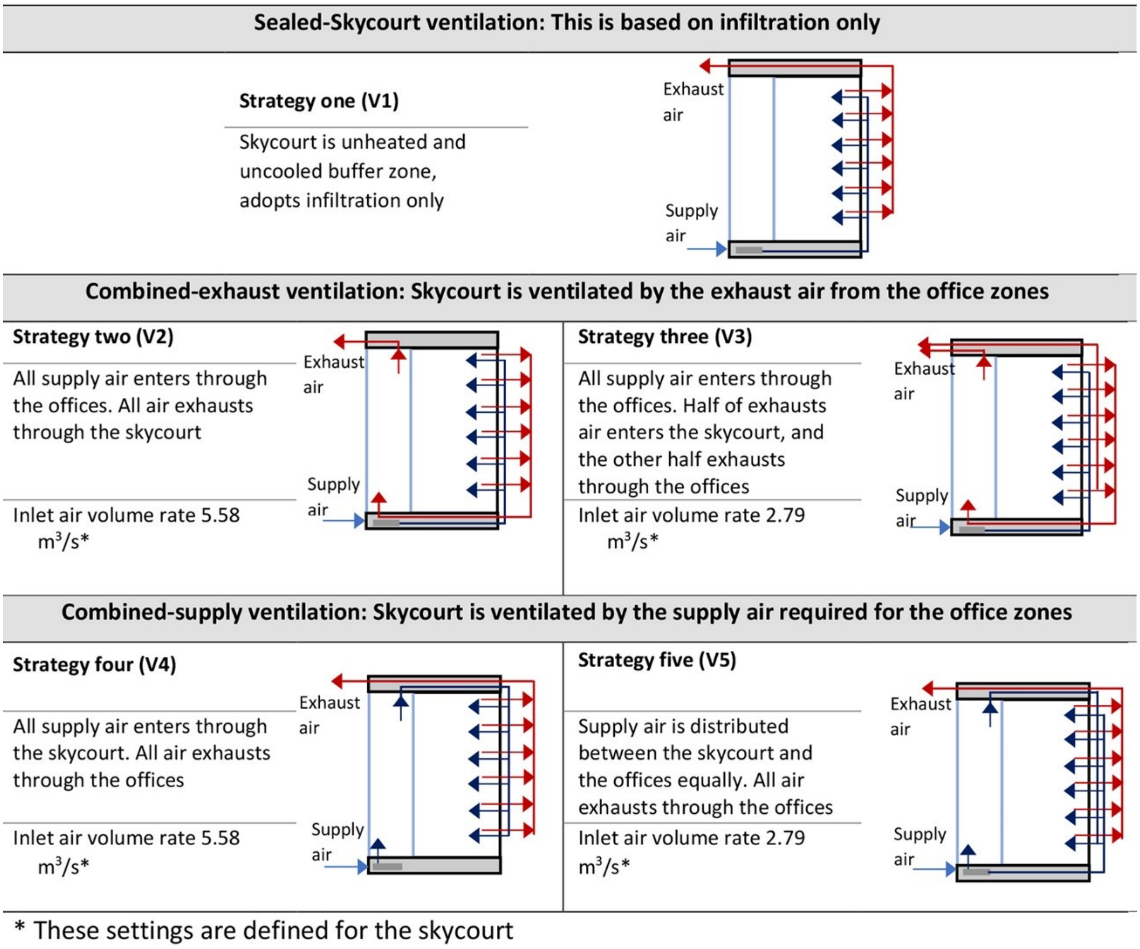


Figure 5. Proposed ventilation strategies for the skycourt: Unheated and uncooled skycourt.

*Sensitivity analysis*

In order to define the key factors in design for the skycourt connected with the optimal ventilation strategy that was outlined in the previous section, a systematic sensitivity analysis was performed. Therefore, the model with the optimum ventilation strategy was used as a base case here while comparing the impact of each parameter. In addition, during the investigation of a single parameter, all the other parameters maintain the default settings. Then, the results were compared to the base case to evaluate the impact of the change made on the simulation results. The investigation involves two issues: the skycourt geometry and the air openings in the skycourt (Table 2).

Table 2. Parameters of sensitivity analysis for the skycourt.

| Geometric Parameters of Skycourt | |
|---|---|
| **Height** | (a) Six-floor height, (b) Three-floor height, (c) Nine-floor height |
| **Orientation** | (a) South, (b) North, (c) West, (d) East |
| **Area to GIA:** | (a) 12% of GIA, (b) 8% of GIA, (c) 4% of GIA |
| **Length and Depth:** | (a) 22.5m × 7.5m, (b) 5m × 7.5m, (c) 7.5m × 15m, (d) 7.5m × 7.5m |
| **Ventilation Parameters of Air Openings** | |
| **Air inlet and outlet vertical location:** | (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.<br>(b) Air inlet and outlet openings are distributed between the floor and the ceiling levels of the skycourt.<br>(c) Air inlet and outlet openings are located at the floor level of the skycourt.<br>(d) Air inlet and outlet openings are located at the ceiling level of the skycourt.<br>(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. |
| **Air inlet and outlet horizontal position:** | (a) Inlet openings are closer to the external wall, and outlet openings are closer to the internal wall of the skycourt.<br>(b) Inlet openings are closer to the inner wall, and outlet openings are closer to the external wall of the skycourt.<br>(c) Both inlet and outlet openings are closer to the external wall of the skycourt.<br>(d) Both inlet and outlet openings are closer to the internal wall of the skycourt. |

Several studies found that orientation (Delgarm et al. 2018), height, length, depth, size and form (Wang et al. 2017) are the most effective elements in building energy performance, when considering ventilation. Therefore, this study considered the skycourt geometry in terms of orientation, height, percentage of area to GIA and length to width as illustrated in Figure 6.

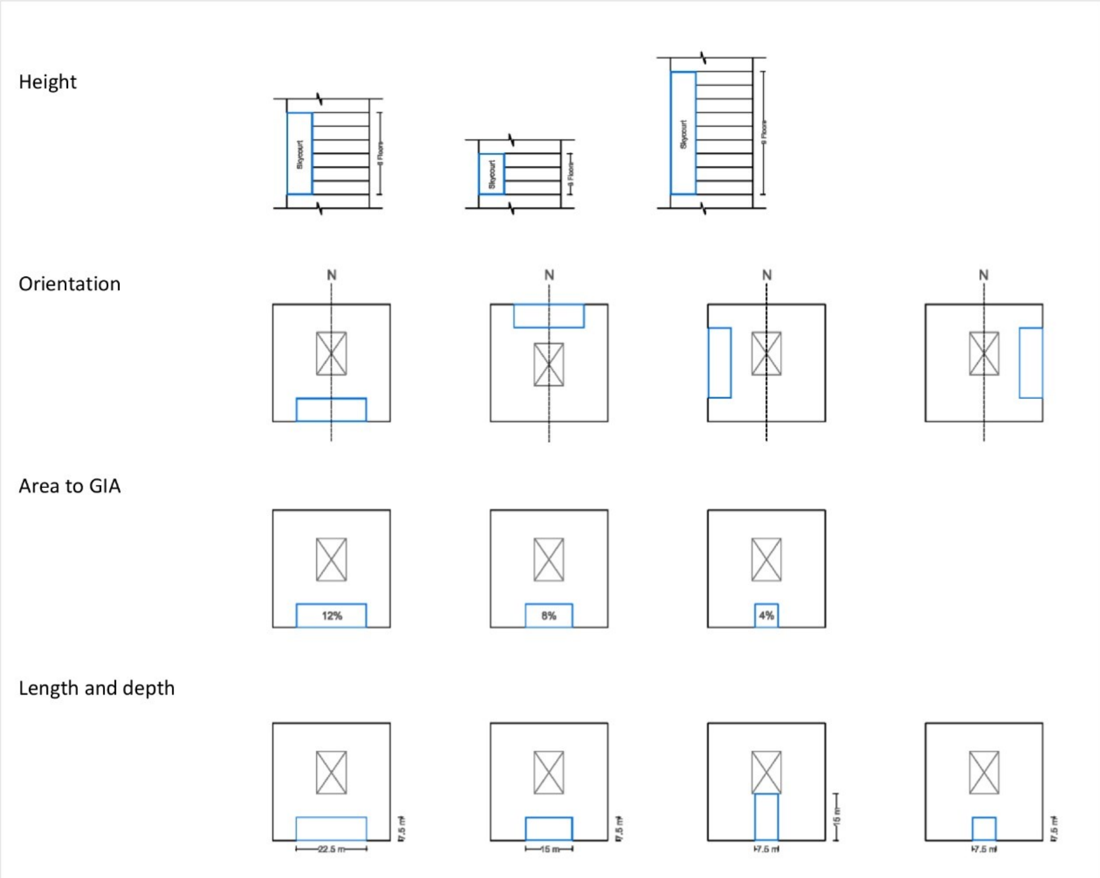


Figure 6. Geometric parameters of sensitivity analysis for the skycourt.

Air openings' characteristics influence the ventilation performance (Awbi 1998). In this study, the improvements of the ventilation strategy in terms of vertical distribution and horizontal position of air inlet and outlet openings in the skycourt are considered. The simulated cases that investigate the impact of the locations of air inlet and air outlet openings on the airflow performance regarding their vertical distribution between the floor and the ceiling of the skycourt are illustrated in Figure 7. Then four alternatives of air inlet and outlet openings were considered for their horizontal positions to the external façade and internal wall of the skycourt (Figure 8).

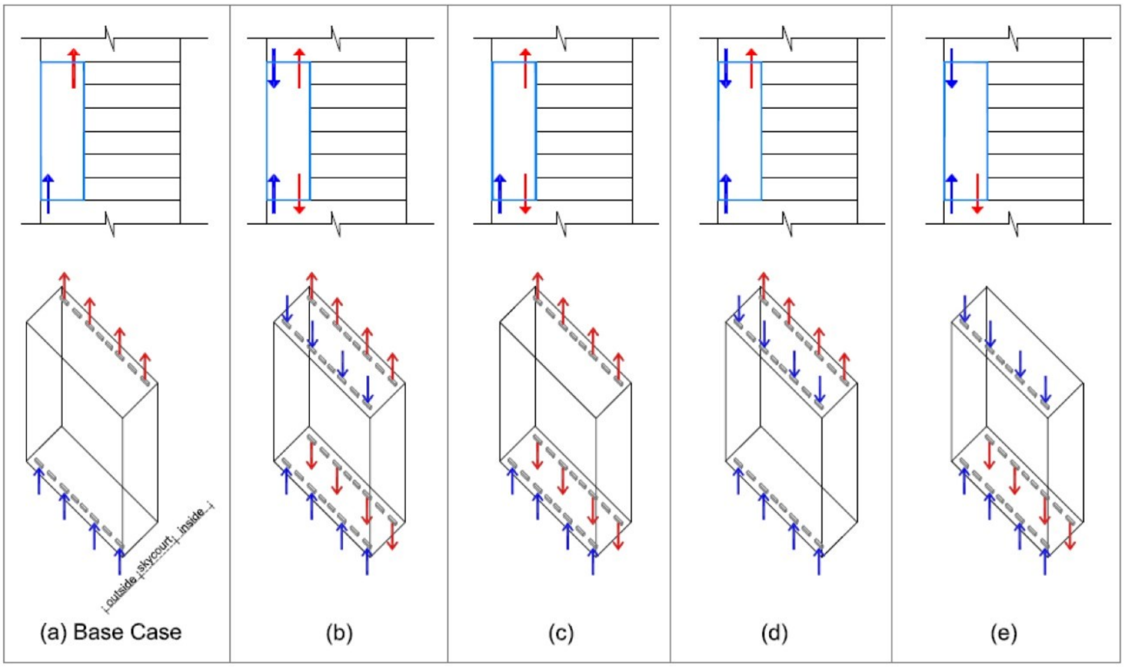


Figure 7. Ventilation parameters of sensitivity analysis: Air inlet & outlet openings' vertical location.

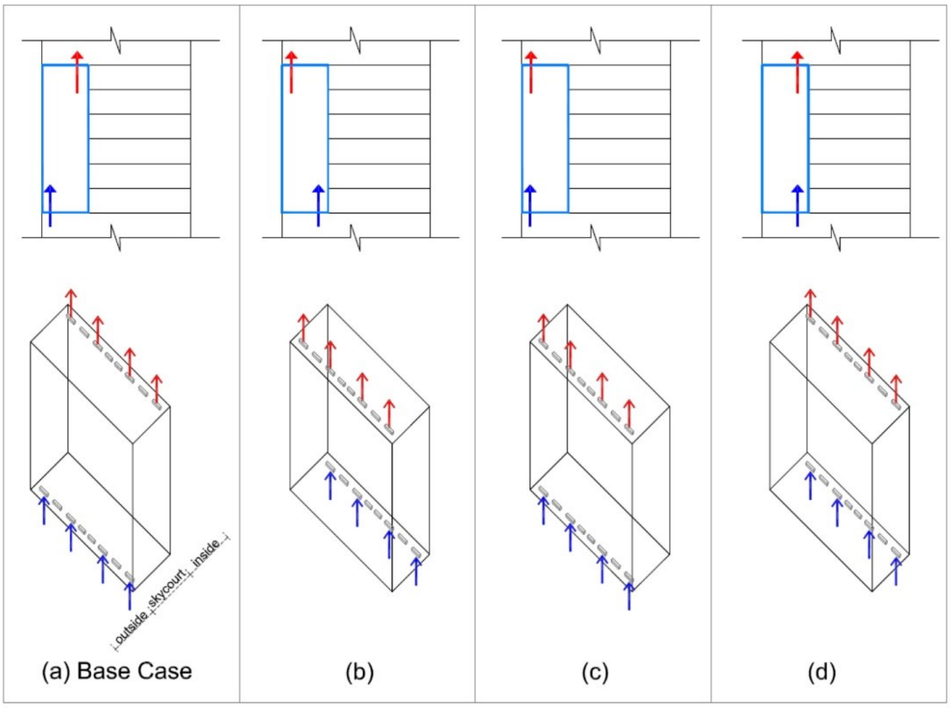


Figure 8. Ventilation parameters of sensitivity analysis: Air inlet & outlet openings' horizontal positions.

*Improved Configurations*

In this stage, the optimum parameters of the sensitivity analysis were correlated to define the best configuration of the six parameters. 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. Then, define design guidelines for ventilated skycourt in office buildings were defined.

## Results and discussion

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 in the three peak hours were adopted as the main criteria for comparing the results.

### ***Energy and thermal performance of the ventilation strategies***

The total heating and cooling demand of the building, and significantly, the cooling load was found to be high when skycourts are treated as air-conditioned spaces. Energy consumption to cool such skycourts required about 220.5 kWh/m$^2$.yr of the total cooling and heating use of the adjacent offices. This result agrees with previous studies, which reported that cooling becomes dominant in contemporary buildings in the UK, particularly, for transitional buffer zones, which consume more energy than other spaces of similar size to accomplish the same level of thermal comfort (Pitts and Saleh 2007). On the other hand, when skycourt is free-cooled and free-heated, the energy demand of the building significantly decreased. The proposed ventilation strategies accounted more than 50% reduction in the total annual energy demand for heating and cooling in comparison with the reference case (Figure 9). For example, the strategies accounted sequentially the following demands: 94.3, 91.9, 93.2, 110.1, and 98.3 kWh/m$^2$/yr.

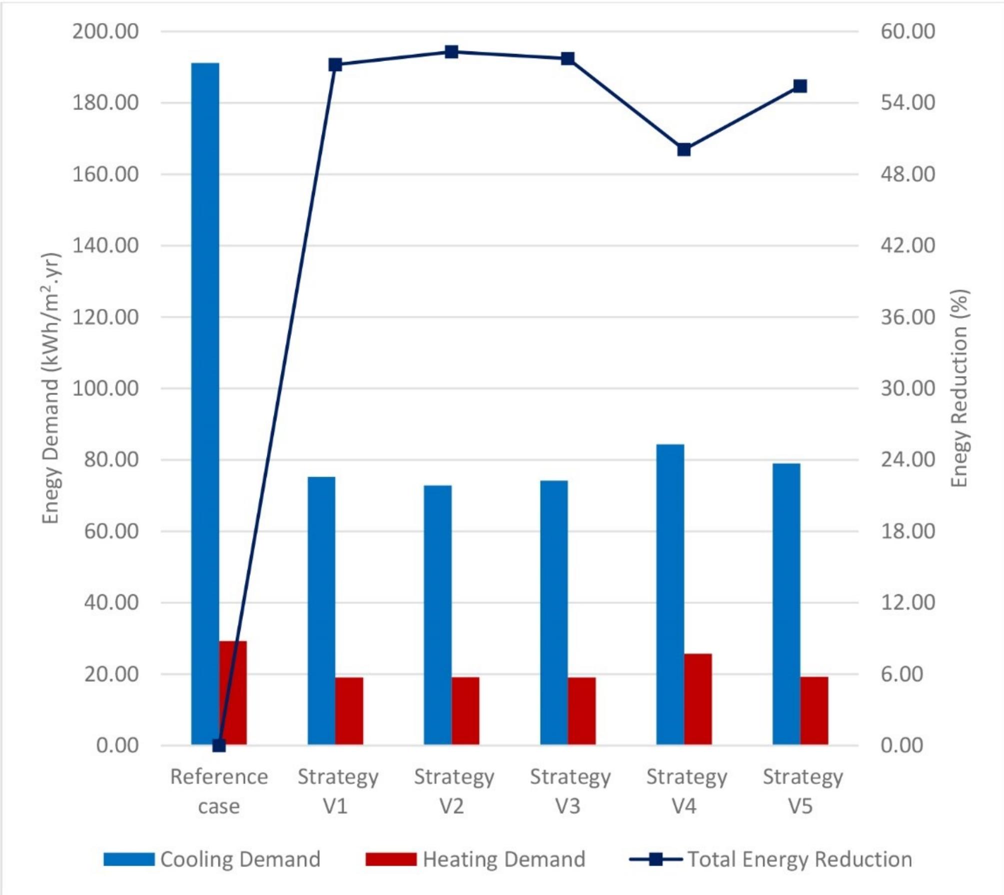


Figure 9. Annual heating and cooling demand comparison for the buildings under the ventilation strategies.

Further analysis of these results showed that under the combined-exhaust ventilation strategy, the skycourt accounted for about 58% 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. 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). This situation agreed with the findings of this study. 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.

It is evident that the skycourt cannot be considered a thermal comfort space without an inlet airflow (Figure 10). 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, less than 8°C at the coldest hour. In addition, the graphs show that the temperatures obtained for strategy two were almost within the comfort temperature range in the different times in the occupied area of the skycourt. CFD results recorded 27°C of 0.2 m/s in summer at the hottest hour, 16°C of 0.3 m/s in winter at the coldest hour and 22°C of 0.17 m/s in transitional season at the typical hour. 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. Although these ranges are higher than comfort ranges in general offices, they can be accepted in transitional skycourts, as a deviation of ±2°C from the standard temperature was accepted by the majority of occupants in transitional spaces. In addition, it should be mentioned that these temperatures were recorded at peak external temperatures.

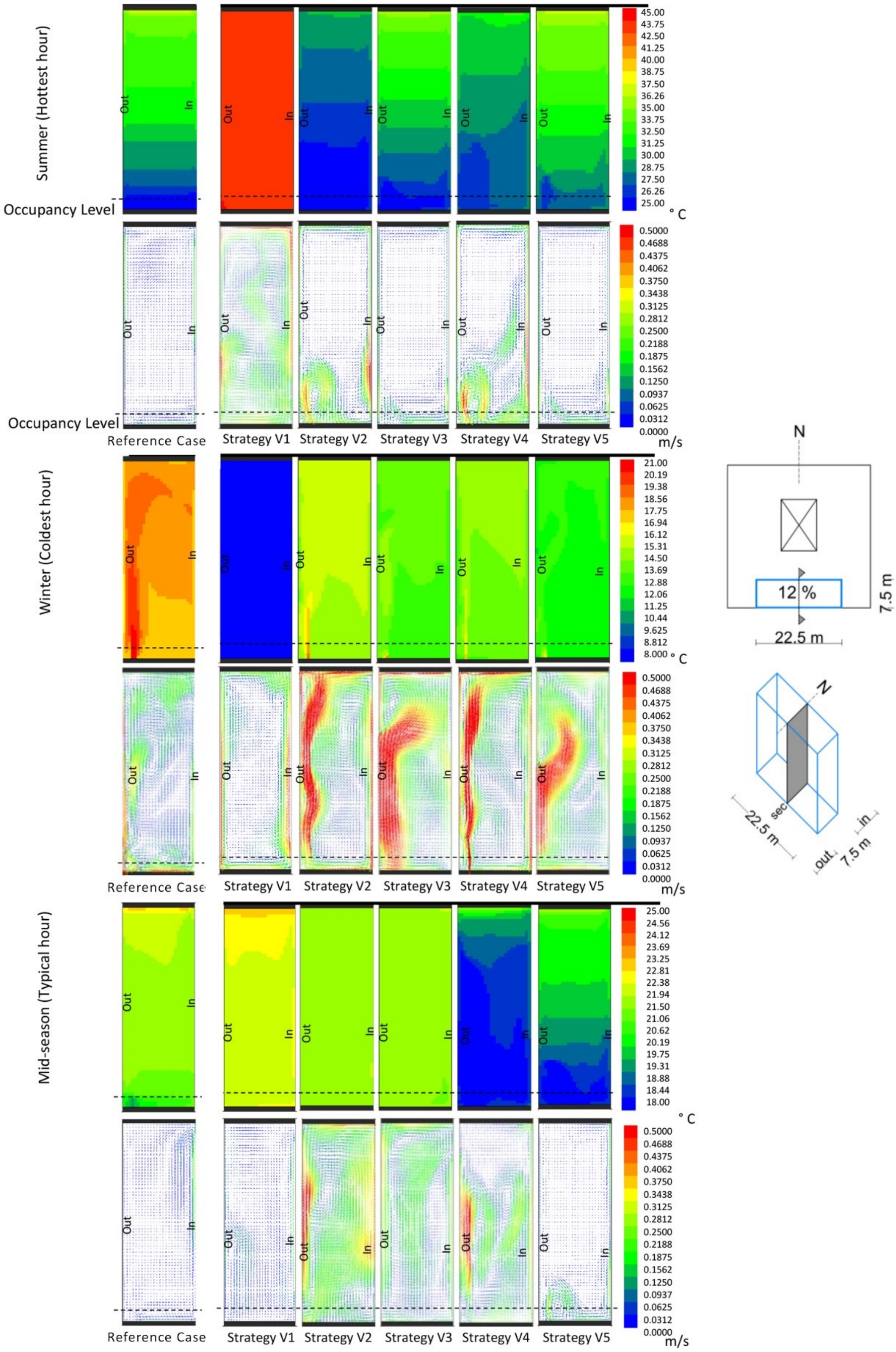


Figure 10. Results of the thermal conditions in the skycourt: ventilation strategies.

The internal environment of the skycourt is influenced by the temperature of the supply air, which affects the ventilation effectiveness. In the combined ventilation strategies, 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. In the combined-supply ventilation, the skycourt is supplied with fresh air of 18°C in winter and transitional seasons and up to 28°C in summer hottest hours. 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. Another factor that influences the thermal conditions of the skycourt is the airflow volume rate. When airflow rate increases, the thermal comfort level rises significantly in the occupied area of the skycourt. Considering the potential of using a combined-exhaust ventilation strategy (V2) in summer and transitional periods, and a combined-supply strategy (V4) in winter, 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.

Taken together, the simulation results highlighted that the combined ventilation strategies for the skycourt have potentials for saving energy and achieving thermal comfort, nevertheless, differently. Strategy two is the optimum ventilation strategy to minimize requirements for energy, besides ensuring thermal comfort at the skycourt during the different seasons. Therefore, it is applied as a ventilation strategy in the next stage.

***Energy and thermal performance of the sensitivity analysis***

The following summarizes the main findings of the sensitivity simulation stage considering ventilation strategy two. Figure 11 illustrates results of the annual heating and cooling demand for the building of the sensitivity analysis stage.

- Orientation: Models of orientations showed that the south oriented skycourts (south-east, and south-east-west) are ensuring maximum energy savings. However, the differences in heating and cooling demands between cases are less than 1%. However, the north orientations (north-east and north-east-west) ensure better thermal comfort conditions (Figure 12). These results could be explained by the fact that the south and the west facades obtain the maximum solar intensity radiation. This result is evident in the work of Danielski et al. (2016) who 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.
- Height: The heating and cooling consumptions displayed that increasing the height of the skycourt provides greater reduction in heating and cooling demands. 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. In addition, more accepted levels of temperature could be achieved, yet airspeed levels were less satisfactory. The 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 (Figure 13). One major factor influences this result is related to the fact that the large size of vertical enclosed spaces attains a better buoyancy-driven airflow effect in high-rise buildings (Lan et al. 2017).

- Floor area: 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% 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 (Figure 14). It seems that this result occurs due to the airflow volume rate inside the skycourt in this 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. 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.
- Length and depth: In terms of skycourt dimensions considering length and depth, a positive correlation was found between energy savings and the skycourt length. Increasing the depth of the skycourt reduced energy savings. 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. 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. 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 smaller length and a larger depth of the skycourt should be adopted (Figure 15). These results agree with previous studies (Rundle et al.

2011) that investigated the impact of geometric parameters of enclosed glazed spaces that are integrated in buildings.

- Air inlet and outlet openings vertical location: 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. 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 1-2°C, whereas it was lower in winter by 0.5-1°C (Figure 16). 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). The floor level air distribution can handle a full space heat load in an acceptable manner; it can balance between buoyancy and momentum forces. In addition, it is recommended to apply low-level air supply systems for achieving energy savings (Karimipanah, Awbi, and Moshfegh 2008). These conclusions agree with the findings of the present study. Therefore, the first alternative is suggested to induce an efficient airflow strategy.
- Air inlet and outlet openings horizontal position: There was no major effect on the occupied area temperature. 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. Yet, there were significant impacts on the average airspeed, and on the adjacent offices of the skycourt (Figure 17). 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 (alternative (a)) is favourable.

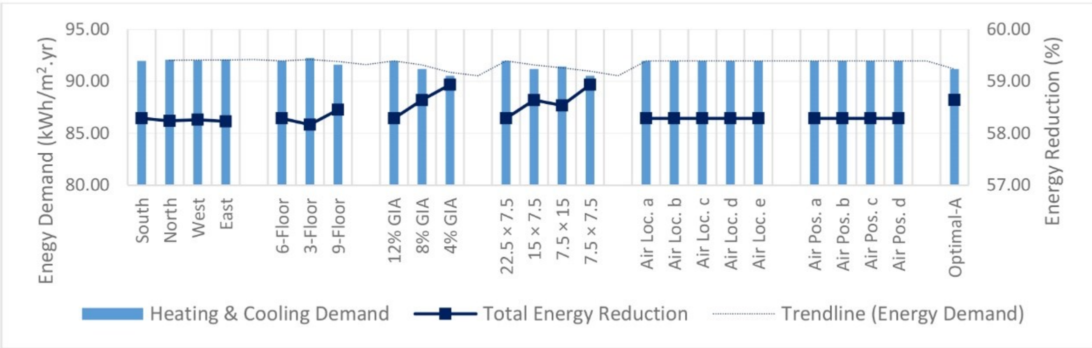


Figure 11. Annual heating and cooling demand for the building: Sensitivity analysis.

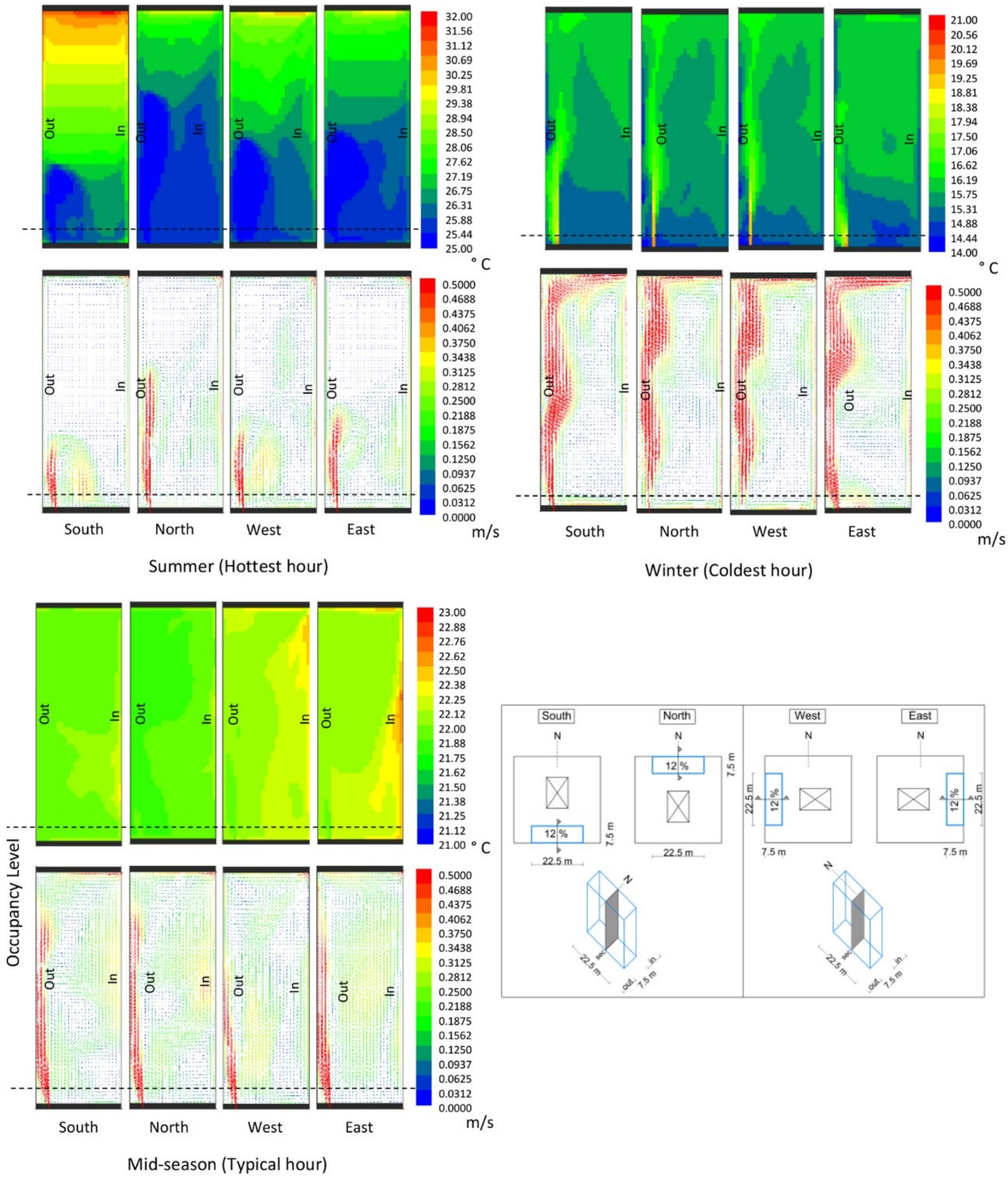


Figure 12. Results of the thermal conditions in the skycourt: Orientation.

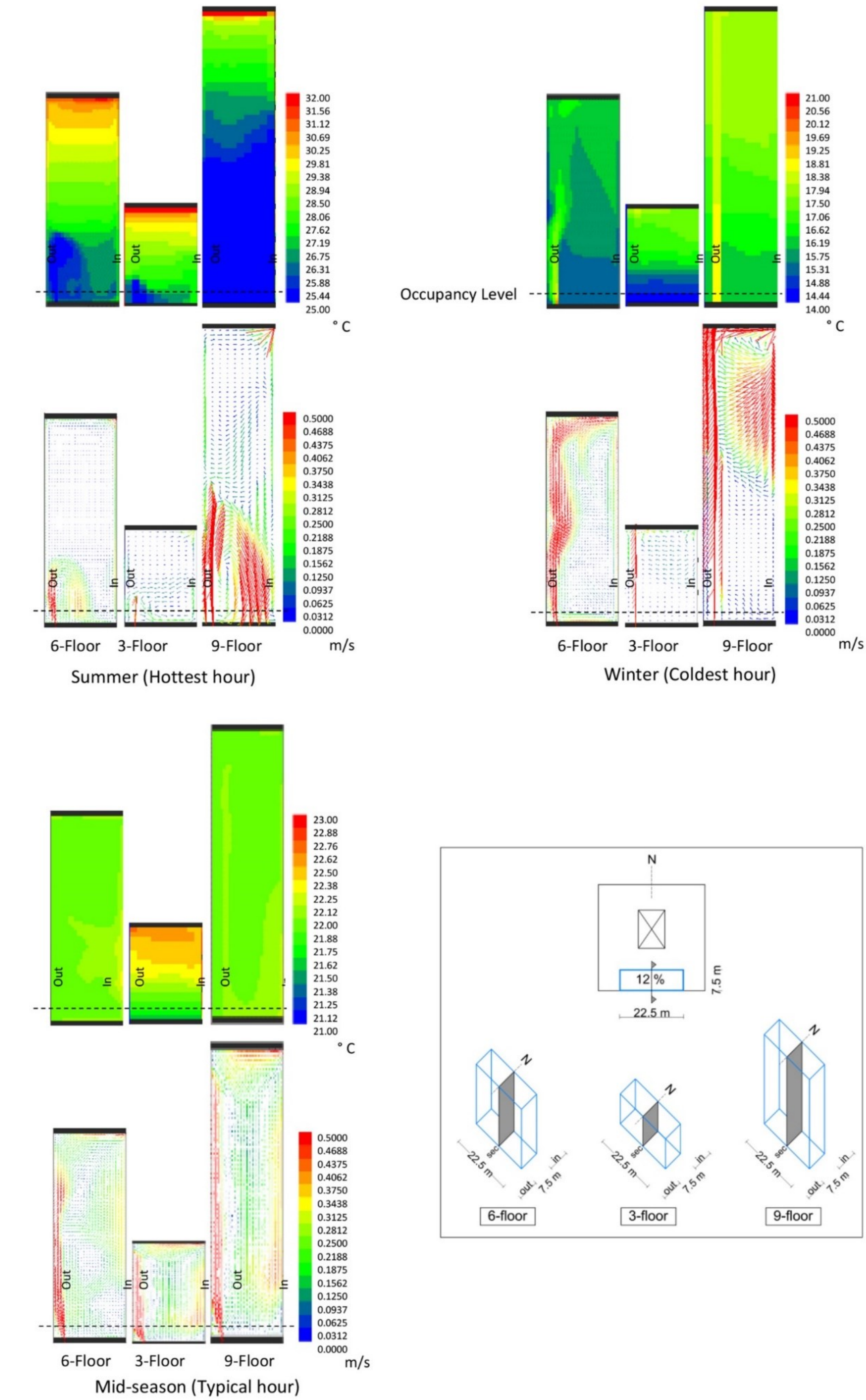


Figure 13. Results of the thermal conditions in the skycourt: Height.

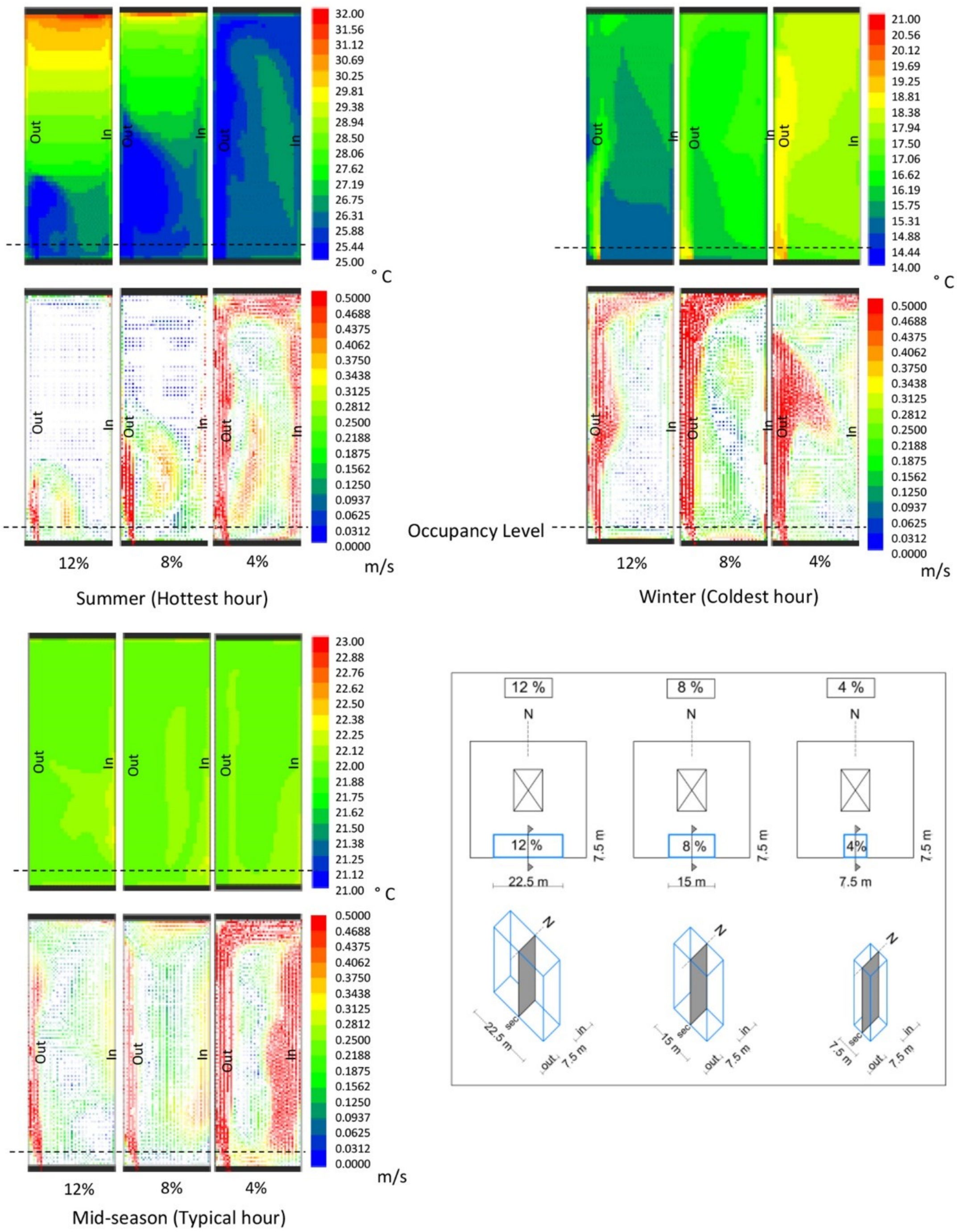


Figure 14. Results of the thermal conditions in the skycourt: Area to GIA.

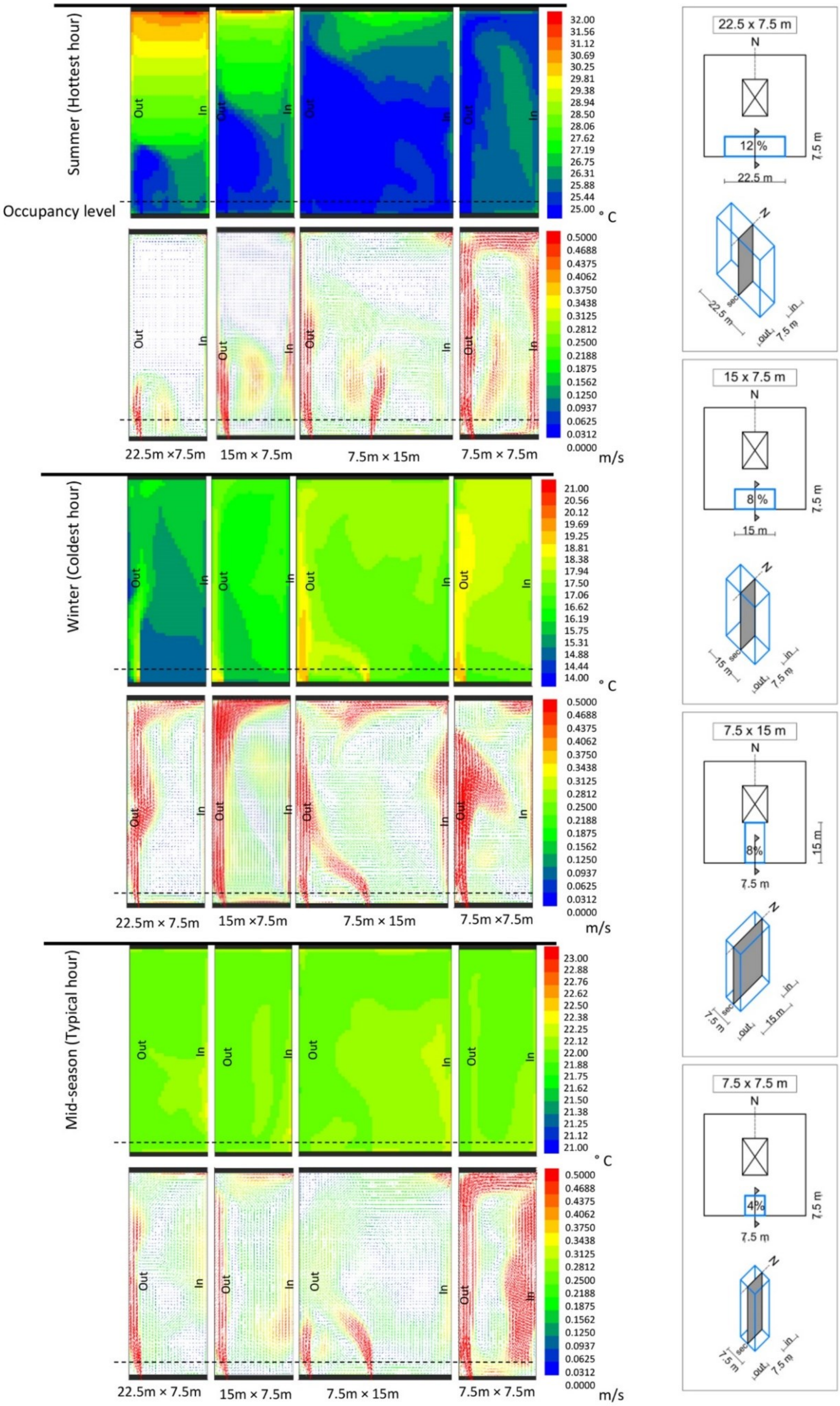


Figure 15. Results of the thermal conditions in the skycourt: Length and depth.

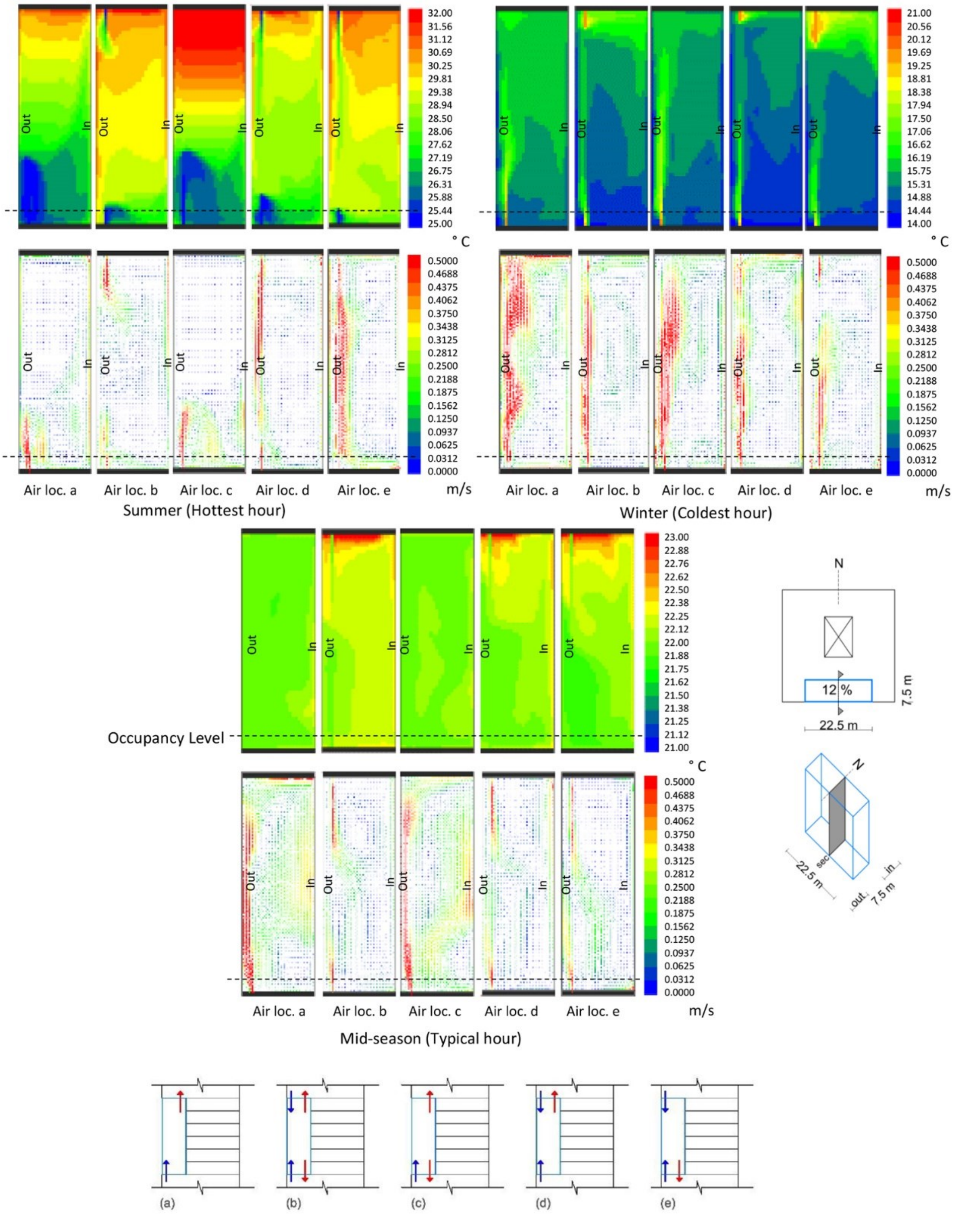


Figure 16. Results of the thermal conditions in the skycourt: Air inlet and outlet openings' vertical location.

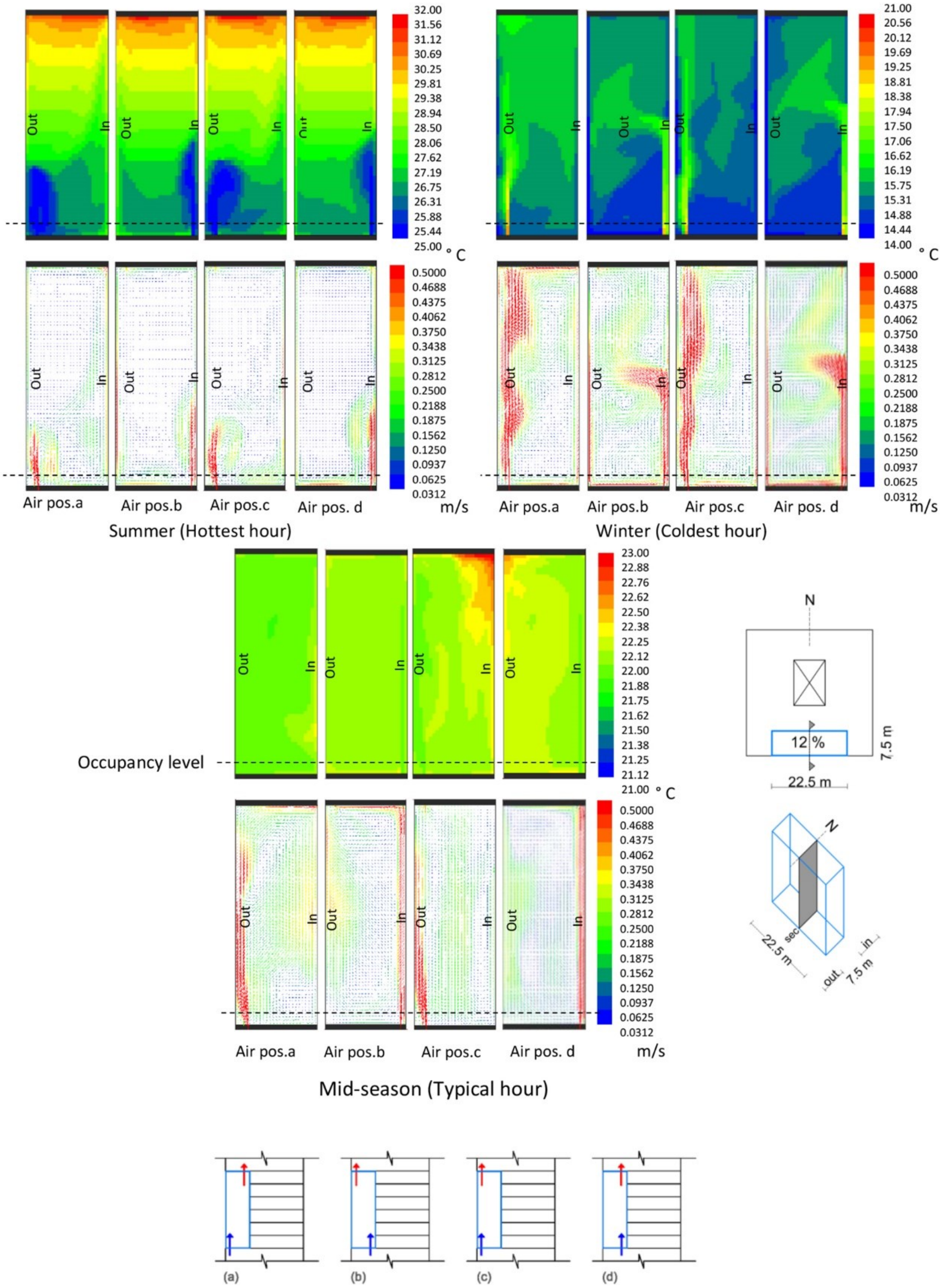


Figure 17. Results of the thermal conditions in the skycourt: Air inlet and outlet openings' horizontal position.

**Performative design guidelines for ventilated skycourt in office buildings in temperate climate**

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. For example, in summer hot days, when external temperature is over 28°C, air temperature in the ventilated 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 (Figure 18). In London, the average high temperature of summer is 22°C and rarely rises 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 for all the different seasons in a temperate climate, such as in London.

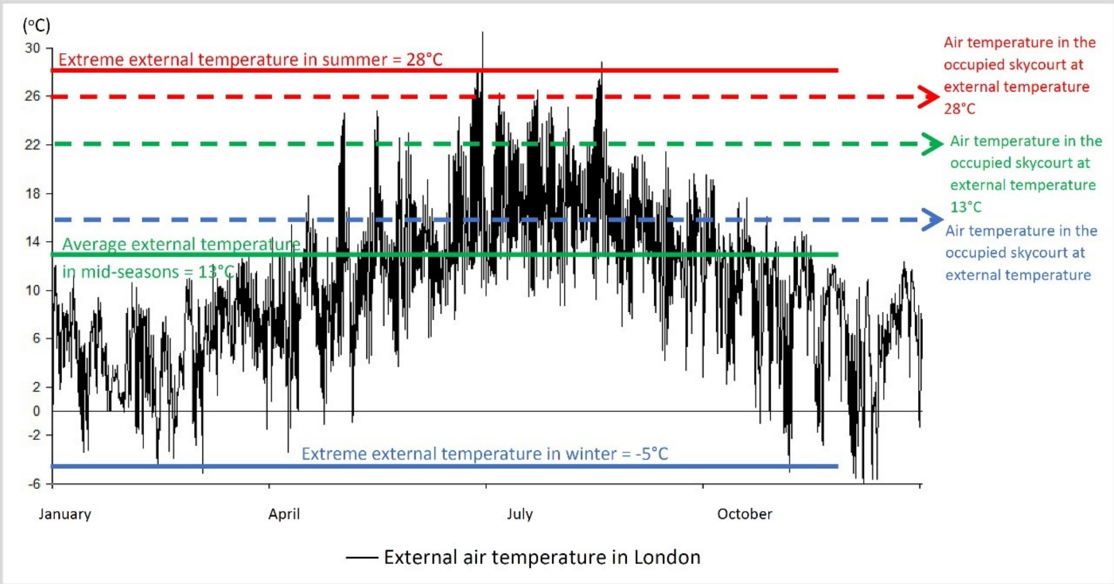


Figure 18. External air temperatures, and air temperatures in the occupied area in skycourt under the combined-exhaust ventilation strategy.

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% of 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 skycourt. However, a comparison of the optimal configurations of the skycourts show that there are small differences between the cases in terms of energy impact and thermal conditions. 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 (Figure 19).

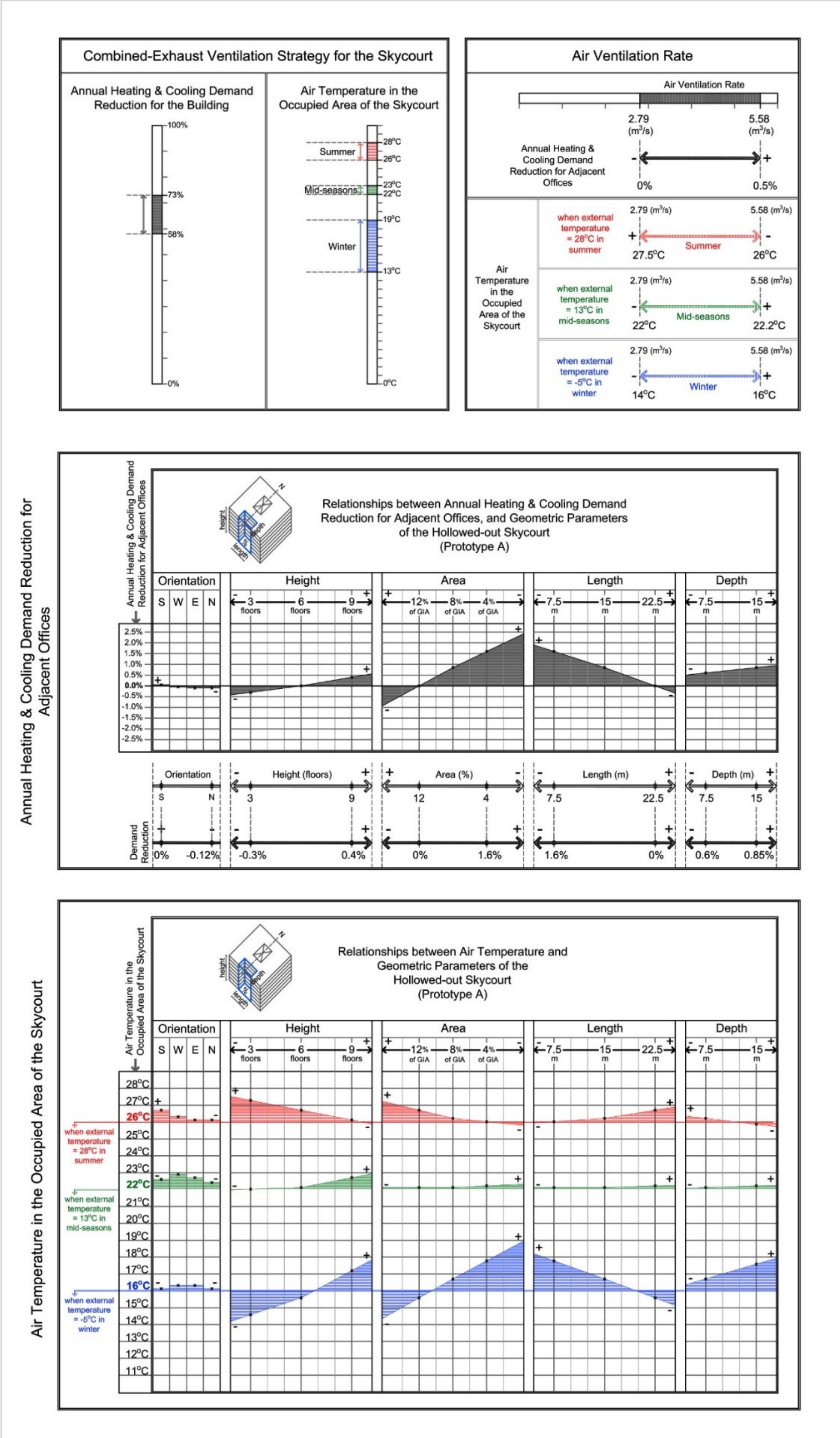


Figure 19. Relationships between design parameters for ventilated skycourts, annual heating and cooling demand reduction for buildings, and air temperature in the occupied area of skycourts.

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 a 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. However, in order to maximize 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.

## Conclusion

In this study potentials of skycourts to reduce the heating and cooling demands of the building, and ensure an accepted level of thermal comfort in the skycourt were investigated. The following conclusions can be drawn from the present study:

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. 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 more than 55% saving per year. In addition, thermal comfort conditions in the occupied area of the skycourt were attained.

The study found that the combined-exhaust strategy, which depends on ventilating the skycourt by air exhausted from the adjacent spaces is an efficient approach. This strategy can induce heating and cooling savings for high-rise office buildings compared to typical air-conditioning strategies, and provide occupants thermal comfort in enclosed transitional buffer areas such as skycourts.

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. Rectangular shapes for skycourts are more effective for ventilation than square shapes; moreover, they could achieve acceptable air temperatures. In terms of the height of the skycourt, heating and cooling demands decrease when the skycourt becomes taller.

However, it is important to mention that the investigated parameters of the skycourt show small differences in terms of thermal conditions and energy impact. This provides variety of spatial and geometric configuration of skycourts, and allows flexibility for the design process.

Although the results of this research are encouraging, this study is limited to consider 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 this study correspond with results of previous studies. The study has revealed two directions for future investigations. The first considers the potential of implementing passive strategies, such as wind-induced and night ventilation mechanisms into the skycourt.  The second considers potential influence of skycourts in terms of social dimension.

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