**Periodicals of Engineering and Natural Sciences** ISSN 2303-4521
Vol. 8, No. 4, October 2020, pp.2045-2067

# Low-cost ventilation strategies to improve the indoor environmental quality by enhancing the natural ventilation in multistory residential buildings

**Shouib Mabdeh[1], Saba Ahmad[2], Tamer Alradaideh[3], and Asma Bataineh[4]**
Department of Architecture, Jordan University of Science and Technology, Irbid 22110, Jordan

## ABSTRACT

Indoor environmental quality (IEQ) influences a building's livability. Because most people spend ~65% of their time at home, methods and design strategies to achieve high-quality indoor environments are worth investigating. This study investigates the performance of the indoor environmental quality through implementing various low-cost natural ventilation strategies on a typical apartment in the multistory residential buildings in Amman, Jordan. A simulation software was used to conduct a detailed data analysis based on the ventilation rate, indoor operative temperature, relative humidity, and CO2 concentration in the base case apartment unit and propose design strategies. The simulation results were compared with the results obtained in the base case, analyzed, and discussed to determine the most efficient ventilation strategy. The proposed strategies improved the indoor air quality most of the time when compared to the base case, and maintain it within relevant international standards. The results provide a foundation to improve the IEQ in newly developed residential apartments by providing architectural design guidelines for achieving an effective natural ventilation system.

**Keywords**: low-cost ventilation strategies; Multistory residential buildings; Indoor environmental quality; Ventilation rate; Architectural design guidelines

***Corresponding Author:***

Author Name, Shouib Mabdeh
Departement, Department of Architecture
University , Jordan University of Science and Technology
Address, Irbid 22110, Jordan
E-mail: Snmabdeh@just.edu.jo

## 1. Introduction

Generally, several passive and active design strategies are utilized to achieve an acceptable indoor environmental quality (IEQ) inside buildings. However, the increased energy consumption of the buildings that rely on non-renewable resources and their related negative impacts on environment and human health have increased the difficulty associated with the enhancement of the IEQ by utilizing passive techniques. IEQ and energy consumption are two interdependent parameters that should be considered during the preliminary stages of the building design. The largest amount of energy is consumed by the residential sector for satisfying the various needs of the residents to achieve a desirable indoor condition and an acceptable level of IEQ inside their homes. Recently, a wide range of passive techniques, such as natural ventilation, solar shading, building insulation, materials selection, water features, and atrium space have been widely applied in residential buildings to provide improved levels of indoor air quality (IAQ) and thermal comfort (TC) while reducing energy consumption and the negative environmental impact  Natural ventilation is a widely used technique and controls many environmental parameters, including the ventilation rates (VRs), air temperature, air velocity, and air humidity, to control the indoor environment  Architectural design strategies can be used to influence natural ventilation when they are properly applied and understood  To ensure effectiveness in terms of cost, natural ventilation should be initiated and integrated as a design strategy during the early stages of the design process  with respect to various factors, such as the orientation of the building, the location of the space within the building, the characteristics of windows, the use of shading devices, and interior layout and organizat[1-3]

The researchers considered the prevailing wind direction and studied the effect of the variation of the window area on the natural cross-ventilation performance; he observed that increasing the WWR of the space could increase the natural ventilation potential. compared the influence of various window types on the natural ventilation potential; the results denoted that the side hung windows exhibited the best performance owing to their large operable area, resulting in maximum VR and reduced indoor air temperature with respect to the outdoor conditions. researchers observed that the natural ventilation performance can be improved by adding supplementary interior openings to the interior walls, minimizing the resistance of airflow, increasing the latter's effectiveness, and reducing the maximum indoor air temperature. evaluated the impact of different building conditions on the indoor building ventilation; they observed that the layout design of the interior spaces should support air movement to obtain good indoor natural ventilation performance. Therefore, this study suggests that the implementation of some passive design strategies with respect to multistory residential buildings can enhance their natural ventilation performance[4-6]. The objective of this research is to focus on the early design-stage decisions that may enhance natural ventilation and the IAQ performance in multistory residential buildings. Further, zero and low-cost natural ventilation design guidelines are suggested and evaluated from the viewpoint of providing improved VR levels, indoor operative temperature, relative humidity, and $CO_2$ concentration. The results obtained in this study will provide architects and designers with recommendations and architectural design guidelines to assist them during the preliminary design stages, improving their design decisions to enhance the IEQ while satisfying the client's requirements of affordability (no or minimal added cost)[7-9].

## 2. Research methodology

Herein, the simulation software, Integrated Environmental Solution–Virtual Environment (IES–VE), was used to investigate the suggested zero and low-cost ventilation strategies with respect to the natural ventilation performance in low income residential apartment buildings by evaluating the VR, $CO_2$ concentration, indoor operative temperature, RH, and energy consumption in the existing situation and after the implementation of the proposed ventilation strategies. IES–VE is a user-friendly and well-established simulation tool that can be used to analyze the performances of different building systems and allows their optimization with respect to comfort and energy [10-13].The indoor air temperatures of the BC model were validated using site measurements to validate the simulation results. The indoor air temperatures for R1 and R2 were recorded for two typical weeks during June and September while the apartment was occupied. Because the sizes of the thermal zones R1 and R2 were not considerably large, only one data logger was installed in each zone. Extech SD800 datalogger was used with an accuracy of 0.8°C. The dataloggers were mounted 1.2 m above the floor in the middle of each zone, and the temperature was recorded at 15-min intervals. The results obtained from the simulation program were in a good agreement, within 4%- 6% variance, with the measured results[14-16].

Further, the data related to the family size, air exchange, internal gains, and other specifications used to run the simulation are presented in Table 1 in accordance with the typical life pattern of the Jordanian families. The building's construction materials in all the scenarios represent the most prevalent materials in the construction field, as presented in Table 2.

Table 1. Input data and model settings

| Input data | Value |
|---|---|
| Family size | 6 members |
| Metabolic rate | 0.8 met |
| Summer clothing | 0.5 clo |
| Infiltration rate | 0.2 $ach^{-1}$ |
| Occupants | 80 W/P |
| Lighting | 5 $W/m^2$ |
| Appliances | 0 W |

Table 2. B.C. construction specifications

| Element | Material | Thickness (cm) | U value ($W/m^2$-K) |
|---|---|---|---|
| **Exterior walls** | Stone | 5 | |
| | Concrete | 18 | |
| | Insulation | 3 | 0.79 |

| Element | Material | Thickness (cm) | U value (W/m$^2$-K) |
|---|---|---|---|
| | Block | 10 | |
| | Plaster | 2 | |
| **Internal partitions** | Plaster | 2 | 1.90 |
| | Block | 10 | |
| | Plaster | 2 | |
| **Internal ceiling/floor** | Ceiling tiles | 3 | 1.20 |
| | Mortar | 3 | |
| | Sand | 7 | |
| | Water insulation | 0.5 | |
| | Reinforced concrete | 25 | |
| | Plaster | 2 | |
| **Roof** | Pebbles/gravel | 10 | 1.80 |
| | Inclined concrete | 5 | |
| | Water insulation | 0.5 | |
| | Reinforced concrete | 20 | |
| | Plaster | 2 | |
| **Windows** | Aluminum frame and single glazing | 0.6 | 5.70 |

In all the cases, the entirely naturally ventilated mode was applied to the residential unit. The occupancy and ventilation time for R1 and R2 are presented in Table 3.

Table 3. Time of occupancy and ventilation

| | **Occupancy time** |
|---|---|
| **R1** | 9am-10 pm |
| **R2** | 10pm- 9am |
| | 3pm- 5pm |
| | **Ventilation time** |
| | As long as outside conditions allows (within comfort range) |

### 2.1. Description of the BC

Multistory residential apartment buildings constitute the most common housing type in the public domain in Amman. BC was selected based on a detailed study of the common characteristics of the multistory apartment buildings with respect to the floor layout, area, building form, orientation, construction materials, and characteristics of the architectural elements, including window sizes and areas[17-19].

The building has four floors and rises to approximately 12 m above the ground level. Each floor has two apartments that exhibit the same floor layout and area. The selected residential unit is located on the first floor and has a total floor area of 163 m$^2$ with a ceiling height of 2.70 m. It has three exterior facades that are exposed to the outdoors. Figure 1 shows the floor plan of the case study apartment. Two spaces were selected in this study.

Space 1 (R1) represents the living zone with a total floor area of 23.8 m$^2$, two exterior walls, and one opening oriented to the west. Space 2 (R2) represents the sleeping zone with a total floor area of 14 m$^2$ and one exterior wall oriented toward the south. The characteristics of R1 and R2 are summarized in Figure 2. The investigation of the effect of the various strategies on the natural ventilation inside the two spaces was based on the evaluation of the IAQ conditions (with respect to the VR, $CO_2$ concentration, indoor operative temperature, and RH) and energy consumption. The ventilation strategies were classified into two main categories (see Figure 3), i.e., zero-cost ventilation strategies, which involved investigation of the effect of the building orientation and desiging a new floor plan layout, and low-cost ventilation strategies, which involved investigation of the effect of the window type, WWR, adding shading device, and wind channel system[20-22].

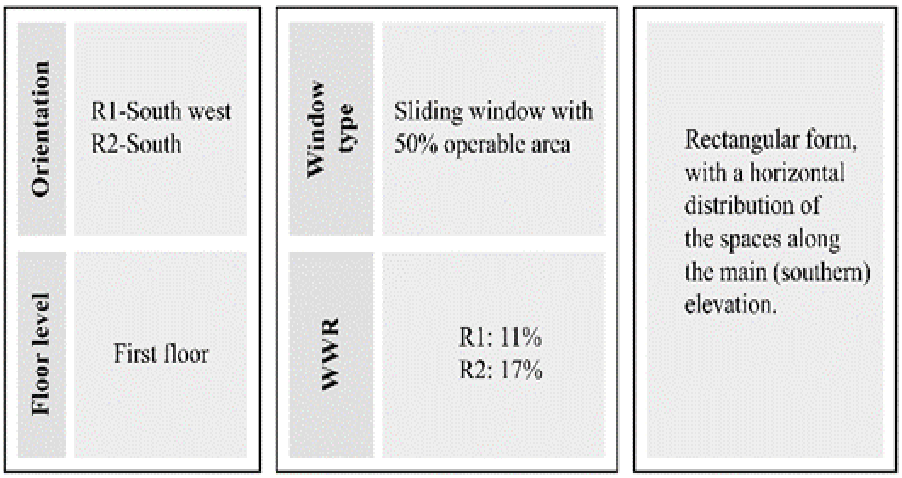


Figure 1. Floor plan of the B.C. apartment that denotes the spaces under investigation

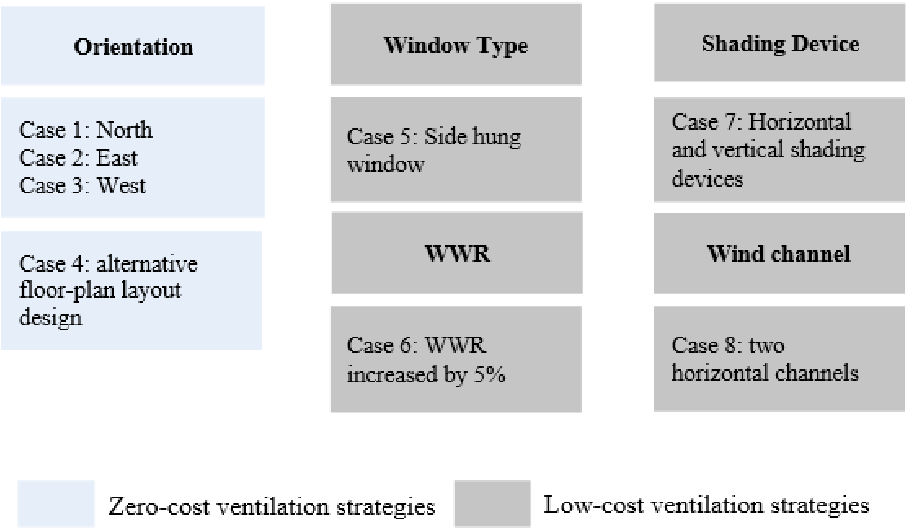


Figure 2. B.C. characteristics

### 2.2. Proposed ventilation strategies

The proposed ventilation strategies were applied to different architectural elements within the residential unit, and they were considered to be influential strategies in the field of natural ventilation because they impact the effectiveness of natural ventilation in buildings and are within the scope of this study. Eight main strategies were chosen and categorized according to their cost (zero cost and low cost). Each case investigates the impact of the implementation of one strategy while maintaining the remaining tested parameters fixed; this is conducted to evaluate the impact of each ventilation strategy on the natural ventilation performance inside the investigated spaces.

#### 2.2.1. Zero cost ventilation strategies

- Case 1: The building orientation. The long axis is east–west, and the longest facade is oriented toward the north.
- Case 2: The building orientation. The long axis is north–south, and the longest facade is oriented toward the east.
- Case 3: The building orientation. The long axis is north–south, and the longest facade is oriented toward the west.

- Case 4: An alternative floor-plan layout design. An alternative floor-plan layout was designed to investigate the manner in which the natural ventilation performance would be affected (Figure 5). The typical distribution of the two apartments located within the same floor in the BC was altered by separating two units with a void. The addition of a void created an additional wind path, enhancing the pressure difference between the two sides of the building and increasing the natural ventilation performance. Furthermore, the arrangement of the rooms and the addition of supplementary interior openings that measured 1.0 m × 0.4 m were implemented above some doors to allow free circulation of the airflow and minimize airflow resistance (Figure 6). The characteristics of R1 and R2 were changed to those presented in Table 4.

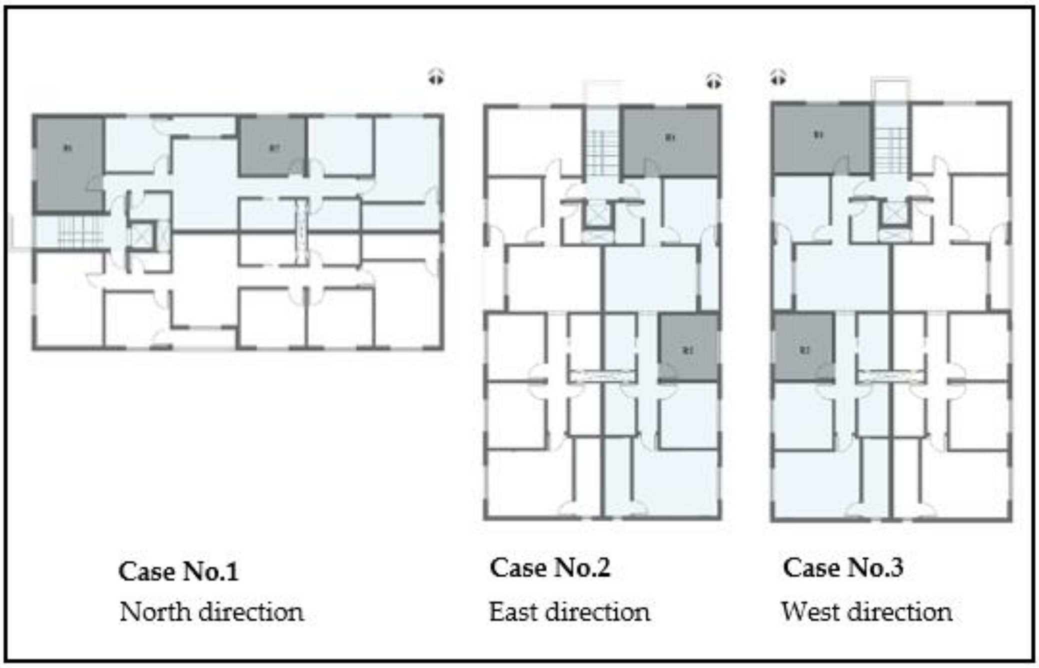
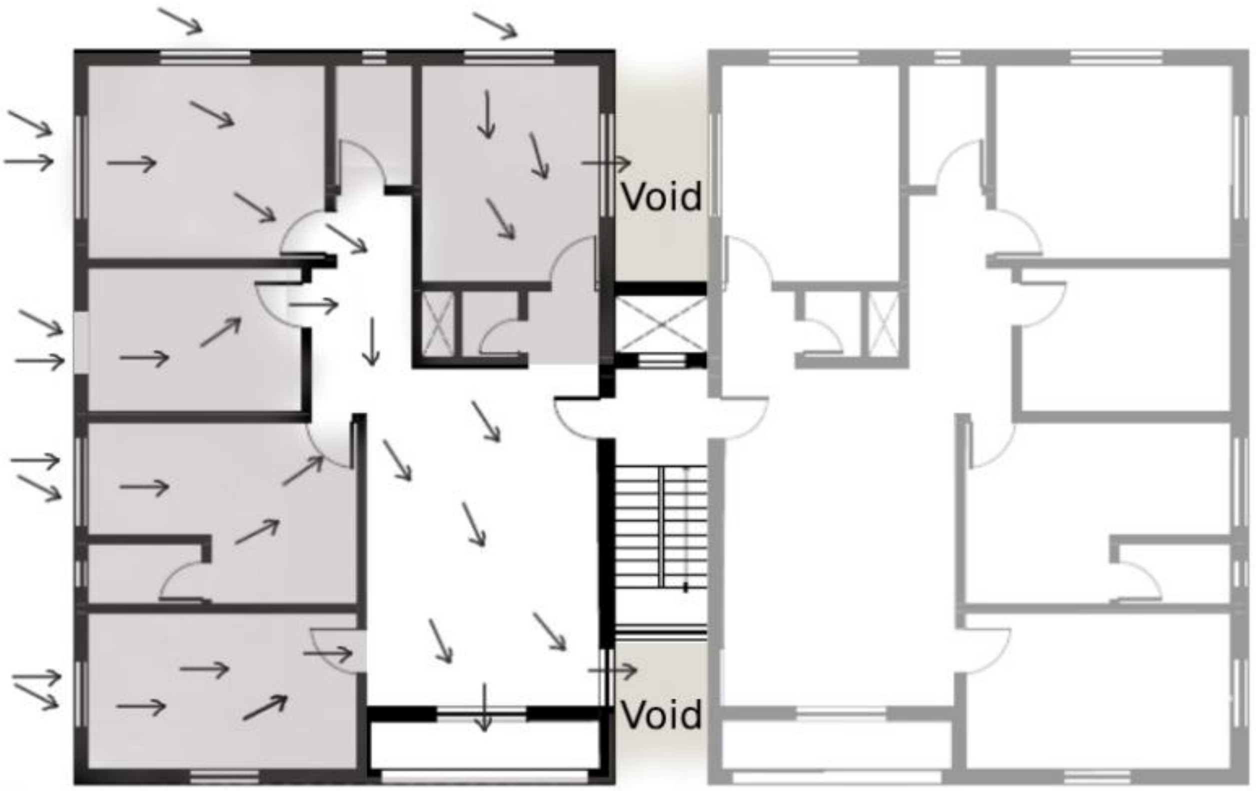


Figure 3. Zero-cost ventilation strategies/ building orientation

Figure 4. The alternative floor-plan layout investigated in Case

Case No.4



B.C

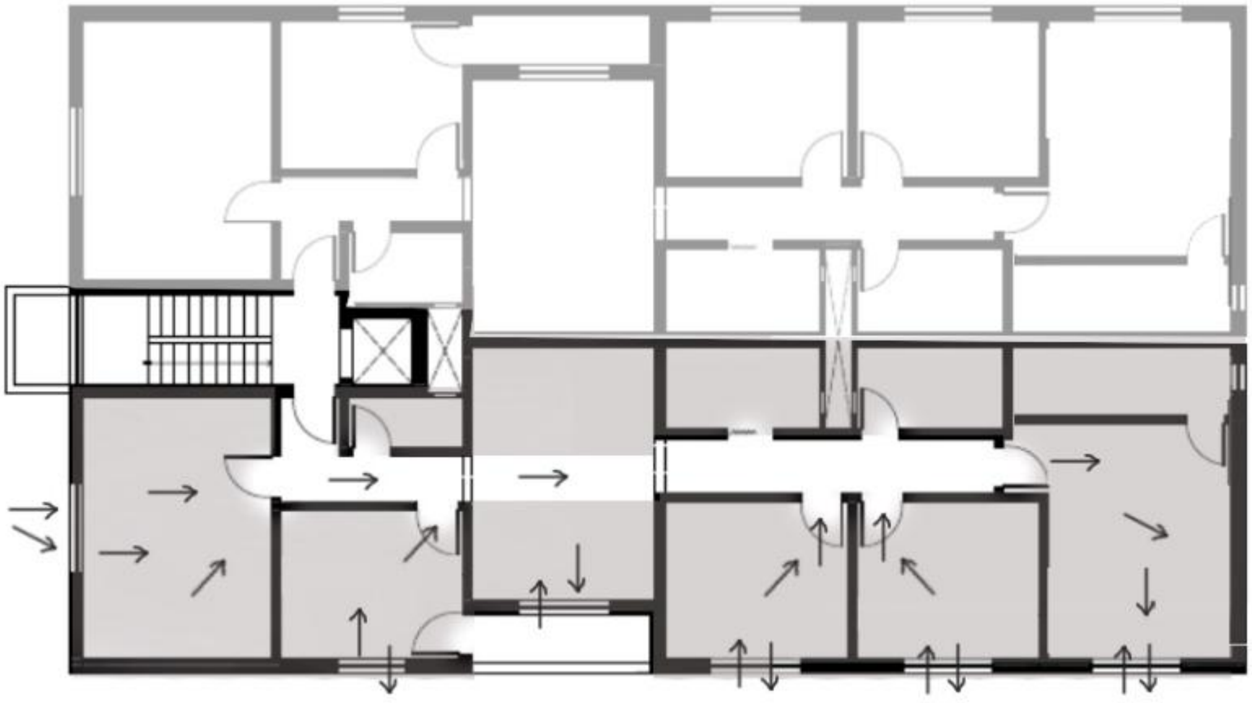


Figure 5. Arrangements of the two apartments in Case 4 (top) and the B.C. (bottom) along with their wind paths

Table 4. Characteristics of R1 and R2 in B.C. and Case 8

| | Area | Orientation | Exterior walls | Openings | Interior openings |
|---|---|---|---|---|---|
| **R1** | | | | | |
| **BC** | 23.8 $m^2$ | SW | 2 | 1 | - |
| **Case 10** | 20.5 $m^2$ | SW | 2 | 2 | 1 |
| **R2** | | | | | |
| **BC** | 14 $m^2$ | S | 1 | 1 | - |
| **Case 10** | 22.6 $m^2$ | NW | 2 | 2 | 1 |

### 2.2.2. Low cost ventilation strategies

- Case 5: The window type. The window type changed from sliding to side hung. The operable area of the window was increased from 50% in case of sliding windows (BC) to 90% in side hung windows, whereas the thermal and lighting properties remained the same as those in BC.
- Case 6: The WWR. WWR was increased by 5%, i.e., 16% and 22% in R1 and R2, respectively.
- Case 7: Addition of the shading devices. A 0.60-m deep horizontal plastered concrete shading device was added to the south-facing window (R2), whereas vertical sunshade was added to the west-facing window (R1) while retaining the WWRs in Case 7.
- Case 8: Addition of a wind channel system. The system applied two horizontal channels, with two facade
- openings on opposite sides of the building located in the ceiling and under the floor to connect the leeward
- rooms with the high-pressure windward facade and the windward rooms with the low-pressure leeward

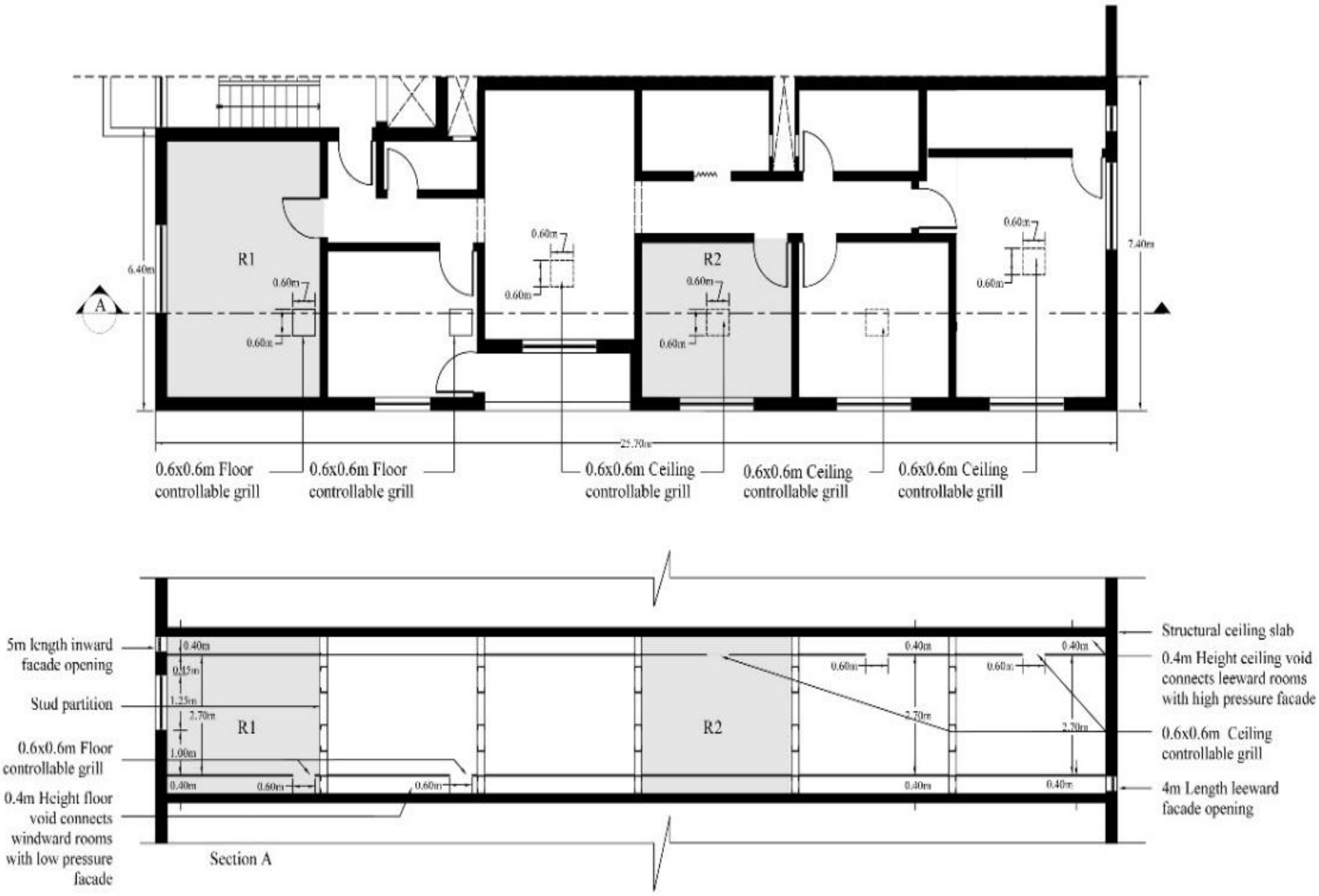


Figure 7. Low cost ventilation strategies (window type, WWR, and shading device)

facade through a suitable and controllable ceiling/floor grill, allowing the cross-ventilation of the spaces. The wind channel characteristics proposed by Gomaa[23] were used herein. 0.40-m high ceiling and floor channels were used, which are considered to be suitable for providing sufficient airflow at a feasible cost. A 0.60 m × 0.60 m diffuser was used with 5- and 4-m-long windward and leeward facade openings, respectively, as shown in Figure 8.

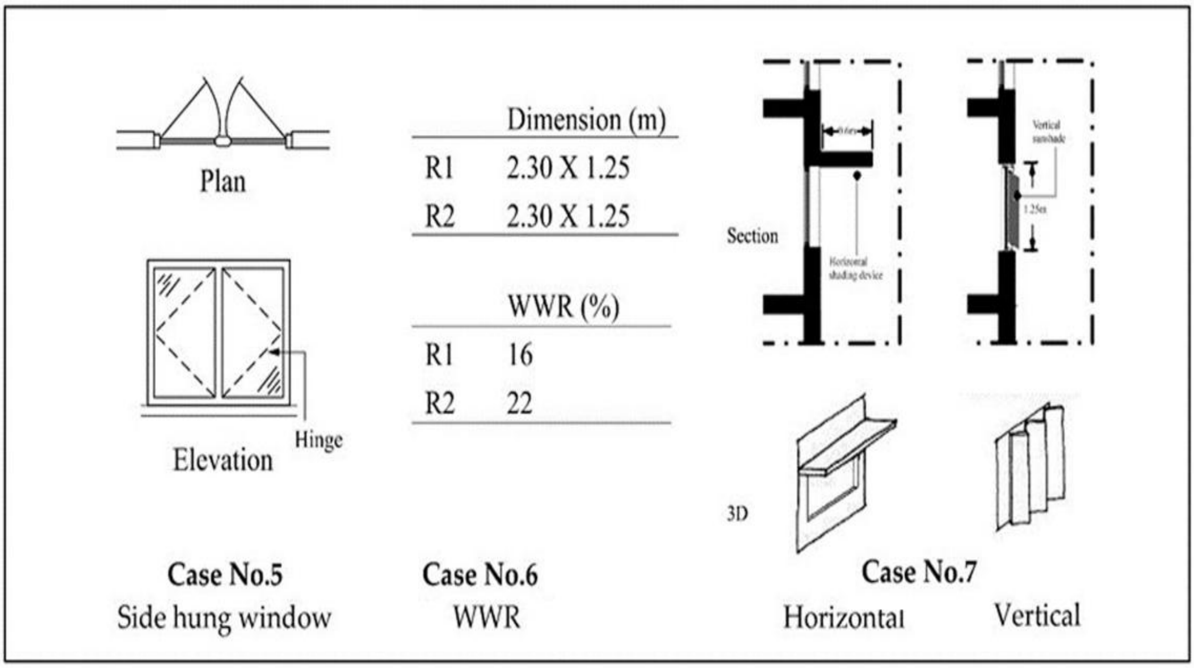


Figure 8. Floor plan (top) and section (bottom) of the apartment unit with a wind channel system

## 3. Results and discussion

In this section, the impact of various zero and low-cost ventilation strategies on the natural ventilation performance in R1 and R2 during two weeks in June and September is presented. The IAQ parameters (VR, $CO_2$ concentration, indoor operative temperature, and RH) and energy consumption of the B.C and various cases were evaluated and analyzed. The evaluation is performed based on the ASHRAE standards, which define the acceptable ranges of environmental parameters that can be used to obtain acceptable IAQ and thermal conditions. According to the ASHRAE standard 62.2-2019, which defines the acceptable IAQ in residential buildings. The standard does not specify a recommended limit regarding VR and CO2 concentration inside an occupied space. However, it defines the minimum limit of RH (should not become lower than 30%). Regarding the indoor operative temperature, the acceptable comfort range as specified by ASHRAE standard 55-2017 should not exceed 23.3°C–28.1°C in June and 23.9°C–28.3°C in September[24-26].

### 3.1 V.R and $CO_2$ Concentration

Referring to previously mentioned figures, it can be concluded that cases with higher VRs delivered lower $CO_2$ concentration; through allowing larger amount of fresh air to flow into the spaces, thus decreasing the concentration of $CO_2$ during the typical weeks. Consequently, Case 5 and Case 4 delivered the largest decrease in $CO_2$ when compared with other cases. In R1, the $CO_2$ in Case 5 decreased by approximately 322 and 318 ppm in June and September, respectively, whereas in R2, $CO_2$ decreased by approximately 258 and 226 ppm in June and September. The results are comparable to that obtained by Wargocki [27] who concluded that reduced $CO_2$ concentration is largely related to the provision of high VRs, and with Spentzou [28] who studied the impact of different ventilation strategies on the indoor air properties in multi-story apartment buildings. He found that strategies with high VRs resulted in a lower concentration of $CO_2$ . Furthermore, in case of R1, Case 4 decreased the $CO_2$ by approximately 238 and 237 ppm in June and September, respectively, whereas, in case of R2, the average $CO_2$ concentration was decreased by 86 and 64 ppm in June and September, respectively

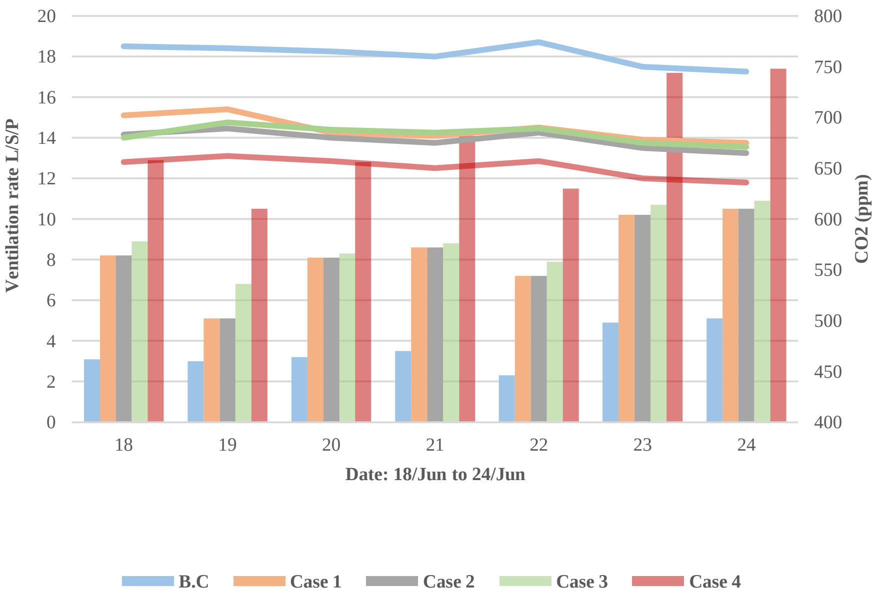


Figure 9. Daily average V.R. and $CO_2$ concentration for the B.C. and zero cost ventilation strategies

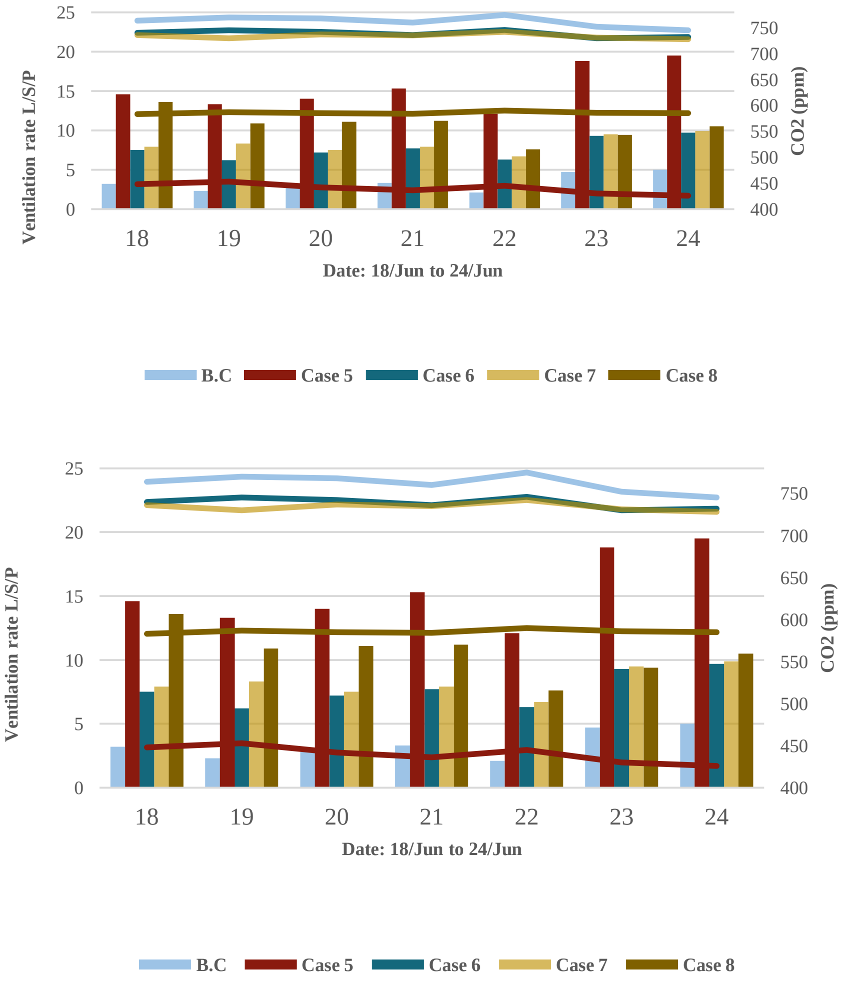


Figure 10. Daily average V.R. and $CO_2$ concentration for the B.C. and) low cost ventilation strategies in R1 (Space 1) during a typical week in June

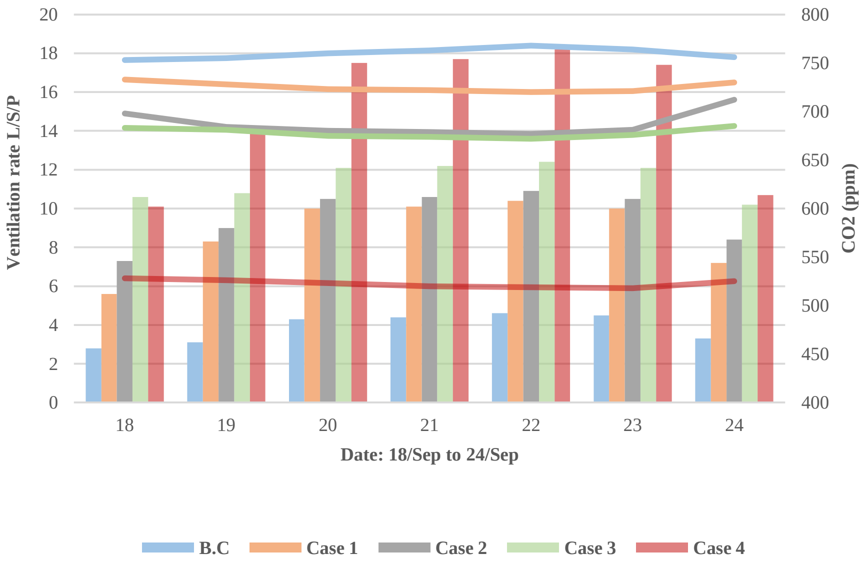


Figure 11. Daily average V.R. and $CO_2$ concentration for the B.C. and zero cost ventilation strategies

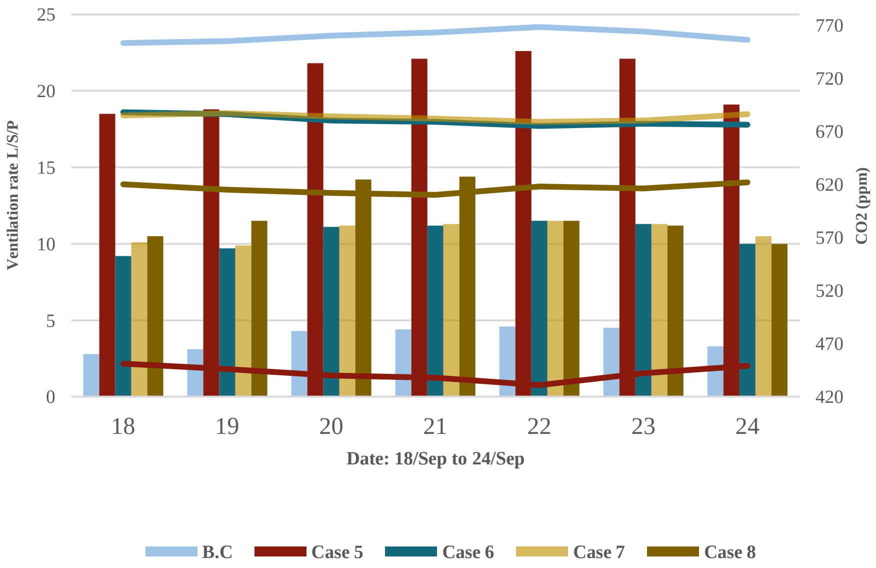


Figure 12. Daily average V.R. and $CO_2$ concentration for the B.C. and low cost ventilation strategies in R1 (Space 1) during a typical week in September

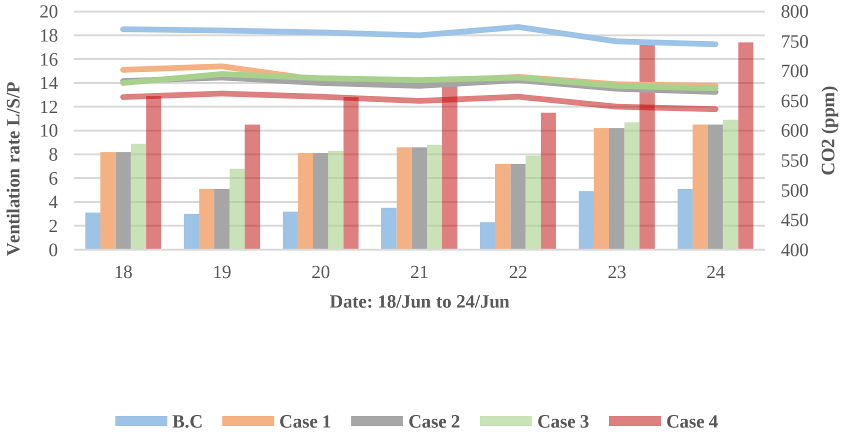


Figure 13. Daily average V.R. and $CO_2$ concentration for the B.C. and zero cost ventilation strategies

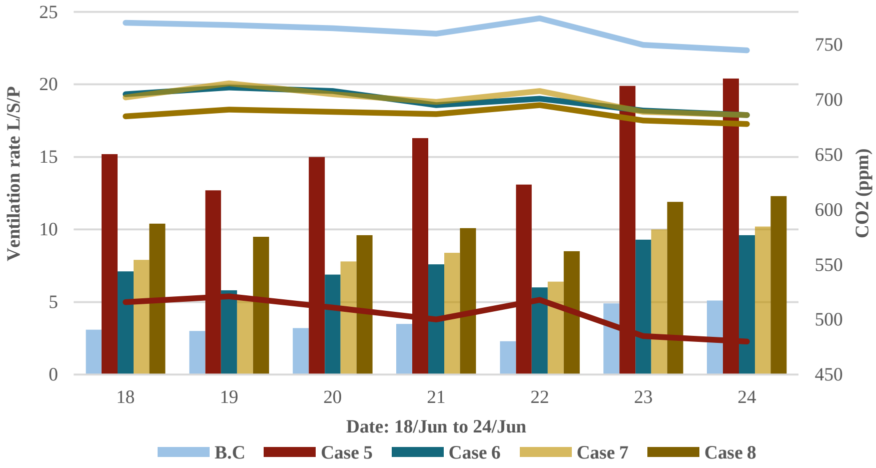


Figure 14. Daily average V.R. and $CO_2$ concentration for the B.C. and low cost ventilation strategies in R2 (Space 2) during a typical week in June.

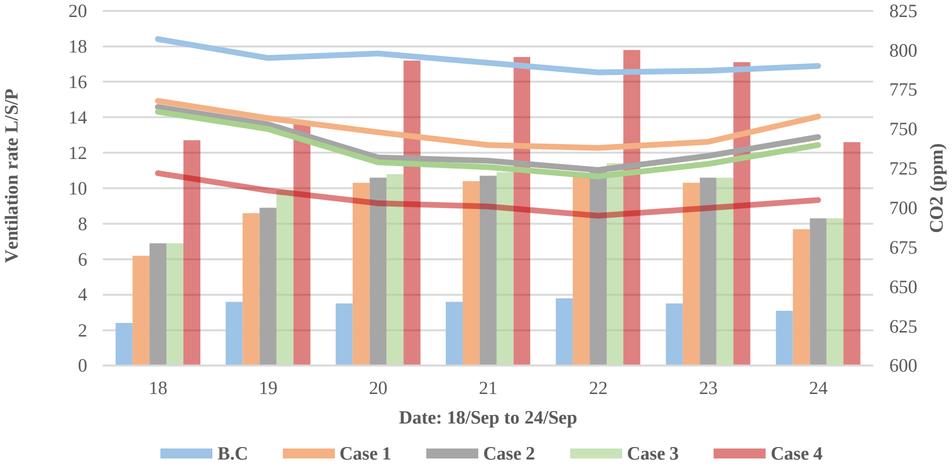


Figure 15. Daily average V.R. and $CO_2$ concentration for the B.C. and zero cost ventilation strategies

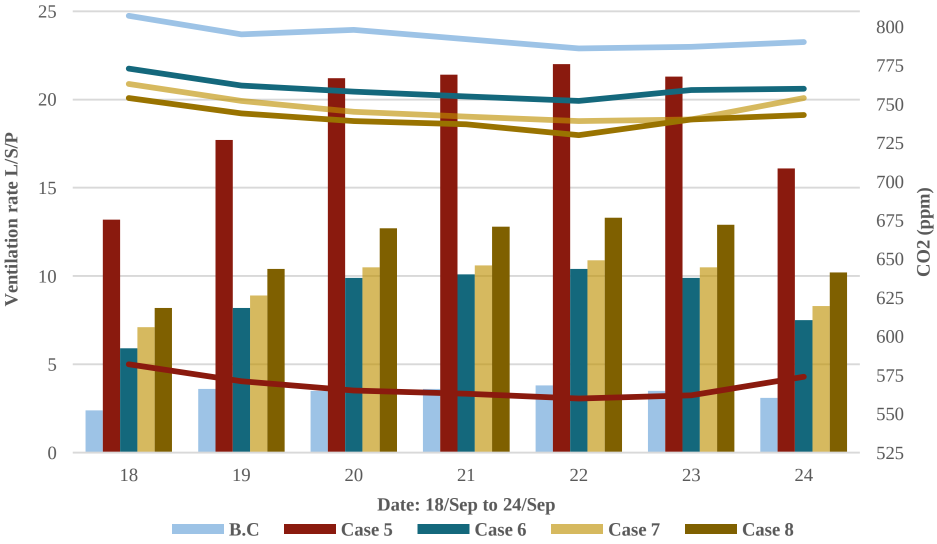


Figure 16. Daily average V.R. and $CO_2$ concentration for the B.C. and low cost ventilation strategies in R2 (Space 2) during a typical week in September

The hours of occupancy, ventilation times, and $CO_2$ concentration for a randomly chosen typical day during June in R1 and R2 are shown in Figures 13 and 14. In R1 the space was ventilated during the daytime only when it was occupied by the users and when outdoor climatic condition was within comfort range [29]. While R2 was mainly used and ventilated at night. It can be concluded from the figures that the concentration of $CO_2$ in a space is relative to its occupancy rate and ventilation times. Higher levels of $CO_2$ were recorded in the spaces when it was used by high number of occupants with low VRs, in contrast, ideal conditions were obtained when there was high VRs with an average number of occupants.

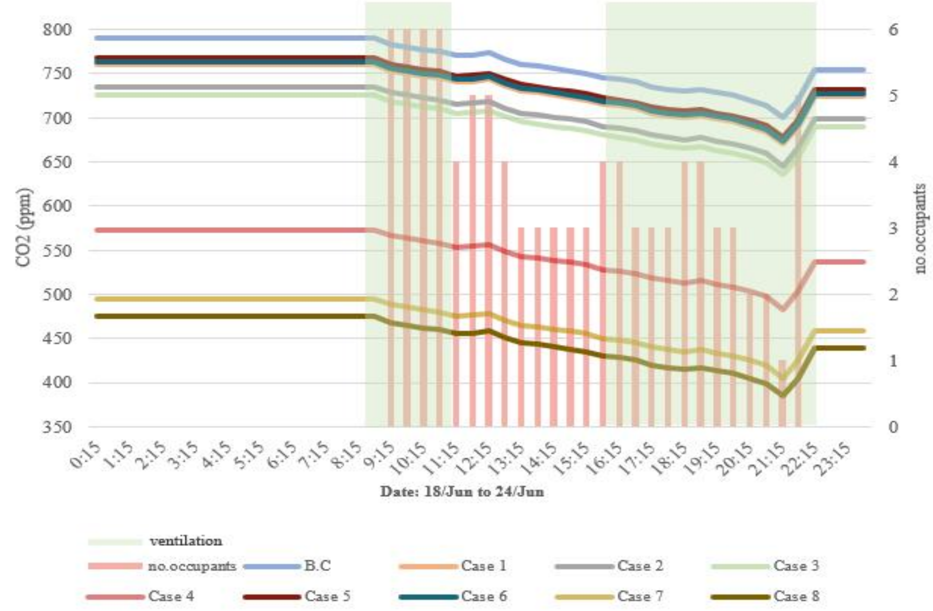


Figure 17. Hourly $CO_2$ concentration, number of occupants, and ventilation times in R1 during a typical day in June for all the case studies

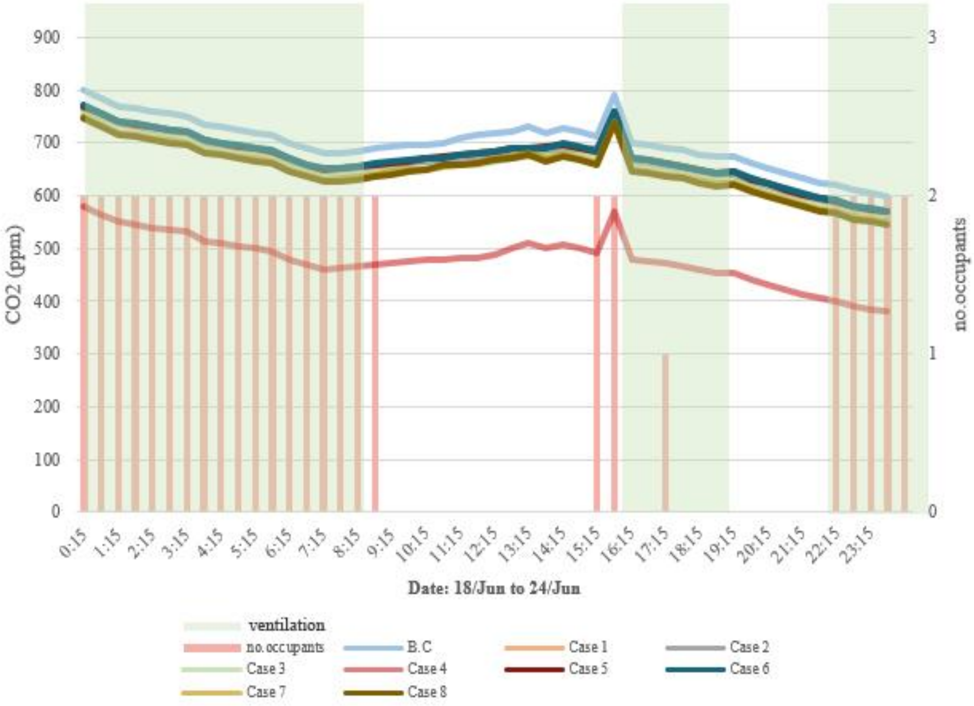


Figure 18. Hourly $CO_2$ concentration, number of occupants, and ventilation times in R2 during a typical day in June for all the case studies

Among low-cost ventilation strategies, Cases 5 and 7 have delivered a decrease in the indoor operative temperature. The average indoor operative temperature reduced by 3.5°C and 3.9°C in June and by 1.5°C and 3.4°C, respectively, in September, in Cases 5 and 7. However, the minimum value reduced by 3.3°C and 3.6°C in June and by 1.1°C and 2.9°C in September, respectively. Furthermore, the maximum value reduced by 4.2°C and 4.6°C in June and 2°C and 4.1°C in September in Cases 5 and 7, respectively. The decrease in the average operative temperature in Case 5 can be attributed to the increased V.R., which reduced the indoor temperature when the outside air was cooler than the inside air. Further, the addition of the shading devices in Case 7 prevented direct solar radiation from penetrating the space, reducing the indoor operative temperature. Similar results were obtained by Bakhlah et al. [30] and Liping and Hien [31], who studied the impact of the shading devices on the indoor T.C. and concluded that shading devices play a significant role in reducing the indoor air temperature. On the other hand, increasing the WWR in Case 6 delivered a slight increase in the indoor operative temperature compared to the B.C, exceeding ASHRAE comfort range. During June, the average value increased by 1°C, whereas the average minimum and maximum values increased by 0.2°C and 0.6°C, respectively, in comparison with B.C. In September, the average, average minimum, and average maximum values of the indoor operative temperature increased by 0.5°C, 0.2°C, and 0.2°C, respectively. The obtained results are in agreement with those obtained by Mou [32] who found that increasing the window size can significantly increase the indoor temperture gained by radiant heat during the day which comes through large window openings.

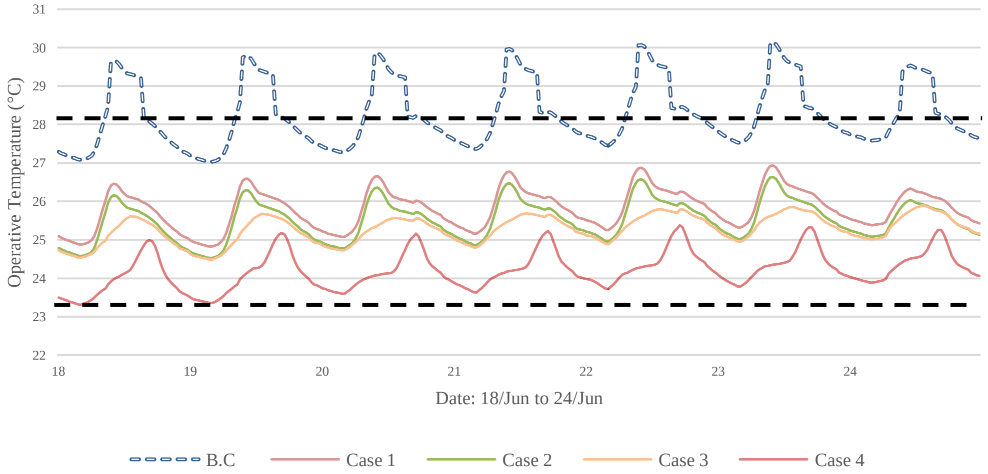


Figure 19. Daily operative temperatures in R1 during a typical week in June for zero cost ventilation strategies

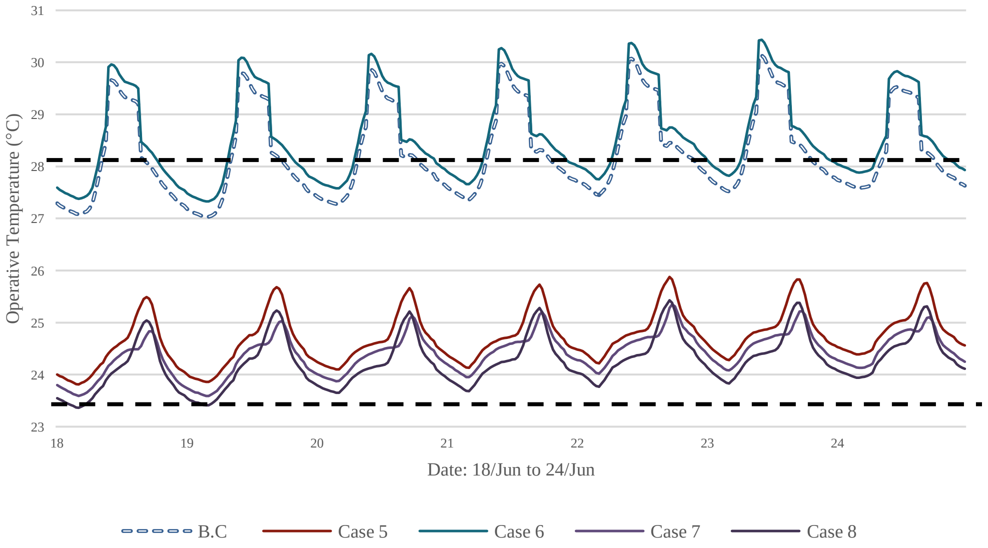


Figure 20. Daily operative temperatures in R1 during a typical week in June for low cost ventilation strategies

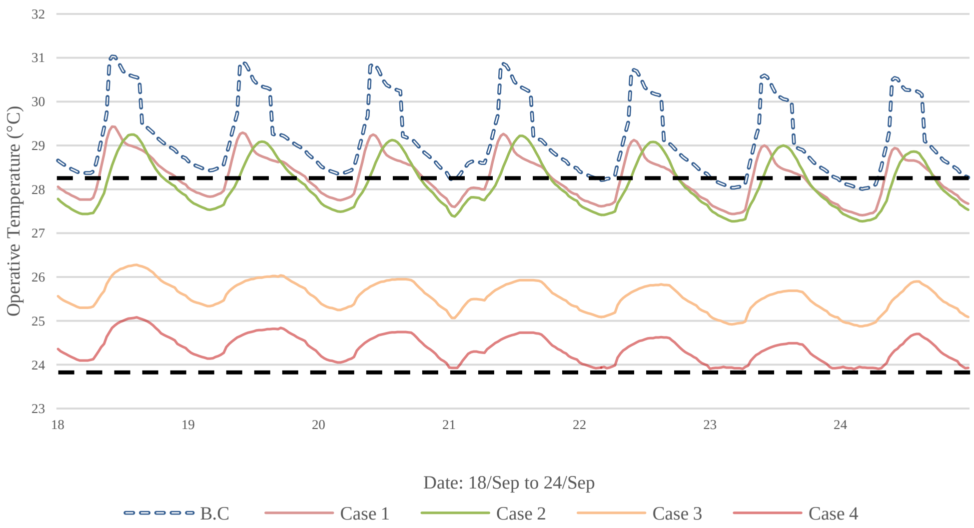


Figure 21. Daily operative temperatures in R1 during a typical week in September for zero cost ventilation strategies

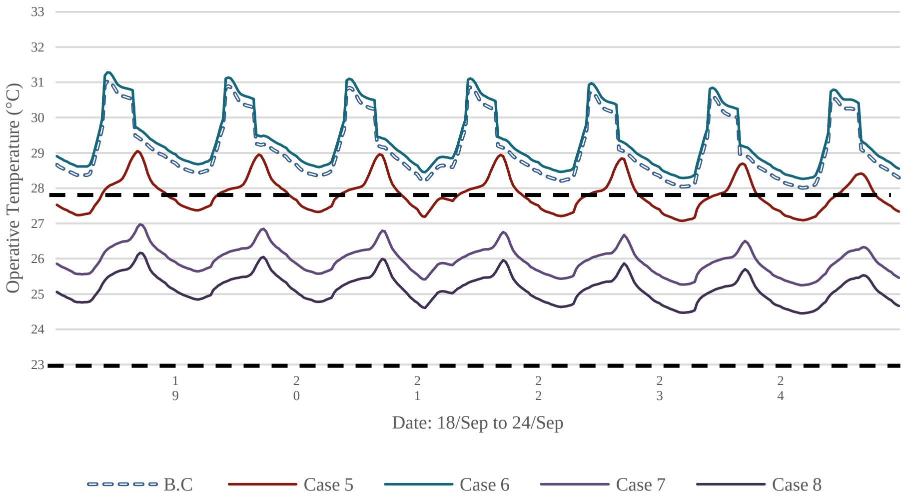


Figure 22. Daily operative temperatures in R1 during a typical week in September for zero cost ventilation strategies

Table 6. Daily operative temperature for the B.C. and zero and low-cost ventilation strategies in R2 during a typical week in June and September

| **June** | **Zero cost ventilation strategies** | | | | | **Low cost ventilation strategies** | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Temperature (°C)** | **B.C** | **Case 1** | **Case 2** | **Case 3** | **Case 4** | **Case 5** | **Case 6** | **Case 7** | **Case 8** |
| **Average** | 28.5 | 25.1 | 25.9 | 26 | 24.1 | 25.7 | 28.8 | 25.1 | 24.7 |
| **Average min.** | 27.6 | 24.5 | 24.9 | 25.1 | 23.1 | 25.3 | 28.2 | 24.5 | 24.1 |
| **Average max.** | 29.6 | 25.6 | 27.1 | 27.5 | 25 | 26.3 | 29.3 | 25.6 | 25.3 |
| **September** | **Zero cost ventilation strategies** | | | | | **Low cost ventilation strategies** | | | |
| **Temperature (°C)** | **B.C** | **Case 1** | **Case 2** | **Case 3** | **Case 4** | **Case 5** | **Case 6** | **Case 7** | **Case 8** |
| **Average** | 29.3 | 25.6 | 27.7 | 27.9 | 25 | 28.1 | 30.1 | 26 | 25.1 |
| **Average min.** | 28.5 | 25 | 26.8 | 27.1 | 23.7 | 27.1 | 29.4 | 25.3 | 23.9 |
| **Average max.** | 30.5 | 26.1 | 28.9 | 29.3 | 26.2 | 29.4 | 31.6 | 26.6 | 26.5 |

Among zero-cost ventilation strategies, the results showed that orienting the R2 window toward the north in Case 1 delivered the optimal results. During June, the average value decreased by 3.4°C, whereas the average minimum and maximum values decreased by 3.1°C and 4°C, respectively, in comparison with B.C. In September, the average, average minimum, and average maximum values of the indoor operative temperature decreased by 3.7°C, 3.5°C, and 4.4°C, respectively.

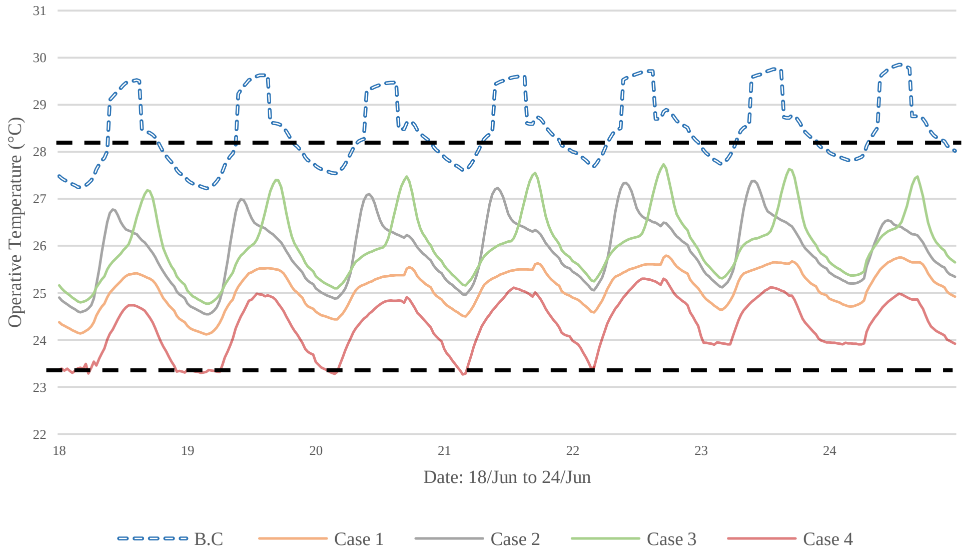


Figure 23. Daily operative temperatures in R2 during a typical week in June for zero cost ventilation strategies

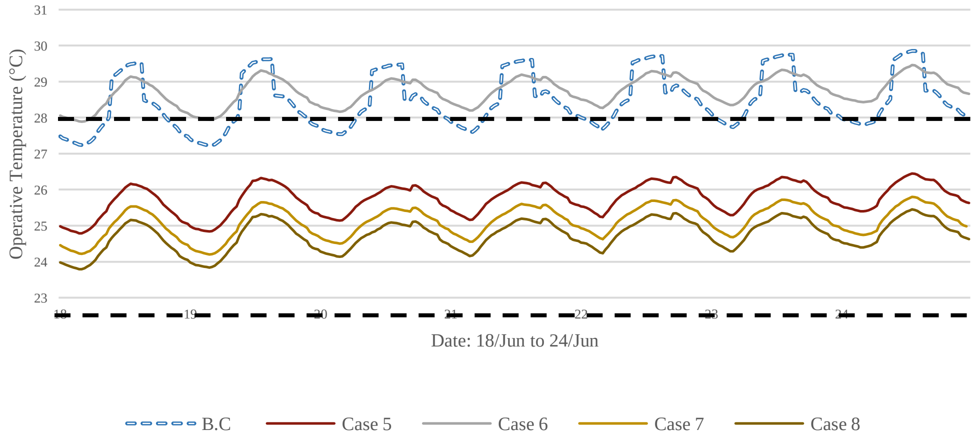


Figure 24. Daily operative temperatures in R2 during a typical week in June for low cost ventilation strategies

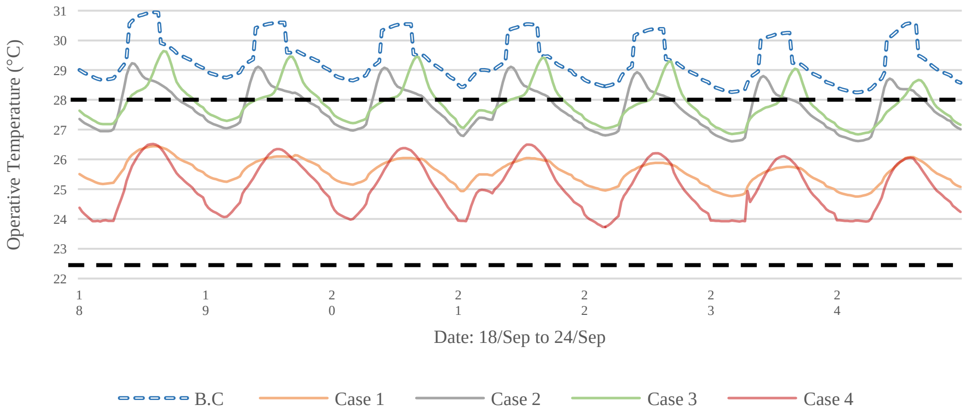


Figure 25. Daily operative temperatures in R2 during a typical week in September for zero cost ventilation strategies

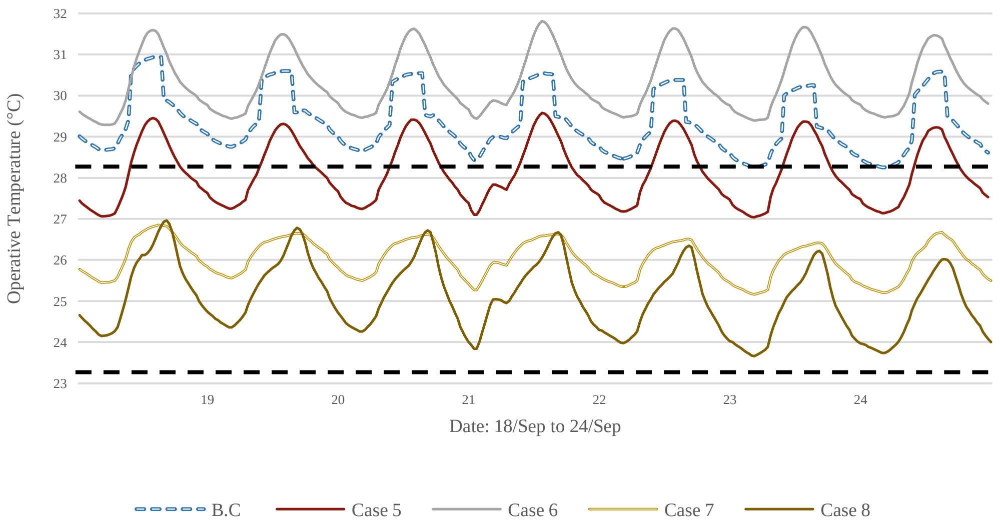


Figure 26. Daily operative temperatures in R2 during a typical week in September for low cost ventilation strategies

Tables 7 and 8 presented the number of comfort hours (which fall within ASHRAE comfort range) in R1 and R2 during the two typical weeks in June and September for all the investigated zero and low-cost ventilation strategies. It can be concluded that during the typical week in June, all ventilation strategies (except Case 6) have increased the number of comfort hours in the two spaces, raising it to 24 hours in most times compared to the B.C. In September, Cases 3, 4, 7, and 8 delivered 24 hours of comfort in R1. While in R2 higher values of comfort hours were obtained in Cases 1, 4, 7, and 8.

Table 7. Number of comfort hours in R1 during the two typical weeks in June and September for all cases

***18/June to 24/June***

| ***Day*** | **B.C** | **Case 1** | **Case 2** | **Case 3** | **Case 4** | **Case 5** | **Case 6** | **Case 7** | **Case 8** |
|---|---|---|---|---|---|---|---|---|---|
| *18* | 16 | 24 | 24 | 24 | 24 | 24 | 13 | 24 | 24 |
| *19* | 14 | 24 | 24 | 24 | 24 | 24 | 12 | 24 | 24 |
| *20* | 13 | 24 | 24 | 24 | 24 | 24 | 9 | 24 | 24 |
| *21* | 12 | 24 | 24 | 24 | 24 | 24 | 8 | 24 | 24 |
| *22* | 9 | 24 | 24 | 24 | 24 | 24 | 7 | 24 | 24 |
| *23* | 11 | 24 | 24 | 24 | 24 | 24 | 6 | 24 | 24 |
| *24* | 14 | 24 | 24 | 24 | 24 | 24 | 9 | 24 | 24 |

***18/Sep to 24/Sep***

| ***Day*** | **B.C** | **Case 1** | **Case 2** | **Case 3** | **Case 4** | **Case 5** | **Case 6** | **Case 7** | **Case 8** |
|---|---|---|---|---|---|---|---|---|---|
| *18* | 0 | 16 | 19 | 24 | 24 | 24 | 0 | 24 | 24 |
| *19* | 0 | 4 | 9 | 24 | 24 | 14 | 0 | 24 | 24 |
| *20* | 0 | 15 | 19 | 24 | 24 | 24 | 0 | 24 | 24 |
| *21* | 2 | 5 | 9 | 24 | 24 | 15 | 0 | 24 | 24 |
| *22* | 5 | 15 | 19 | 24 | 24 | 24 | 0 | 24 | 24 |
| *23* | 8 | 10 | 11 | 24 | 24 | 15 | 1 | 24 | 24 |
| *24* | 8 | 15 | 19 | 24 | 24 | 24 | 3 | 24 | 24 |

Table 8. Number of comfort hours in R2 during the two typical weeks in June and September for all cases

| *18/June to 24/June* | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| *Day* | **B.C** | **Case 1** | **Case 2** | **Case 3** | **Case 4** | **Case 5** | **Case 6** | **Case 7** | **Case 8** |
| ***18*** | 15 | 24 | 24 | 24 | 24 | 24 | 6 | 24 | 24 |
| ***19*** | 12 | 24 | 24 | 24 | 24 | 24 | 6 | 24 | 24 |
| ***20*** | 9 | 24 | 24 | 24 | 24 | 24 | 0 | 24 | 24 |
| ***21*** | 8 | 24 | 24 | 24 | 24 | 24 | 0 | 24 | 24 |
| ***22*** | 7 | 24 | 24 | 24 | 24 | 24 | 0 | 24 | 24 |
| ***23*** | 7 | 24 | 24 | 24 | 24 | 24 | 0 | 24 | 24 |
| ***24*** | 8 | 24 | 24 | 24 | 24 | 24 | 0 | 24 | 24 |
| *18/Sep to 24/Sep* | | | | | | | | | |
| *Day* | **B.C** | **Case 1** | **Case 2** | **Case 3** | **Case 4** | **Case 5** | **Case 6** | **Case 7** | **Case 8** |
| ***18*** | 0 | 24 | 17 | 23 | 24 | 19 | 0 | 24 | 24 |
| ***19*** | 0 | 24 | 13 | 8 | 24 | 11 | 0 | 24 | 24 |
| ***20*** | 0 | 24 | 17 | 24 | 24 | 19 | 0 | 24 | 24 |
| ***21*** | 0 | 24 | 17 | 11 | 24 | 9 | 0 | 24 | 24 |
| ***22*** | 0 | 24 | 17 | 24 | 24 | 19 | 0 | 24 | 24 |
| ***23*** | 3 | 24 | 18 | 13 | 24 | 11 | 1 | 24 | 24 |
| ***24*** | 3 | 24 | 17 | 24 | 24 | 18 | 3 | 24 | 24 |

### 3.3. Relative humidity (RH)

The RH levels for zero and low-cost ventilation strategies during the typical summer weeks in June and September with respect to R1 are presented in Figures 19 and 20, respectively. The results indicate that all the cases (except Case 6) exhibited an increase in RH during the whole period with a slight difference between them, maintaining the values greater than what is recommended by ASHRAE standards.

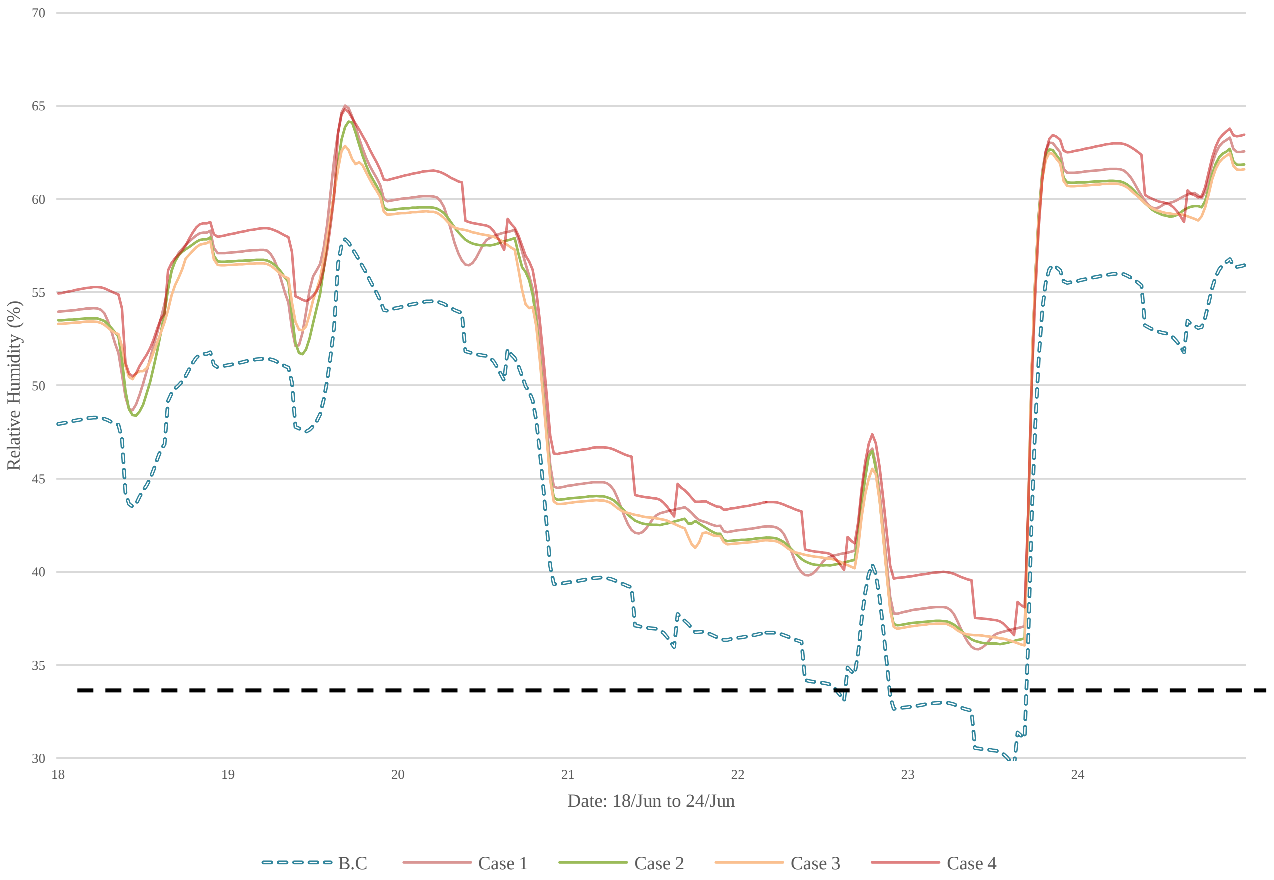


Figure 27. Relative humidity in R1 during a typical week in June for (a) zero cost ventilation strategies

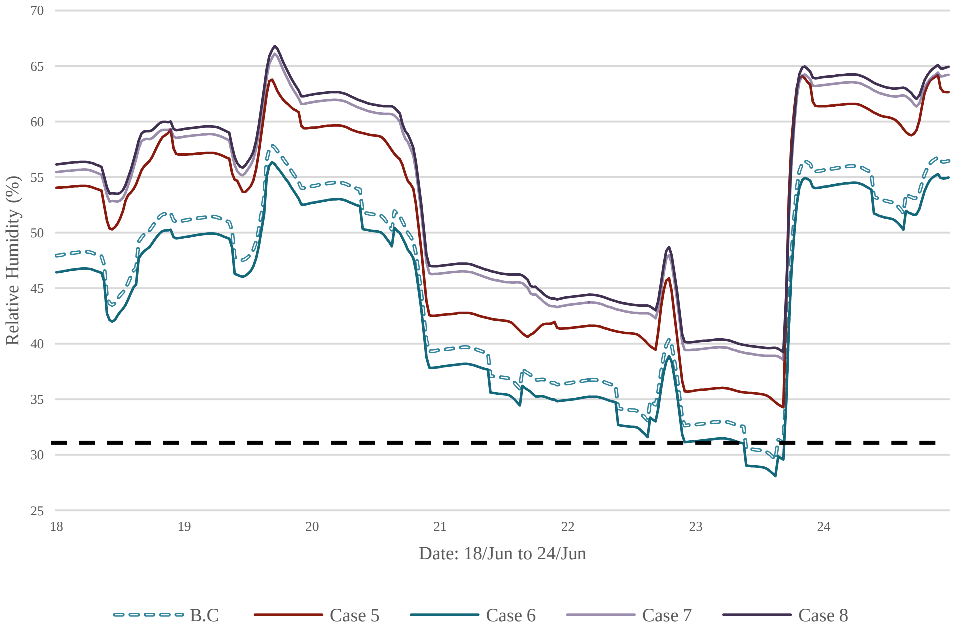


Figure 28. Relative humidity in R1 during a typical week in June for low cost ventilation strategies

Figure 29. Relative humidity in R1 during a typical week in September for zero cost ventilation strategies

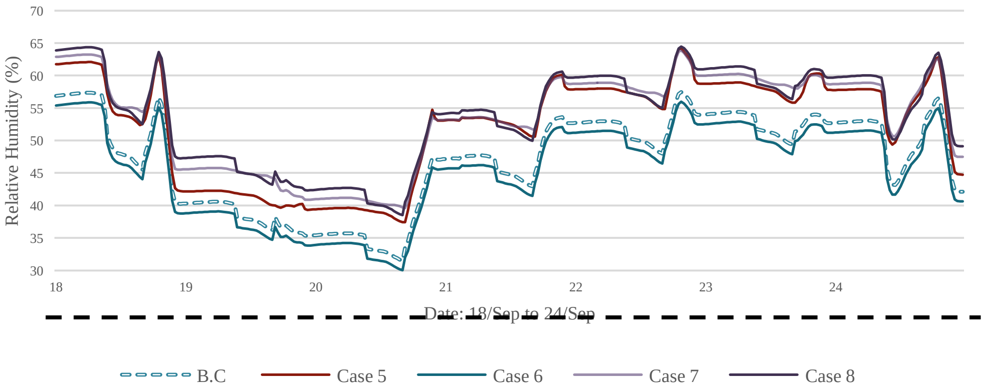


Figure 30. Relative humidity in R1 during a typical week in September for low cost ventilation strategies

According to the figures, Cases 1,2,3,4,5,7, and 8 delivered an average increase by approximately 6.6% in comparison with the B.C during June, while in September the average RH value was increased by approximately 6.5%. However, Case 6 exhibited a decrease by 1.3% and 1.5% in June and September respectively. The decrease in the average RH can be explained by the fact that the RH in a space depends on its indoor air temperature and moisture content. In Case 6, the moisture content was decreased as a result of having a lower dew point temperature, thus decreasing the RH in the space[33-35]

The behavior observed in various cases exhibited similar impacts on the RH in R2 during the two typical weeks in June and September, as shown in Figures 21 and 22. All Cases (except Case 6) delivered an average increase by approximately 8.9% and 14.8% in June and September, respectively. However, Case 6 exhibited a decrease in the average RH by 1.1% and 1.2% in June and September, respectively.

Figure 31. Relative humidity in R2 during a typical week in June for (a) zero cost ventilation strategies

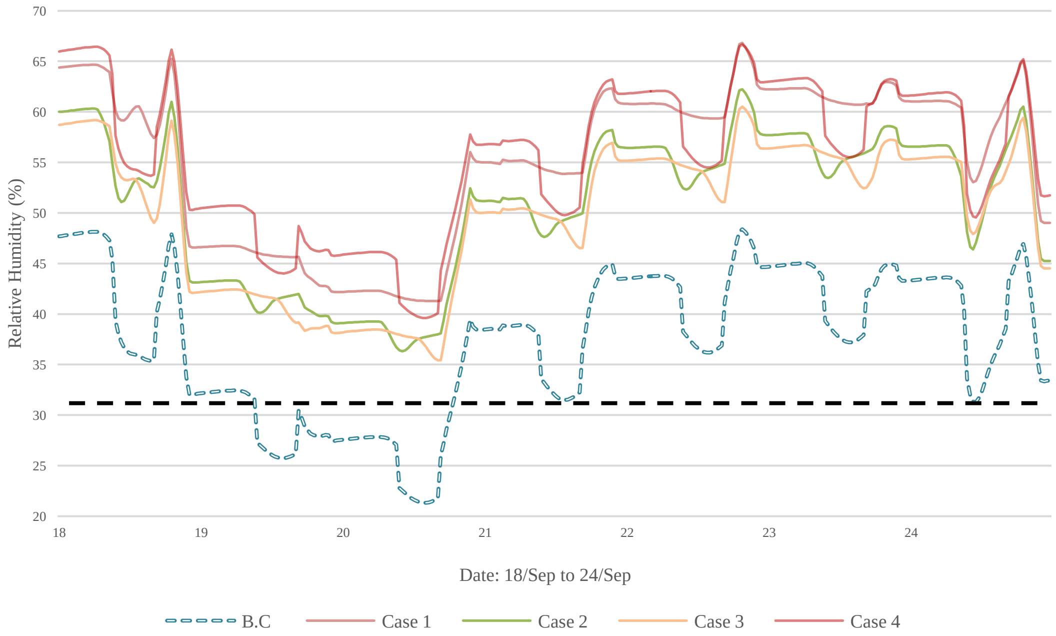


Figure 32. Relative humidity in R2 during a typical week in September for zero cost ventilation

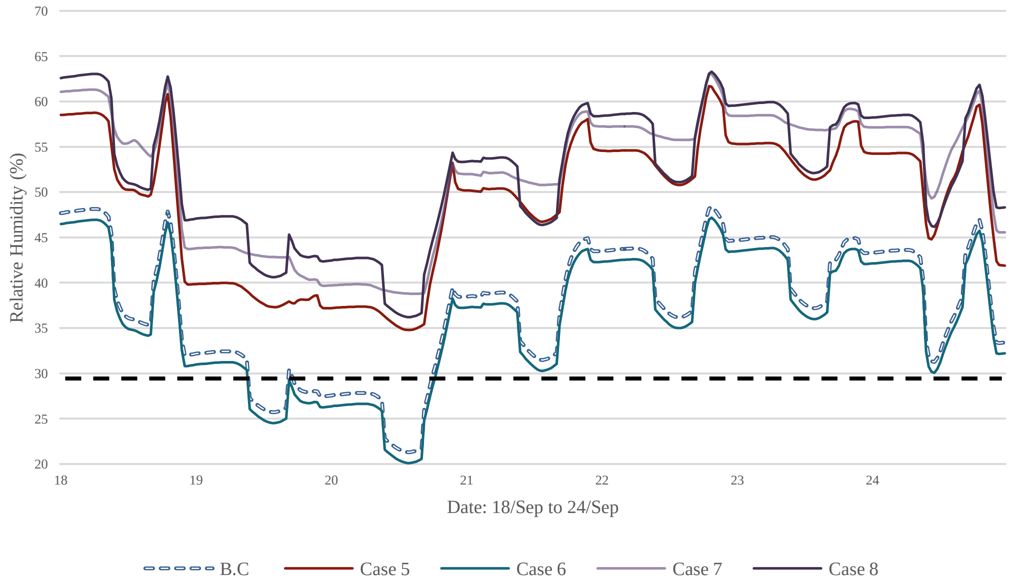


Figure 33. Relative humidity in R2 during a typical week in September for low cost ventilation strategies

## 4. Design recommendations

Based on the observations, this study recommends the following architectural design guidelines to enhance the performance of the natural ventilation system in case of newly developed low-income residential apartment buildings.

- The floor-plan layout design (within zero-cost ventilation strategies) should be carefully considered during the early design stages because it delivers the best performance of the natural ventilation system in the apartment unit. The arrangement of the rooms in the floor-plan layout should support the air flow path by being as open as possible to minimize the obstacles in the air flow path using various methods, such as by adding supplementary interior openings in the partitions and allowing the free circulation of the airflow.
- The addition of voids that separate the apartment units within the same floor and maximization of the outdoor exposure of the facades in multistory residential buildings will enhance the internal natural ventilation. The added void will increase the pressure differences across the windows on both sides of the building and encourage the air to flow into the spaces.
- Rooms should be designed in accordance with the cross-ventilation strategy owing to its positive impacts on the natural ventilation performance rather than the single-sided ventilation strategy.
- Cross-ventilation can be achieved in multistory residential buildings with deep plans by designing a wind channel system that connects inward rooms with low-pressure facades, and vice versa.
- The building should be oriented toward the south or north because these directions resulted in lower indoor operative temperatures than those induced by the east or west orientations. Further, this minimizes the heat gain from the high-angle summer sunrays and allows the low-angle winter sun rays to penetrate the space.
- Windows with large operable areas, i.e., side hung windows, should be used to allow a large amount of air to flow into the space, improving the IAQ.
- Rooms with a large WWR should be equipped with shading devices to minimize the penetration of the space by the direct solar radiation and enhance the pressure difference across the window, admitting more air into the space and improving the IAQ.
- Spaces with high V.R.s could utilize ventilative cooling and reduce the indoor operative temperature, providing an improved indoor thermal environment. To appropriately utilize the V.R.s, the cooling rooms should be ventilated by both daytime and nighttime ventilation. Nighttime ventilation allows the thermal mass of the building to act as a heat sink on the following day.
- Integration of the natural ventilation requirements during the preliminary design stages is crucial to obtain an improved natural ventilation performance and IAQ.

## 5. Conclusions

Herein, the performances of selected zero and low-cost natural ventilation strategies were evaluated to enhance the ventilation performance in low-income residential apartment buildings and provide improved IAQ and energy consumption. The zero-cost ventilation strategies included the variation of the orientation and suggesting an alternative floor plan (by adding a void between the units, adopting a new room arrangement, and adding supplementary interior openings). Low-cost ventilation strategies included the variation of the window type and WWR as well as the addition of shading devices and a wind channel system. The results related to the values of V.R, CO2 concentration, indoor operative temperature, RH, and energy consumption were obtained using IES–V.E. The main conclusions obtained from this study are summarized as follows.

- Among the two investigated natural ventilation strategies, i.e., zero-cost and low-cost, almost all the proposed strategies significantly increased the average V.R in comparison with the B.C. However, changing the window type to side hung in Case 5 (Within low-cost ventilation strategies) and changing the plan layout in Case 4 (within zero-cost ventilation strategies) exhibited the largest increase in V.R. compared to those in other cases. In R1, the V.R. in Case 5 increased by approximately 12.1 and 16.9 L/s/p in June and September, respectively, whereas in R2, V.R. increased by approximately 12.5 and 15.5 L/s/p in June and September. Furthermore, in case of R1, Case 4 increased the V.R. by approximately 10.6 and 11.3 L/s/p in June and September, respectively, whereas, in case of R2, the average V.R. was increased by 10.2 and 12.1 L/s/p in June and September, respectively.
- Regarding the indoor operative temperature, the simulation results indicate that changing the plan layout in Case 4 within zero-cost strategies and the addition of a wind channel system in Case 8 within low-cost strategies have delivered the largest decrease compared to other cases. In R1 Case 4 decreased the average indoor operative temperature by approximately 4.3°C and 5°C during June and September, respectively, while in R2 there was a decrease by 4.4°C and 4.3°C in June and September, respectively. However, In R1 Case 8 delivered a decrease by 4°C and 4.2°C in June and September, respectively, while in R2 the average value was decreased by 3.8°C and 4.2°C during June and September, respectively.
- Regarding the RH levels, the simulation results indicate that all cases (except Case 6) have delivered an increase in the average value with a slight difference between them. In R1, the RH was increased by approximately 6.6% and 6.5% in June and September, respectively, while there was a decrease by 1.3% and 1.5% in June and September, respectively, which was obtained by Case 6. Furthermore, in R2 there was an increase in the average value by approximately 8.9% and 14.8% in June and September, respectively, while Case 6 delivered a decrease by 1.1% and 1.2% in June and September respectively.

## References

[1] V. Sakhare and R. J. A. S. R. Ralegaonkar, "Indoor environmental quality: Review of parameters and assessment models," vol. 57, no. 2, pp. 147-154, 2014.

[2] E. Spentzou, M. J. Cook, and S. Emmitt, "Natural ventilation strategies for indoor thermal comfort in Mediterranean apartments," in *Building Simulation*, 2018, vol. 11, no. 1, pp. 175-191: Springer.

[3] O. H. Yahya, H. Alrikabi, I. A. J. I. J. o. O. Aljazaery, and B. Engineering, "Reducing the Data Rate in Internet of Things Applications by Using Wireless Sensor Network," vol. 16, no. 03, pp. 107-116, 2020.

[4] M. Inusa, H. Z. J. I. J. o. E. R. Alibaba, and Application, "Application of Passive Cooling Techniques in Residential Buildings; A Case Study of Northern Nigeria," vol. 7, no. 1, pp. 22-30, 2017.

[5] W. Al-Azhari and S. Al-Najjar, "Challenges and Opportunities Presented by Amman's Land Topography on Sustainable Buildings," in *Proc. ICCIDC-III Conf*, 2012.

[6] H. Alrikabi, A. H. Alaidi, and K. J. I. J. o. I. M. T. Nasser, "The Application of Wireless Communication in IOT for Saving Electrical Energy," vol. 14, no. 01, pp. 152-160, 2020.

[7] S. Shamout, P. Boarin, and A. Melis, "Energy retrofit of existing building stock in Amman: state of the art, obstacles and opportunities," in *Advanced Studies in Energy Efficiency and Built Environment for Developing Countries*: Springer, 2019, pp. 133-145.

[8] B. Yang, T. J. I. Olofsson, and B. Environment, "A questionnaire survey on sleep environment conditioned by different cooling modes in multistorey residential buildings of Singapore," vol. 26, no. 1, pp. 21-31, 2017.

[9] J. M. J. I. A. P. Delgado-Saborit, "Indoor Air as a Contributor to Air Pollution Exposure," vol. 48, p. 158, 2019.

[10] K. W. Mui, T. W. Tsang, L. T. Wong, Y. P. J. I. William Yu, and B. Environment, "Evaluation of an indoor environmental quality model for very small residential units," vol. 28, no. 4, pp. 470-478, 2019.

[11] F. T. Abed, H. T. S. ALRikabi, and I. A. Ibrahim, "Efficient Energy of Smart Grid Education Models for Modern Electric Power System Engineering in Iraq," in *IOP Conference Series: Materials Science and Engineering*, 2020, vol. 870, no. 1, p. 012049: IOP Publishing.

[12] T. Sharpe, P. Farren, S. Howieson, P. Tuohy, J. J. I. j. o. e. r. McQuillan, and p. health, "Occupant interactions and effectiveness of natural ventilation strategies in contemporary new housing in Scotland, UK," vol. 12, no. 7, pp. 8480-8497, 2015.

[13] A. Meiss, M. A. Padilla-Marcos, and J. J. E. Feijó-Muñoz, "Methodology applied to the evaluation of natural ventilation in residential building retrofits: A case study," vol. 10, no. 4, p. 456, 2017.

[14] B. Wang, A. J. S. c. Malkawi, and society, "Design-based natural ventilation evaluation in early stage for high performance buildings," vol. 45, pp. 25-37, 2019.

[15] D. J. A. Suszanowicz, "Optimisation of heat loss through ventilation for residential buildings," vol. 9, no. 3, p. 95, 2018.

[16] Z. Tan and X. J. A. Deng, "Assessment of natural ventilation potential for residential buildings across different climate zones in Australia," vol. 8, no. 9, p. 177, 2017.

[17] H. J. S. Alibaba, "Determination of optimum window to external wall ratio for offices in a hot and humid climate," vol. 8, no. 2, p. 187, 2016.

[18] S. Tong, N. H. Wong, E. Tan, S. K. J. B. Jusuf, and Environment, "Experimental study on the impact of facade design on indoor thermal environment in tropical residential buildings," vol. 166, p. 106418, 2019.

[19] A. Anunobi, O. Adedayo, S. Oyetola, E. Siman, H. J. J. o. E. Audu, and E. Science, "Assessment of Window Types in Natural Ventilation of Hotels in Taraba State," vol. 5, no. 2, pp. 117-125, 2015.

[20] X. Xie, O. Sahin, Z. Luo, and R. J. R. E. Yao, "Impact of neighbourhood-scale climate characteristics on building heating demand and night ventilation cooling potential," vol. 150, pp. 943-956, 2020.

[21] I. A. Aljazaery, H. T. S. Alrikabi, and M. R. J. i. Aziz, "Combination of Hiding and Encryption for Data Security," vol. 14, no. 9, p. 35, 2020.

[22] Z. Cheng, L. Li, W. P. J. B. Bahnfleth, and Environment, "Natural ventilation potential for gymnasia–Case study of ventilation and comfort in a multisport facility in northeastern United States," vol. 108, pp. 85-98, 2016.

[23] B. Gomaa, "A Wind Channel Passive Ventilation System for Deep-Plan, High-Rise Residential Buildings," *International Journal of Ventilation*, vol. 11, no. 3, pp. 247-254, 2012.

[24] A. Munir and S. Wonorahardjo, "The performance of single-sided natural ventilation induced by wind-driven flow (Case study: Classroom, ITB Bandung)," in *SENVAR5-The 5th international seminar on sustainable environmental architecture*, 2004.

[25] I. Z. H. Mou, "Study on the impact of window size and proportion on indoor air temperature of bedrooms in apartments," 2017.

[26] H. Tuama, H. Abbas, N. S. Alseelawi, H. T. S. J. P. o. E. ALRikabi, and N. Sciences, "Bordering a set of energy criteria for the contributing in the transition level to sustainable energy in electrical Iraqi Projects," vol. 8, no. 1, pp. 516-525, 2020.

[27] I. Al-Barazanchi and H. R. Abdulshaheed, “Designing a library management system for Gazi Husrev-beg library using data structure and algorithm”, Heritage and Sustainable Development, vol. 1, no. 2, pp. 64-71, 2019.

[28] E. Spentzou, "Refurbishment of apartment buildings in the Mediterranean Region for natural ventilation: implications for building design," Loughborough University, 2015.

[29] R. McMullan, *Environmental science in building*. Palgrave Macmillan Education, 2017.

[30] W. Liping and W. N. Hien, "The impact of façade designs: orientations, window to wall ratios and shading devices on indoor environment for naturally ventilated residential buildings in Singapore," in PLEA2006 The 23rd Conference on Passive and Low Energy Architecture Geneva Switzerland, 2006, pp. 6-8.

[31] M. Bakhlah, M. R. Ismail, and A. M. A. Rahman, "The Effect of Exterior Shading Devices on Indoor Climate," presented at the International Conference on Social Sciences and
Humanities, Malaysia, 18-20 June 2008, 2008.

[32] B. Duraković and A. Cosic, “Impact of quality and innovation strategies on business performance of Bosnian B2B and B2C companies”, Sustainable Engineering and Innovation, vol. 1, no. 1, pp. 24-42, 2019.

[33] M. A. A. H. Al-Obaidi and P. J. I. j. o. l.-c. t. Woods, "Investigations on effect of the orientation on thermal comfort in terraced housing in Malaysia," vol. 1, no. 2, pp. 167-176, 2006.

[34] S. M. E. A. Bekkouche, T. Benouaz, M. K. Cherier, M. Hamdani, M. R. Yaiche, and R. J. T. S. Khanniche, "Influence of building orientation on internal temperature in Saharan climates, building located in Ghardaïa region (Algeria)," vol. 17, no. 2, pp. 349-364, 2013.

[35] T. Alsmo and C. J. J. o. E. P. Alsmo, "Ventilation and relative humidity in Swedish buildings," vol. 2014, 2014.