# Monitoring the performance of a naturally ventilated performing arts building in London during a heatwave

**LIDA SYKARA** MARCH, MSC
UCL Institute for Environmental Design and Engineering, Bartlett School of Environment, Energy and Resources [1]
lida.sykara.21@ucl.ac.uk

EUR ING **SUNG MIN HONG** MSC, PHD, CENG, MCIBSE
UCL Institute for Environmental Design and Engineering, University College London
s.hong@ucl.ac.uk

DR **DAVID HAWKINS** MENG, MRES, ENGD, CENG, MCIBSE
Skelly & Couch Ltd
david.hawkins@skellyandcouch.com

## Abstract

The application of natural ventilation in buildings can help reduce overheating and demand for cooling and can play a key role in helping the UK meet its 2050 net-zero targets. During the summer of 2022, including a heatwave, a POE was conducted in a performing arts academy in London, which exploits multiple natural ventilation techniques and high thermal mass materials. Through monitoring the temperature, relative humidity and $CO_2$ concentration of seven dance and acting studios, interviewing the building management team, the ventilation of the studios is mostly adequate, providing acceptable thermal comfort levels. Specifically, during the heatwave, the indoor temperature ranged from 5 to 9 $^oC$ less than external levels concluding the thermal performance successful. However, possible operational changes could further enhance the building's performance.

**Keywords** *natural ventilation, post occupancy, performing arts buildings, thermal comfort, heatwave*

## 1.0 Introduction

The building stock in the UK accounts for around 20% of the total emissions and is mostly related to energy used for the heating, cooling and ventilation (HVAC) systems of buildings (1). HVAC systems contribute nearly two-thirds of the total non-industrial energy consumption and as temperatures are continuously increasing, and the possibilities of overheating rise, the need for cooling is very likely to increase in the next two decades in countries that currently predominantly require heating (1). Therefore, a reduction in the energy and associated GHG emissions required to heat, cool, and ventilate buildings is of high importance (2).

One way to substantially reduce energy consumption of buildings is the use of passive measures that could replace HVAC systems. Natural ventilation (NV) or

[1] Savills UK

hybrid ventilation systems (HVS) when implemented properly can contribute to reducing the cooling requirement of buildings. As the demand for lower carbon emissions grows, more engineers and designers see the importance of NV in the future of sustainable buildings and choose to integrate it (3). Several studies have found that a high thermal mass construction with an effective nighttime ventilation technique can have a reduced peak temperature by 5 K (4). Similarly, the cooling potential of different passive cooling NV strategies have been evaluated in several climates and applications (5).

Especially when using passive measures, Post-Occupancy Evaluations (POE) can help provide feedback on the design, implementation and performance of the measures and buildings, thus leading to valuable information for future reference (6). However, most of the studies, that are evaluating the performance of NV buildings are focused on building types such as commercial, educational, and residential buildings. Additionally, current industrial guides and standards for mechanically ventilated and even free-running buildings (7) are only considering sedentary activities with office-type clothing levels.

Several industrial guidelines have been developed over the years to help establish acceptable thermal comfort (TC) conditions and guidelines. Some of these are BS EN 16798-1:2019, CIBSE Guide A, CIBSE AM10, CIBSE TM52 and ASHRAE Standard 55. There are also online tools available to the designers that can support defining acceptable indoor environment conditions for buildings based on the different standards developed above (8). These standards also include relevant guidance on relative humidity levels or other factors that might affect TC and can help incorporate passive design features in buildings. The adaptive TC methods included in these guidelines were established to obtain comfortable operative internal air temperature in free-run mode buildings (9) which eventually leads to wider TC ranges (10). Moreover, these guidelines were used in the study to establish TC conditions and be able to evaluate the thermal performance of the case study building.

The following research assessed the operation and performance of a NV performing arts (PA) building in London and evaluated its thermal comfort during the summer season, in the scope of a post-occupancy evaluation, to understand how a building with natural ventilation and high thermal mass would perform during a heatwave. The term heatwave is defined as an extended period of hot weather compared to the anticipated conditions of a specific area at a certain season (11). Temperature, Relative Humidity were measured to test the thermal conditions and $CO_2$ was measured as a proxy for ventilation rates (12). Furthermore, it evaluated its viability in extreme weather conditions such as those of the heatwave that could be indicative in future climate scenarios where these conditions might be more common.

## 2.0 Methods

### *2.1 Case study building*

The case study building is a PA academy located in south London. The building was selected due to the variety of NV techniques that are being utilised, its urban location, the high metabolic rate activities that are taking place and the intensity of its occupancy periods. It spans across 4 levels and consists of two interlocking buildings, the theatre block, and the studio block. The studio block accommodates the dancing and acting studios which are arranged around a central atrium space that acts as a circulation area and a meeting space for the students. The studio block was the part of the building that was evaluated, specifically the dancing and acting studios which are placed on both sides of the centrally located atrium, Figure 1.

The building is designed taking into consideration several passive design measures regarding the materials, the HVAC strategy and energy performance. The intention was to optimise the building's system and create an environment with minimal cooling and heating loads. Specifically, the studio spaces exploit several NV strategies as well as high thermal mass exposed concrete and solar control glazing. The NV strategy of the building uses the stack effect through the centrally located atrium, stack ventilation through atrium (SVA). The air inlets are located in the facade of the building and air enters the studio spaces through acoustically designed ventilation louvres. Then through attenuators, the air escapes to the atrium and due to the temperature difference, it finally exits the atrium from the outlets on the skylight on top of the atrium, Figure 1. The air inlets are separated in two parts, the upper and the lower level and these are manually operated. Essentially, the atrium not only acts as a main characteristic in the layout of the building but is also crucial for the performance of the studio block.

Some studios are solely exploiting cross ventilation (CV) where the air enters and escapes through the louvres only. Some others are using stack effect ventilation (SV), but their outlet is a manually operated rooflight at the top of their ceiling. The atrium outlets have rain sensors and are also manually operated. During the summer season, the ventilation louvres are always open (day and night) and during the winter season, they are open only during the occupied hours (day).

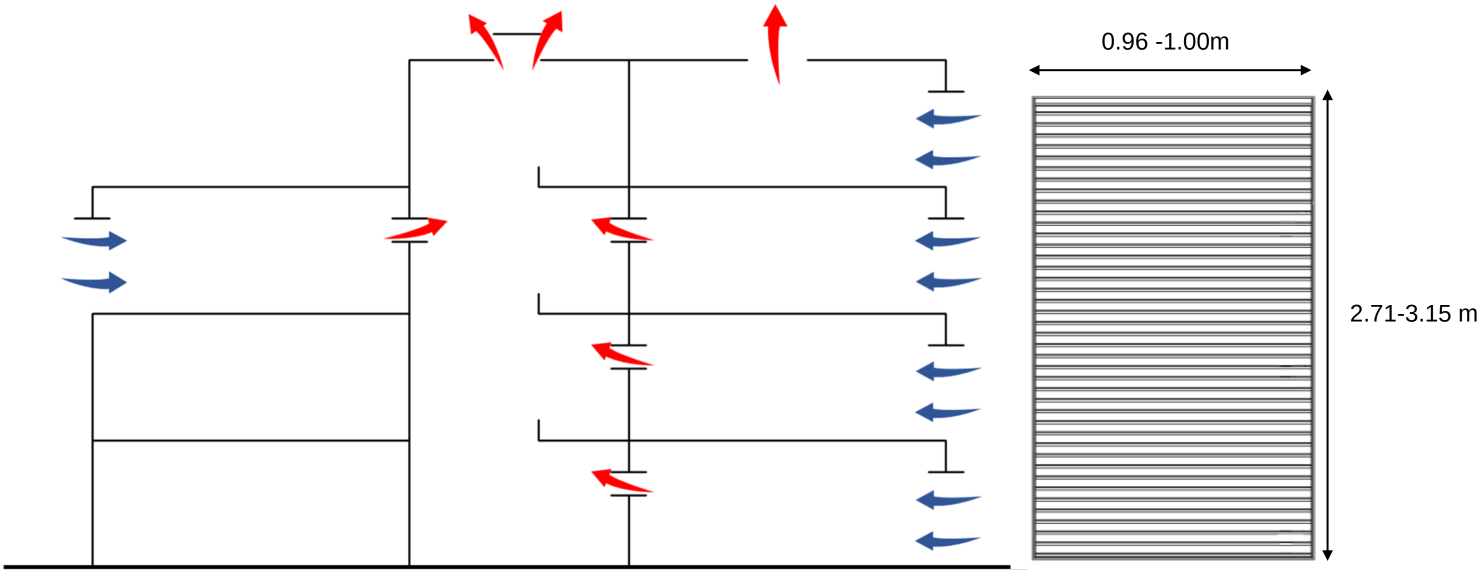


**Figure 1 Environmental strategy of the building on the left, and indicative elevation and dimensions of the façade louvres on the right**

## *2.2 Environmental Monitoring Methodology*

Short-term environmental monitoring took place from 25/6/2022 to 23/7/2022 to measure Temperature (T), Relative Humidity (RH) and Carbon Dioxide ($CO_2$) concentration. T and RH were used to assess the thermal performance and overheating fraction of the building and $CO_2$ was used as a proxy for the effectiveness of the ventilation (2)(13).

Due to the variety of ventilation strategies seven studios were chosen to be monitored with three sensors placed strategically in each space, collecting data in 5-minute intervals. Two of them were placed on opposite walls measuring T, RH and one measuring $CO_2$. The selected studios were based on the NV strategy, activity taking place (dancing or acting), orientation, level located in the building, and adjacent spaces. In Table 1 their characteristics are summarised. Their arrangement in the layout can be found in Figure 2. The building was fully occupied until the 15th of July. Afterwards, it was sparsely occupied for rehearsals and summer courses. During the study period, extreme weather conditions were experienced with previously never seen high temperatures in the UK and is the key focus of this paper.

**Table 1 Studios selected for monitoring and their characteristics**

| | **Studio $N_o$** | **Floor area ($m^2$)** | **Opening orientation** | **NV strategy** | **Shading device** | **Adjacency** | **Activity** | **Effective Area ($m^2$)** |
|---|---|---|---|---|---|---|---|---|
| **1st level** | 5 | 131 | SW & NW | cross ventilation (CV) | White colored fabric curtains | Exterior & studio | Dancing | 3.1 |
| | 7 | 105 | SW | stack ventilation through atrium (SVA) | White colored fabric curtains | Studio & studio | Dancing | 2.5 |
| **2nd level** | 11 | 91.5 | NE | stack ventilation through atrium (SVA) | Opaque glazing | Studio & studio | Acting | 2.1 |
| | 14 | 92 | NE & NW | cross ventilation (CV) | Opaque glazing on NE facade | Exterior & studio | Acting | 2.9 |
| | 18 | 132.6 | SE & SW | cross ventilation (CV) | White colored fabric curtains | Exterior & studio | Dancing | 3.1 |
| **3rd level** | 21 | 92 | SW | stack ventilation (SV) | White colored fabric curtains | Studio & studio | Acting | 2.0 |
| | 23 | 103 | SE & SW | stack ventilation (SV) | White colored fabric curtains | Exterior & studio | Acting | 2.0 |

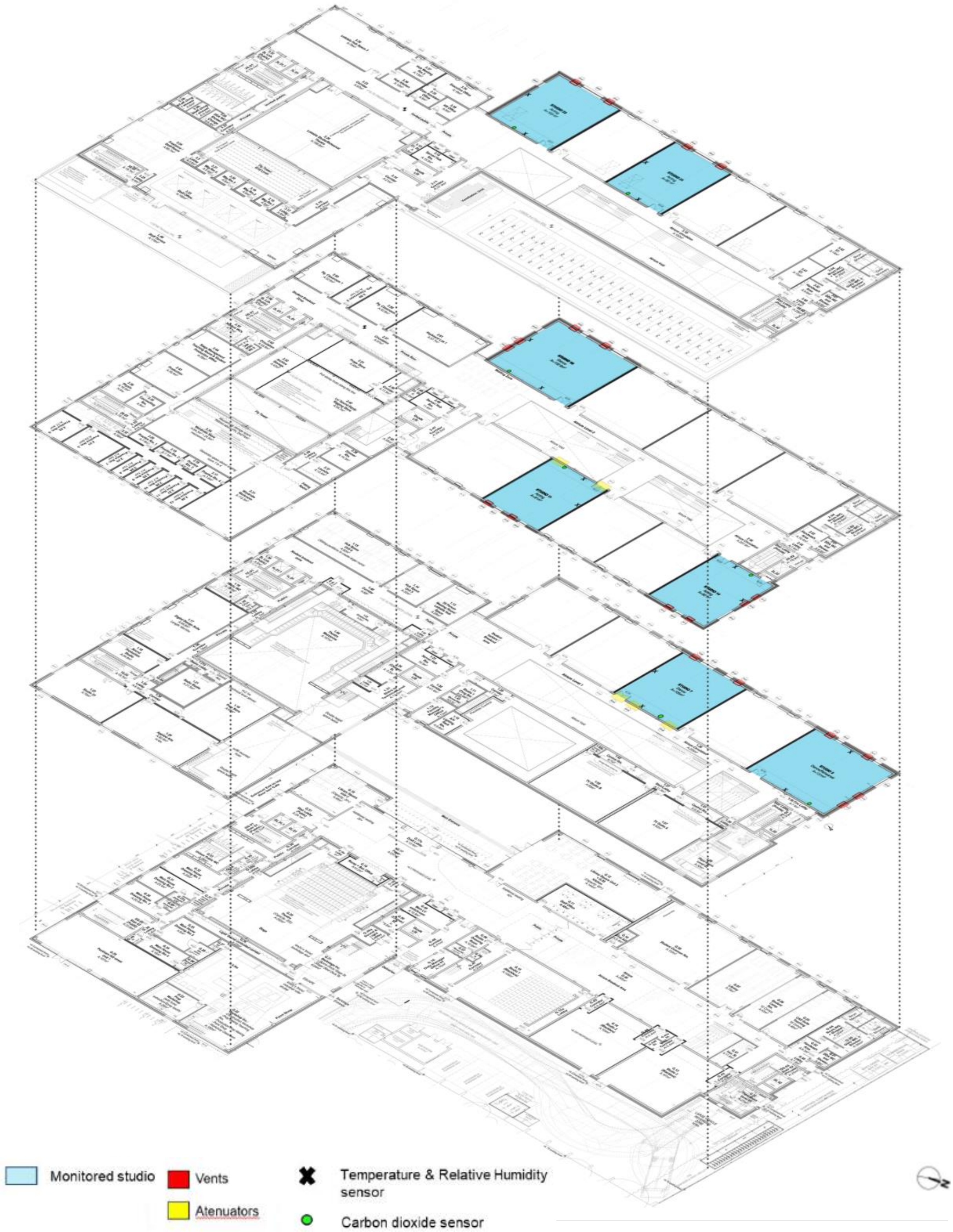


**Figure 2 Overview of the selected studios and their location in the building**

Regarding the placement of the data loggers and since the distribution of the occupants could not be estimated, the sensor locations were placed at breathing level and 1.0 m inward from the centre of each of the room's interior and exterior walls (10). HOBO U12-12 was chosen to monitor the T and RH and HOBO MX $CO_2$ logger to monitor the $CO_2$. Regarding the external conditions, information from the weather station that is installed at the Central House building at University College London, on the Bloomsbury campus, was collected for the study period. The locations of the weather station and the case study building were considered sufficiently close; thus, the weather conditions were assumed as similar. These included dry bulb T and outdoor RH data.

The adaptive thermal comfort and overheating analysis method, as established in CIBSE TM52, were used to understand the thermal performance of the building. In particular, the method described in criterion 3 was applied in the study, since several limitations did not allow for a complete overheating analysis. The range of TC (Tlower, Tmax) was defined as well as the upper T limit (Tupper). Particularly, the indoor operative T of the building was compared against the maximum (Tmax) and Tupper which should define whether the acceptable TC range is exceeded (14).

**Table 2 Guidelines and standards for data analysis**

| Parameter | Range | Reference | Notes |
|---|---|---|---|
| **Thermal comfort range in the summer season** | • Tlower=0.33 Trm + 15.8<br>• Tmax = 0.33 Trm + 21.8<br>• Tupper =Tmax + 4 | CIBSE TM 52 (Adaptive thermal comfort criteria) | Category \|\| |
| **Relative Humidity** | 40-70 % | CIBSE Guide A | - |
| **Carbon dioxide** | 1000 ppm | BS EN16798-1:2019 (15) | Category \| |

## *2.3 Qualitative methodology and semi-structured interview*

In many cases, NV is being operated by the occupants of the building (e.g., windows). In the case study building, the management staff is primarily responsible for the operation of the manually operated louvres and during the day the occupants (students, teachers) potentially control them. Therefore, it was decided to conduct semi-structured interviews with the building management team, to investigate how the manually operated louvres are being operated, and whether there are any concerns from the management or the occupants of the building. This form of interview was selected as it is commonly used in qualitative research for data collection (16). Audio recording of the interviews was considered an appropriate choice and interviews with the facility manager, deputy manager and student administrative were conducted on the 29th of July 2022. Participation was voluntary and the interviewees were approached due to their role in the daily operation of the building.

The interview results provided background information to support the review of the monitoring results. The questions of the interview were focused mainly on the below:

- Schedule and occupied times of the building
- Number of occupants during weekdays and weekends
- Operation of the manually operated ventilation louvres
- Complains or comments from the students

The responses provided a better insight regarding the areas mentioned above and some of them include:

- The building is occupied almost all day with most of the students being in the building between 9.00-18.00 and sparsely between 18.00-21.00.
- An overage occupancy number in each studio is 20 students.

- The ventilation strategy is operated as intended; the louvres are left open during the night to allow for night cooling, depending on the external temperatures of the following day
- The rooflight on the 3rd floor are not being opened by the management team, hence the studios of the 3rd floor operate as single side ventilation rather than utilising the stack effect, unless the occupants open the rooflights
- There are occasional complaints from the students about studios being warmer than they feel comfortable

## 3.0 Results

Each variable was analysed initially separately. The values of T, RH and $CO_2$ levels were examined over one month, from 25/6/22 to 23/7/22, including the extreme weather conditions on 18/7/22 and 19/7/22 experienced fortuitously during the study period. Furthermore, the diurnal variations in T on the heatwave days were evaluated and grouped for each different ventilation strategy utilised in the building (SVA, SV, CV) to distinguish the viability of the strategies and for comparison. The measured data were statistically analysed against guidelines, literature as well as outdoor weather data and are presented in Table 2. Even though the relevant standards refer to buildings with sedentary activities they were also considered appropriate for the case study building.

### *3.1 External conditions*

The weather conditions during the study period presented high T and very little precipitation overall. A record-breaking outdoor T was experienced in the UK reaching 38 $^oC$ on the 18th and 19th of July, with exceptionally high T during both day and night . For the purpose of the analysis, and as previously defined, these conditions are referred to as a heatwave.

**Table 3 Selected descriptive statistics for the external conditions**

| | External Temperature ($^oC$) | External Relative Humidity (%) |
|---|---|---|
| **Median** | 20 | 48 |
| **Min** | 11 | 13 |
| **Max** | 38 | 75 |
| **St Dev** | 5 | 14 |

### *3.2 General observations at building level for the whole monitoring period*

Firstly, an overview of the variables at building level, across each studio will be conducted. For this purpose, each studio has been coded and presented based on:

1. its allocated number in the building
2. the level on which it is located
3. its activity

For example, S5L1D means Studio 5 Level 1 Dancing, S11L2A means Studio 11 Level 2 Acting, S18L2D means Studio 18 Level 2 Dancing and S21L3A stands for Studio 21 Level 3 Acting. In Table 4 selected descriptive statistics for these spaces and for all the variables monitored are summarised. No extreme differences can be observed in the median, minimum and maximum values among the seven studios in the different variables.

**Table 4 Selected descriptive statistics for the monitored studios**

| | | Stack Ventilation through atrium | | Cross Ventilation | | | Stack Ventilation through rooftop | |
|---|---|---|---|---|---|---|---|---|
| | | Studio 7 1st level | Studio 11 2nd level | Studio 7 1st level | Studio 14 2nd level | Studio 18 2nd level | Studio 21 3rd level | Studio 23 3rd level |
| | | S7L1D | S11L2A | S5L1D | S14L2A | S18L2D | S21L3A | S23L3A |
| Temperature (°C) | Median | 23 | 24 | 23 | 23 | 23 | 25 | 25 |
| | Min | 17 | 20 | 19 | 20 | 18 | 20 | 21 |
| | Max | 31 | 30 | 32 | 29 | 32 | 32 | 32 |
| | St Dev | 3 | 2 | 2 | 2 | 2 | 2 | 2 |
| Relative Humidity (%) | Median | 53 | 48 | 51 | 48 | 49 | 47 | 48 |
| | Min | 33 | 35 | 33 | 33 | 30 | 31 | 32 |
| | Max | 70 | 61 | 62 | 60 | 63 | 59 | 60 |
| | St Dev | 6 | 4 | 5 | 4 | 6 | 5 | 5 |
| Carbon Dioxide (ppm) | Median | 507 | 523 | 544 | 497 | 670 | 500 | 543 |
| | Min | 447 | 450 | 226 | 453 | 423 | 449 | 445 |
| | Max | 1490 | 1797 | 2739 | 1190 | 3360 | 970 | 1422 |
| | St Dev | 134 | 136 | 265 | 84 | 281 | 53 | 104 |

In Figure 3 the internal T variations, outdoor T (Tout), Tupper, Tmax and Tlower are presented for all the monitored studios throughout the case study period. It is evident that the internal T variations are following the external patterns, which is expected from a free-running building. Additionally, the studios on the higher levels of the building experienced higher internal T. Overall, the internal T is kept below the Tmax and it is illustrated that during the heatwave the indoor operative T presented higher values compared to the rest of the study period in all studios. The performance of the studios during the heatwave will be analysed in the following section.

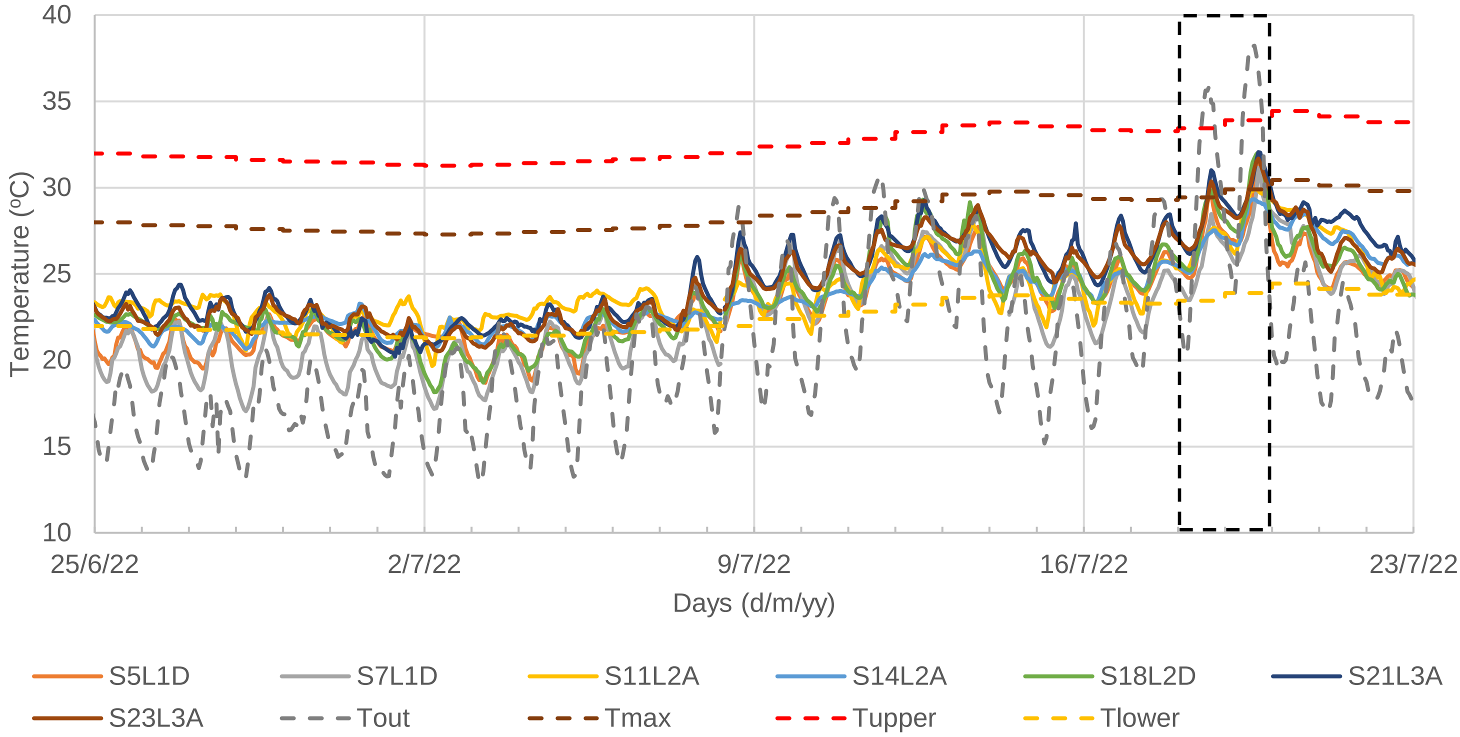


**Figure 3 Outdoor and indoor operative temperature variations during the monitored period including the heatwave (18/7/22-19/7/22) in all the studios. Also shown are the diurnal variations of the maximum (Tmax), upper (Tupp) and lower temperature threshold (Tlower)**

In Figure 4 it is illustrated that the RH levels inside the studios are maintained within the range for almost all of the one-month period, with the exception of the heatwave days where the levels reached 32%, 8% lower than recommended levels.

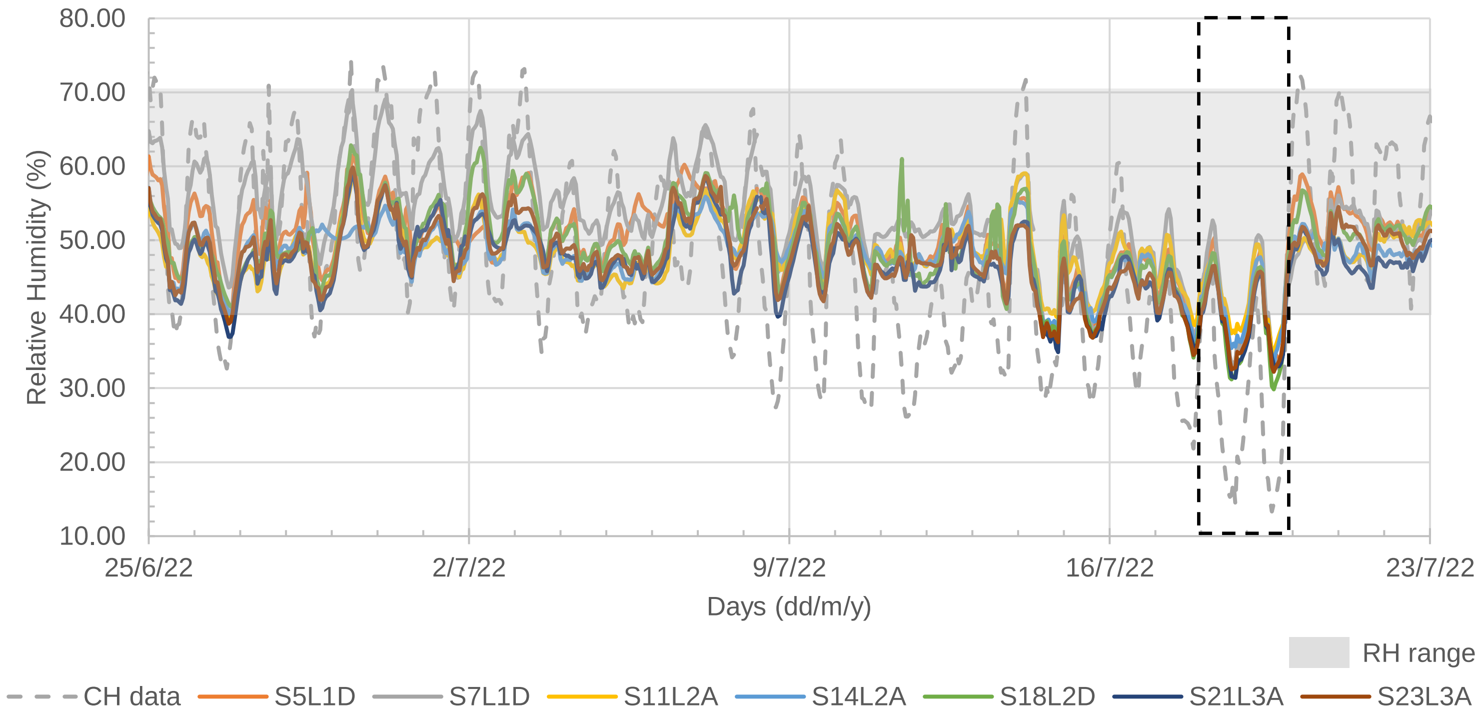


**Figure 4 Daily average variations of RH between 25/6/22 - 23/7/22 including the heatwave (18/7/22-19/7/22) in all the studios. Also illustrated the RH acceptable limits**

Plotting the $CO_2$ concentration, as seen in Figure 5, indicated that indoor air quality levels are mostly kept within the guidelines level. However, S5L1D and S18L2D present higher concentrations, potentially suggesting a higher occupation level compared to the rest of the studios. Additionally, in Figure 5 some slow decays can be seen on the 28th and 29th of June in S14L2A which shows that perhaps the ventilation rate is too low to allow for the $CO_2$ levels to decrease between the occupied periods. A similar trend is visible in S5L1D on the 5th and 6th of July when $CO_2$ concentration reached very high levels, specifically 2700 ppm. This is potentially due to very high occupancy in combination with the dancing activity in the specific studio, thus more $CO_2$ is produced from the occupants. Yet again the ventilation rate is not providing enough fresh air on these two days. In S18L2D, $CO_2$ levels exceed the 1000 ppm threshold during occupied hours and the consistency in its levels indicates consistency in its occupancy as well. Further to the above observations these three studios are exploiting CV. Nonetheless, Figure 6 shows that even though at time the levels do exceed recommended values during occupied times the concentration is mostly below 1000 ppm.

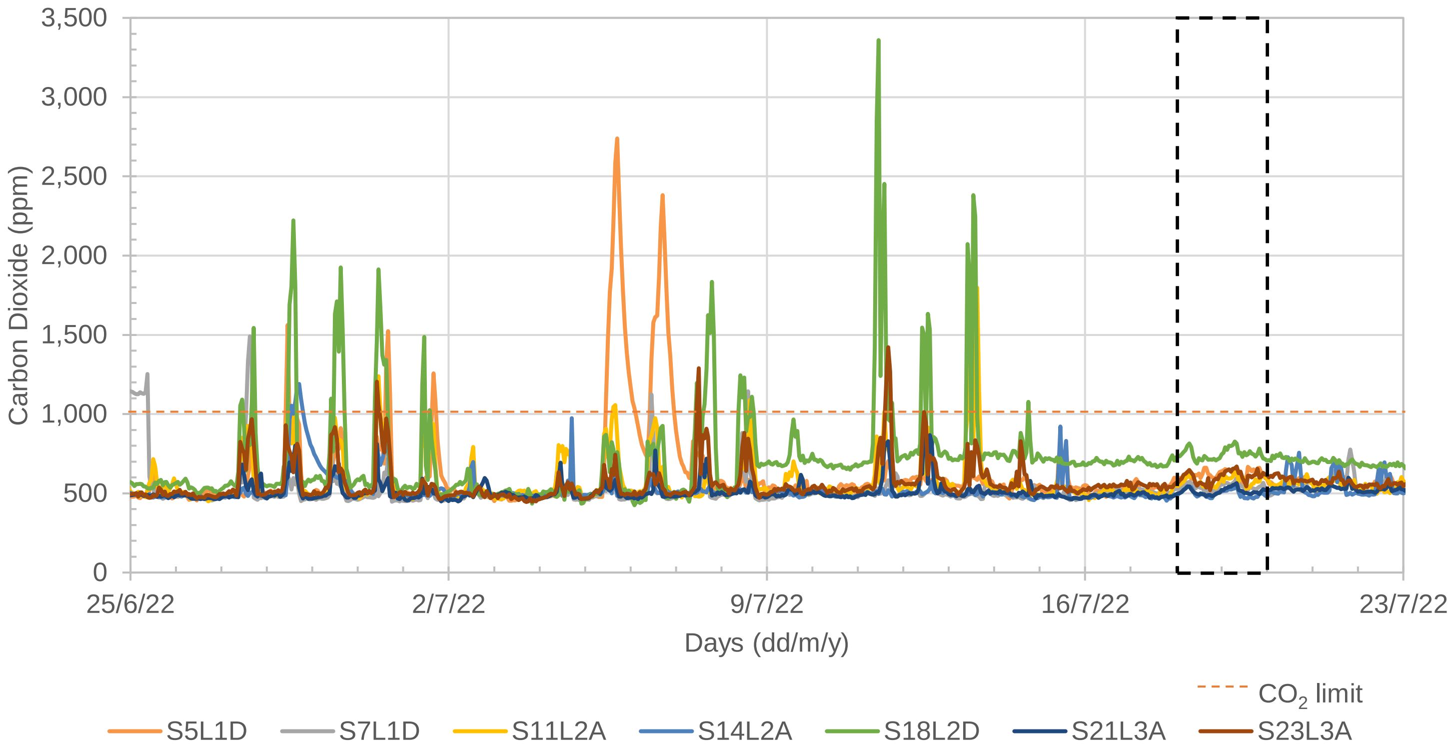


**Figure 5 Carbon dioxide concentrations between 25/6/22 - 25/7/22 including the heatwave (18/7/22-19/7/22) in all the studios**

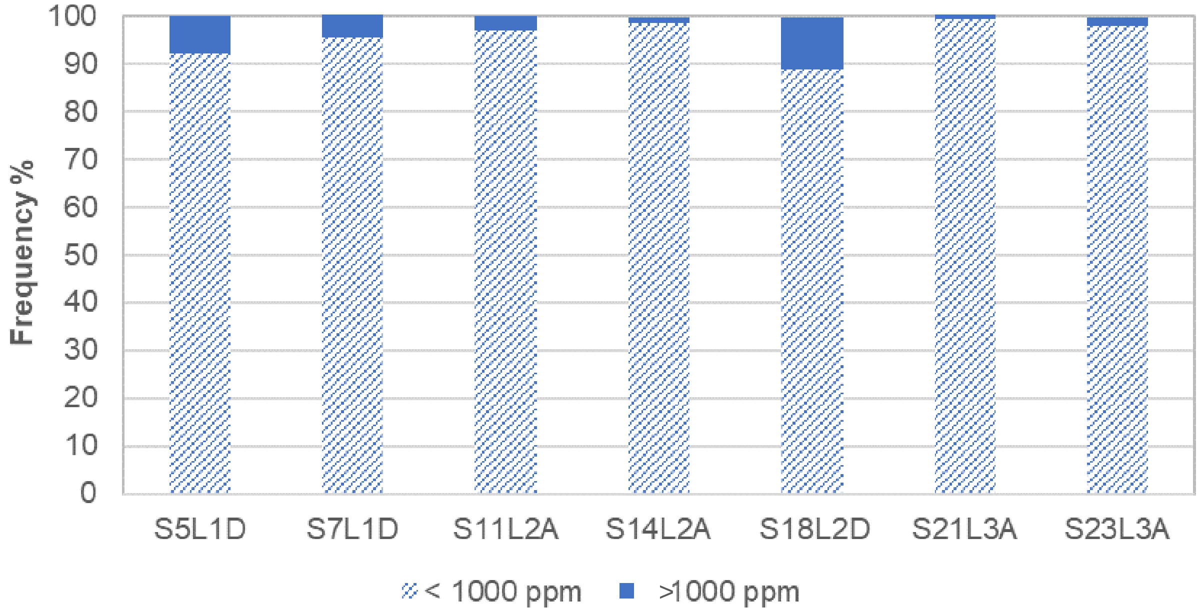


**Figure 6 Carbon Dioxide distribution during occupied hours**

Moreover, to investigate the decays found, the $CO_2$ levels against the inner T were plotted for S5L1D for the 5th and 6th of July in Figure 7 and for S14L2A for the 28th and 29th of June in Figure 8. In both studios, the stable inner T and the $CO_2$ decay is evident. This can potentially be attributed to the occupants controlling the ventilation leading to lower ventilation rates.

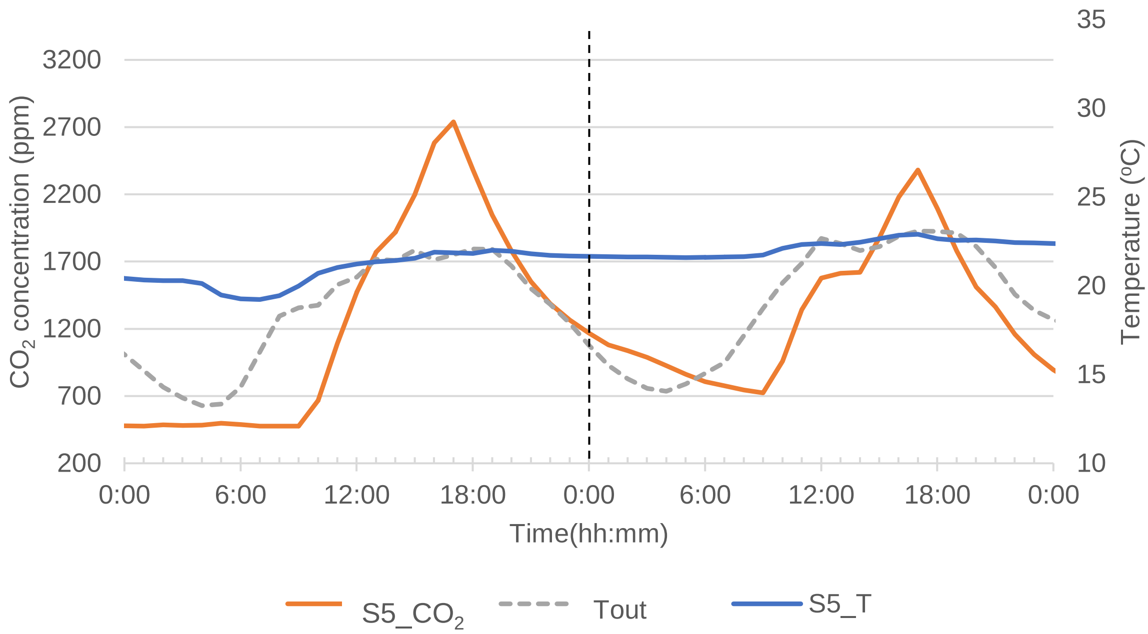


**Figure 7 Carbon dioxide concentration and temperature on the 5th and 6th of July in S5L1D**

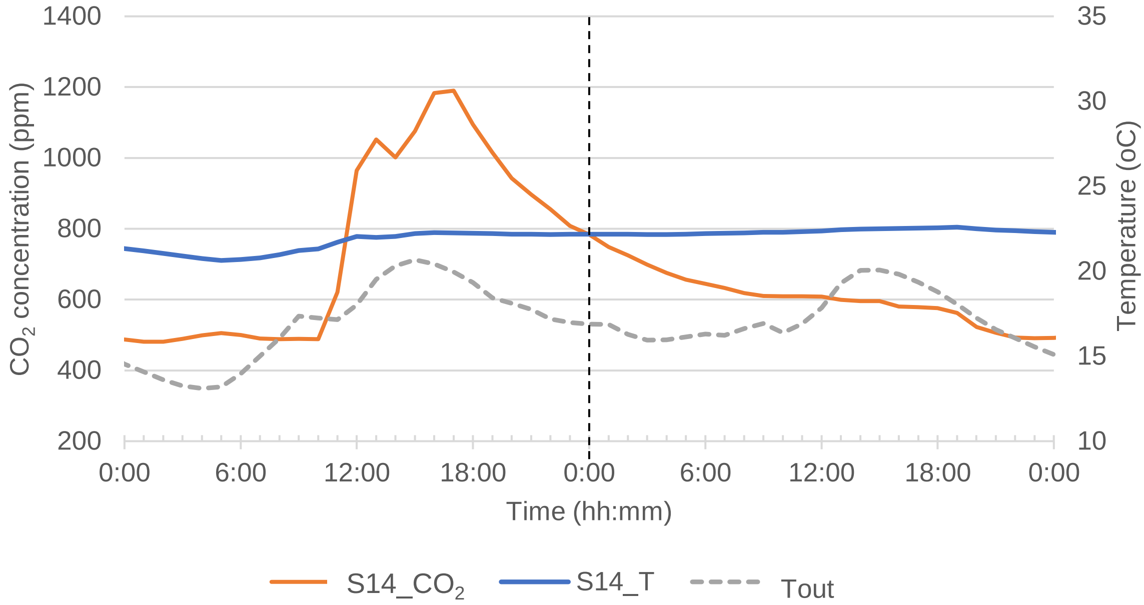


**Figure 8 Carbon dioxide concentration and temperature on the 28th and 29th of June in S14L2A**

## *3.3 Heatwave results*

Figure 9 presents the T levels during the heatwave in the studios that are ventilated exploiting SVA. Specifically, on the first day, there was a delay in the peak internal T by 1 hour in S7L1D and by 4 hours on the second day. In S11L2A on the first day the delay was 3 hours. Regarding the reduction in the peak T, it reached 7.5 and 8 ºC in S7L1D and S11L2A respectively on the first day and around 7 and 8.5 ºC on the second day. Overall, the T was kept below the maximum acceptable T on the first day of the heatwave and on the second day in S11L2A T exceeded the max limit for 16% of the occupied hours.

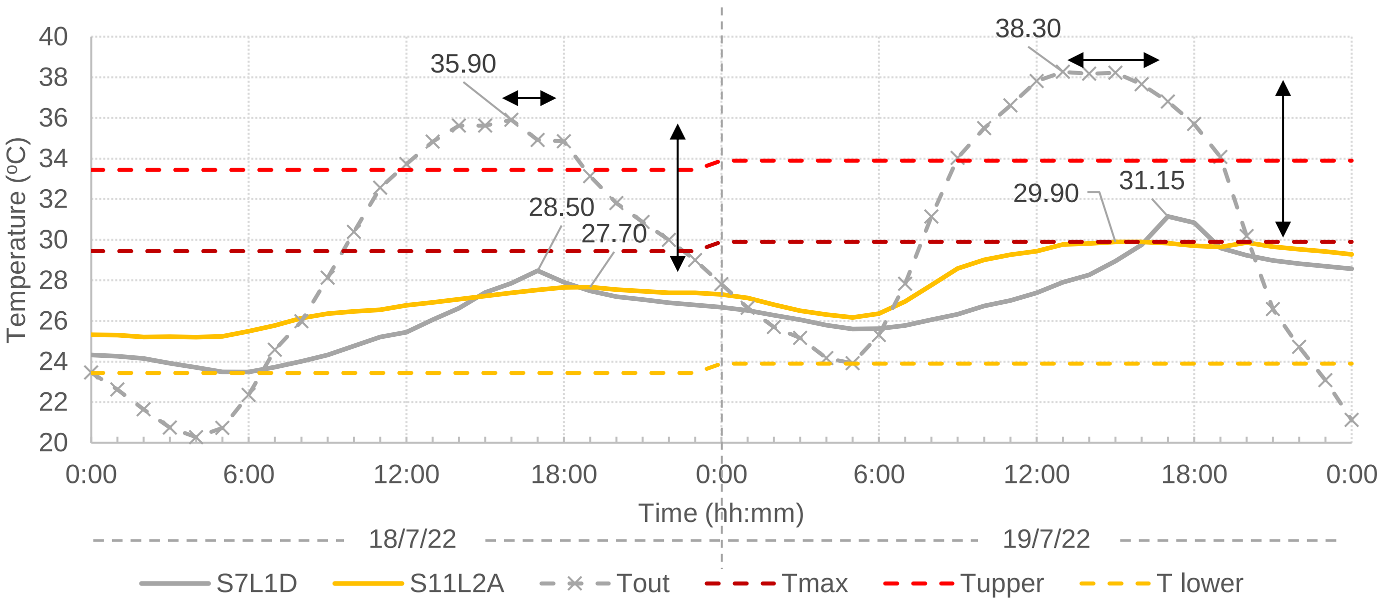


**Figure 9 Temperature variations during the heatwave in S7L1D and S11L2A (18/7/22 & 19/7/22). Also shown are the diurnal variations of the maximum (Tmax), upper (Tupp) and lower temperature threshold (Tlower)**

In the studios that are ventilated exploiting CV, on the first day, there was a delay in the peak internal T by 1 hour in S18L2D and S5L1D and by 3 hours in S5L1D and S18L2D on the second day, Figure 10. The reduction in the peak temperature was 7-8.5 ºC on the first day and around 6.5-8.5 ºC on the second day of the heatwave. In both days the dancing studios presented higher internal T comparing to the acting studio, which can be attributed to the higher internal gains produced by the occupants. The percentage of overheating (T>Tmax) on the occupied hours for both S5L1D and S18L2D, although marginal, was approximately 15% and 25% on the first day. For the second day this increased to 40% and 60% for S5L1D and S18L2D respectively. In any case the inner T was maintained below the Tupper limit.

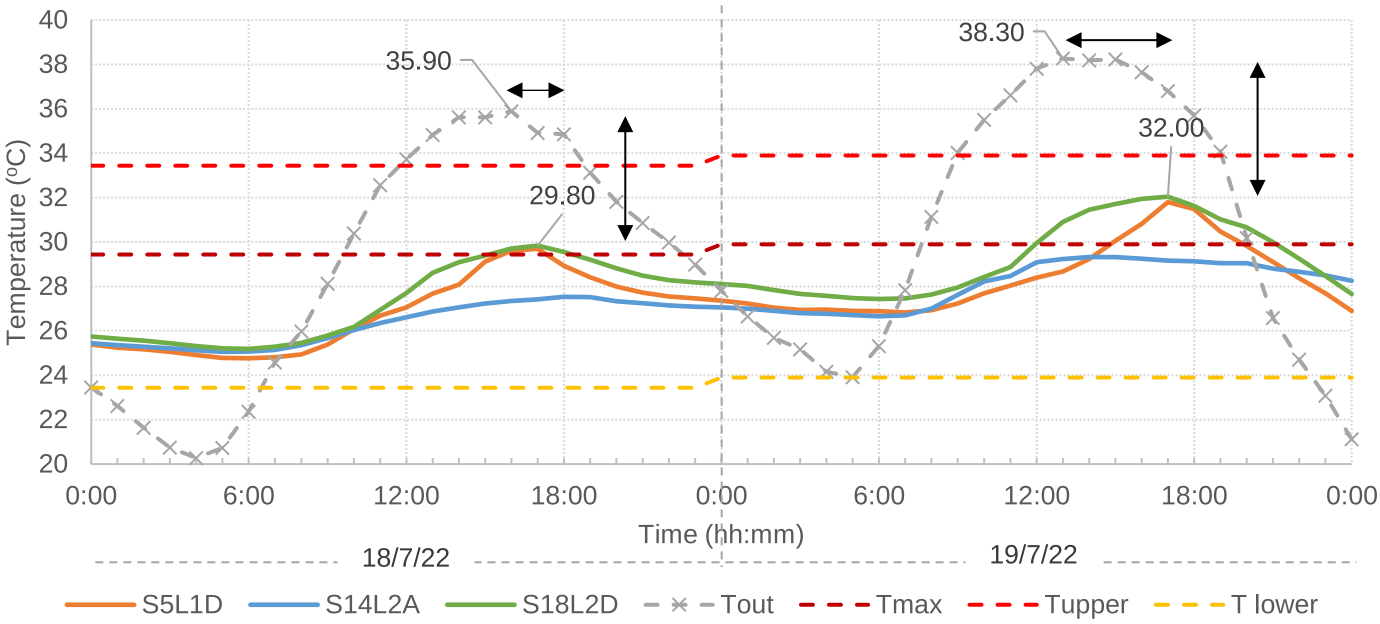


**Figure 10 Outdoor and operative temperature distribution during the heatwave (18/7/22 & 19/7/22), in S5L1D, S14L2A, S18L2D. Also shown are the day-to-day values of the maximum (Tmax), upper (Tupp) and lower temperature threshold (Tlower)**

Lastly on the studios that are exploiting the stack effect through the rooflight on the first day of the heatwave there was a delay in the peak internal T by 1 hour and by 4 hours on the second day in both studios, Figure 11. Regarding the reduction in the peak T, ranged from 5 - 5.5 ºC the first day and 6 ºC on the second day. In both days the internal T exceeded the maximum acceptable limit. Specifically, the percentage of overheating was around 45% and 30% for S21L3A and S23L3A on the first day and around 75% on the second day for both studios.

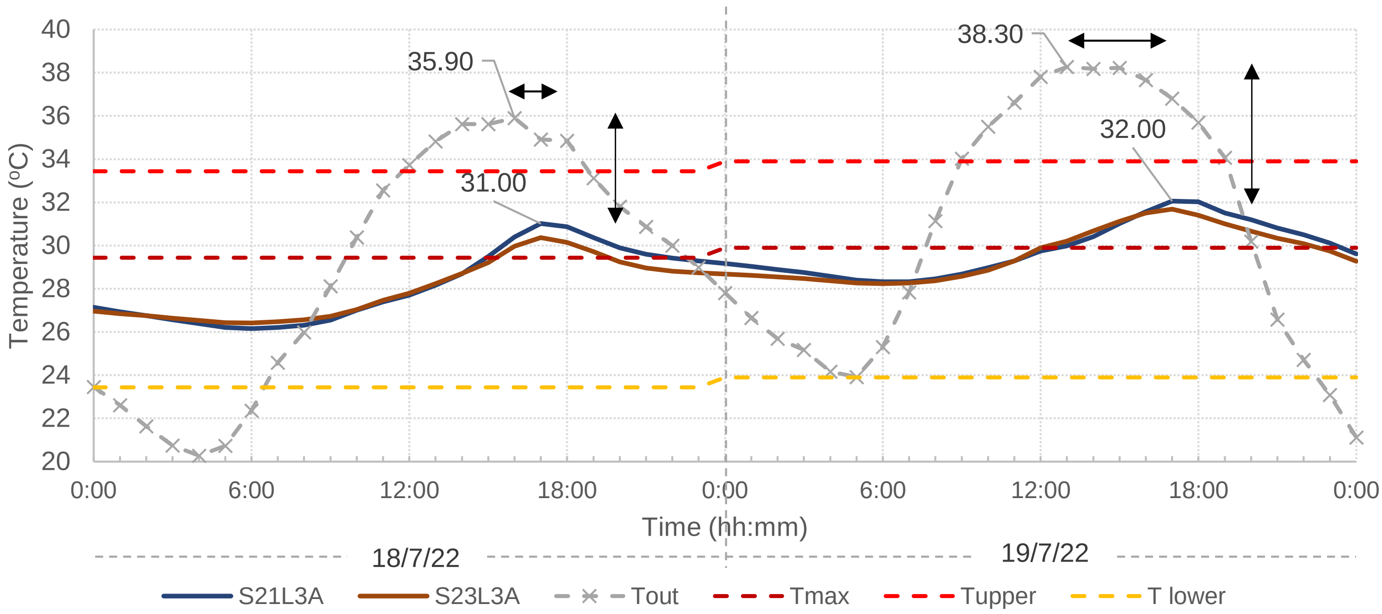


**Figure 11 Outdoor and operative temperature distribution during the heatwave (18/7/22 & 19/7/22), in S21L3A and S23L3A. Also shown are the diurnal variations of the maximum (Tmax), upper (Tupp) and lower temperature threshold (Tlower)**

It can be concluded that the studios using rooflights were found to be generally warmer and exceeded Tmax for a higher amount of time as well as the cross ventilated S18L2D. The studios exploiting stack effect through the atrium performed the best overall. Nevertheless, since during the heatwave the building was not fully occupied, compared to the rest of the study period, it could be a factor that had an impact in avoiding significant overheating occurring due to the lower occupant gains.

## 4.0 Discussion

Overall, the results indicate that the several NV strategies performed adequately for the part of the examined period. The environmental monitoring revealed that the T, RH and $CO_2$ levels were maintained within the relevant thresholds resulting to a healthy environment. On the days of the heatwave, the positive effects of the night cooling and high thermal mass concrete were evident in all the monitored spaces. The difference in peak T ranged from 5 to 8.5 $^oC$ and the time delay from 1 to 4 hours.

Nonetheless, compared to the rest of the study period the thermal performance conditions of the studios were compromised with some of them illustrating internal T higher than others. Among the different strategies SVA illustrated the best results. In addition, during the heatwave, the stack effect through the rooflight studios performed the most poorly regarding the indoor operative T presenting a difference with the outdoor T of 5 - 6 degrees and exceeding Tmax more than 45% of the occupied time. In general, IAQ was found satisfactory with the $CO_2$ concentration levels being maintained under the 1000 ppm threshold for 89-97% of the occupied times. However, cross ventilation studios presented a few slow decays which indicated that the ventilation strategy perhaps is not sufficient and further research is required.

Still, during the heatwave even though there was a decreased T compared to the outdoor levels, it is unknown whether with high-intensity activities such as dancing and acting the internal conditions are bearable for the occupants. Therefore, an occupant survey may better aid in determining the performance of the building. Additionally, even though the high thermal mass of the building helps in maintaining indoor T levels at a lower level than external T, it is potentially negatively affecting the embodied carbon emissions of the case study building, compared to a lightweight construction, and could be further investigated in the future alongside its whole life carbon emissions.

All in all, assessing a NV strategy depending on buoyancy effects and wind is complicated and several factors might affect a free-running building's performance and operation. Additionally, based on the study's qualitative and quantitative findings, it appears that NV in performing arts buildings is an appropriate design solution for current and future climates. Furthermore, among the different strategies, atrium-based ventilation could be recommended as a design approach for similar buildings combined with high thermal mass materials. Additionally, the manual operation of the louvres, assumed as always open, was found to be successful and could be implemented in other buildings as well. Moreover it could potentially be enhanced with complementary automatic control of the vents or more detailed operation from the management team, such as monitoring when and which louvres are open during specific weather conditions.

## 5.0 Conclusion

To tackle climate change and reduce carbon emissions the implementation of passive techniques in the built environment, especially in HVAC systems is essential. Simultaneously, it is important to evaluate the performance of these techniques through POE studies to understand their effectiveness and how they can be applied and improved, thus creating a process of continuous improvement in the construction industry (17). In this study, a NV performing arts building was evaluated during a summer period and specifically with extreme weather conditions to explore the effectiveness of passive techniques for environmental conditioning through monitoring and qualitative analysis. The results of the research present an indication of a future building performance where such extreme weather conditions are likely to become more frequent and whether different ventilation strategies could be implemented in similar type of buildings.

It was concluded that a passive ventilation strategy can be effective when applied in performing arts buildings. Specifically, the different strategies that are employed in the case study building are efficient, and the overall environmental strategy is contributing to reduced inner T throughout the studios. During the heatwave, the monitored spaces maintained lower internal T levels than the external. The IAQ was also found adequate with some exceptions and the interviews revealed some inadequacies regarding students' satisfaction. The study presented several limitations and recommendations for further studies including consideration of the embodied carbon effects of heavyweight constructions in contrast with lightweight solutions, occupant surveys to research any thermal dissatisfaction as well as further investigations of the indoor air quality and collecting data of the louvres operation.

## References

1. Song J, Huang X, Shi D, Lin WE, Fan S, Linden PF. Natural ventilation in London: Towards energy-efficient and healthy buildings. Build Environ. 2021 May 15;195.

2. Dorizas VP, Stamp S, Mumovic. Dejan, Keqin Y, Dimitris MM, Tom L. Performance of a natural ventilation system with heat recovery in UK classrooms: An experimental study. Energy Build. 2018 Nov 15;179:278–91.

3. Saber EM, Chaer I, Gillich A, Ekpeti BG. Review of intelligent control systems for natural ventilation as passive cooling strategy for UK buildings and similar climatic conditions. Energies (Basel). 2021 Aug 1;14(15).

4. Guarino F, Longo S, Tumminia G, Cellura M, Ferraro M. Ventilative cooling application in Mediterranean buildings: impacts on grid interaction and load match. International Journal of Ventilation. 2017 Apr 3;16(2):99–111.

5. Rahman H, Han H. Correlation of ventilative cooling potentials and building energy savings in various climatic zones. Energies (Basel). 2019;12(6).

6. Izadyar N, Miller W, Rismanchi B, Garcia-Hansen V. Impacts of façade openings’ geometry on natural ventilation and occupants’ perception: A review. Vol. 170, Building and Environment. Elsevier Ltd; 2020.

7. CIBSE. Natural ventilation for non-domestic buildings (CIBSE Guide A). London (UK): Chartered Institution of Building Services Engineers; 2014.

8. Tartarini F, Schiavon S, Cheung T, Hoyt T. CBE Thermal Comfort Tool: Online tool for thermal comfort calculations and visualizations. SoftwareX. 2020 Jul 1;12.

9. Albatayneh A, Alterman D, Page A, Moghtaderi B. The significance of the adaptive thermal comfort limits on the air-conditioning loads in a temperate climate. Sustainability (Switzerland). 2019 Jan 10;11(2).

10. Yu Y, Wang B, You S, Ye T, Zheng W, Wei S, et al. The effects of manual airing strategies and architectural factors on the indoor air quality in college classrooms: a case study. Air Qual Atmos Health. 2022 Jan 1;15(1).

11. What is a heatwave? - Met Office [Internet]. [cited 2023 Mar 15]. Available from: https://www.metoffice.gov.uk/weather/learn-about/weather/types-of-weather/temperature/heatwave

12. Claude-Alain R, Foradini F. Simple and Cheap Air Change Rate Measurement Using CO 2 Concentration Decays . International Journal of Ventilation. 2002 Jun;1(1):39–44.

13. Wargocki P, Porras-Salazar JA, Contreras-Espinoza S, Bahnfleth W. The relationships between classroom air quality and children’s performance in school. Build Environ. 2020 Apr 15;173.

14. CIBSE. The limits of thermal comfort: avoiding overheating in European buildings (CIBSE TM52). London (UK): Chartered Institution of Building Services Engineers; 2013.

15. Lowther SD, Dimitroulopoulou S, Foxall K, Shrubsole C, Cheek E, Gadeberg B, et al. Low level carbon dioxide indoors—a pollution indicator or a pollutant? A health-based perspective. Vol. 8, Environments - MDPI. MDPI; 2021.

16. Jamshed S. Qualitative research method-interviewing and observation. J Basic Clin Pharm. 2014;5(4):87.

17. Li P, Froese TM, Brager G. Post-occupancy evaluation: State-of-the-art analysis and state-of-the-practice review. Vol. 133, Building and Environment. Elsevier Ltd; 2018. p. 187–202.

## Acknowledgements

The authors would like to also thank Dr Samuel Stamp of University College London for his assistance and to the staff of the case study building for their assistance and engagement in the project.