Effect of Façade Design on Visual and Thermal Comfort in a Passivhaus Laboratory Building

A Case Study of the RAD building in Nottingham, UK

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ABSTRACT: Window and façade design plays a vital role in controlling the admission of natural light into a building. The provision of a direct link to daylight has been shown to help create a visually stimulating and productive indoor environment for building occupants. Additionally, design for daylight can lead to energy savings resulting from reduced dependence on supplementary artificial lighting. Whereas daylighting is an important strategy in controlling occupant visual comfort, it can impact on occupant thermal comfort and result in greater energy consumption for thermal controls. The uptake of Passivhaus has increased in recent years, with its main principle being energy efficiency. In this paper, the authors examine the effect of façade design on the visual and thermal comfort in the RAD research building which was designed to meet Passivhaus standards. As part of this post-occupancy evaluation, on-site measurements of illuminance, temperature and relative humidity were taken to analyse the existing indoor conditions, and a questionnaire administered to evaluate occupants' perception of visual and thermal comfort. The study shows that window design, window orientation and glazing-to-wall ratios can significantly impact on occupant visual and thermal comfort; and that key suggestions for improvements are strongly linked to the initial design stages.

KEYWORDS: Window Design, Thermal Comfort, Visual Comfort, Passivhaus, Post Occupancy Evaluation.

1. INTRODUCTION

Building fenestrations such as windows are regarded as one of the most significant elements of a building which if properly designed can have a positive impact on the well-being and health of occupants. Windows also play a great part in controlling the overall building's energy demand [1]. A significant amount of research has found that there is preference for daylighting over artificial lighting in office spaces by users. This preference has been linked to findings that show that daylight helps us in regulating and stimulating our circadian rhythm, and this in turn positively affects our mood and alertness [2]. On the other hand, if windows are not designed appropriately, they can propagate heat gain in the summer and lead to a significant increase in the building cooling load. Around the world, buildings account for around 40% of the energy consumption, with up to 30% of this being apportioned to supplementary lighting requirements. The provision of daylighting does not only impact on visual comfort but can also negatively affect the thermal comfort of users [3]. This risk has been exacerbated by the established trend of buildings with highly glazed facades and insignificant solar control measures. The subsequent solar gain in such buildings has been found to lead to several issues such as overheating [4].

In this paper, the authors examine the effect of facade design on the visual and thermal comfort of a research building designed using Passivhaus tenets and located in the UK. Developed to reduce energy consumption and provide zero carbon and ultra-low energy buildings, the Passivhaus standard aims to provide a well-insulated airtight building which is useful in controlling heat loss in the winter [5]. However, in the summer, a high level of insulation can lead to higher risk of overheating. As the world continues to face climate change and rising temperatures, Passivhaus buildings could be at great risk of overheating due to their high insulation standards [6]. According to previous research, several overheating issues have been found in Passivhaus buildings; additionally, there is a performance gap in the construction output [7]. This being the case, the execution of post-occupancy evaluations (POEs) is essential to providing feedback on existing and future Passivhaus buildings. To contribute to this important and valid discourse, the authors undertook a POE of a Passivhaus non-domestic building in the UK to review its Indoor Environmental Quality (IEQ). Focussing on the buildings visual and thermal performance, data was collected using an occupant survey and on-site data spot and long-term measurements.

2. CASE STUDY

Located in the University of Nottingham, United Kingdom (UK), the Research Acceleration and Demonstration (RAD) building was opened in mid-2018. The building was designed to house a crossdisciplinary energy hub that was developed as part of the Energy Research Accelerator initiative (ERA). As is shown in Figure 1, the building is orientated with its longitudinal axis north to south. It is divided into two main parts - the southern zone houses laboratory spaces and the northern zone consists of office spaces for the research and administrative staff. Both parts are connected by a central atrium (see Figure 1). The RAD building was designed to be one of the first research centres in the UK to achieve both the Passivhaus and BREEAM sustainability standards. Mainly made up of a steel frame, concrete intermediate floors, triple glazed windows (openable only in the office spaces) and curtain walling which consists of structural insulated panels (SIPs) and zinc cladding [8], the building was designed to have a very high level of airtightness and insulation.

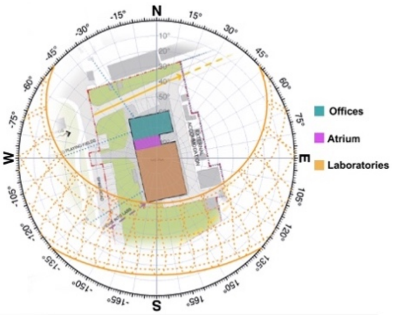


Figure 1: RAD building orientation and zoning.

Figure 2: RAD building showing the irregular design of the windows on the North and West facing facades.

The RAD building is mainly ventilated using an MVHR (Mechanical Ventilation with Heat Recovery) system that has three air handling units (AHUs) which supply fresh air to the different zones of the building. The office spaces also have local wet radiators for any supplementary heating. This system aims to supply fresh air throughout the building with temperatures ranging between 18°C and 22°C. The ventilation supply is controlled by a Variable Air Volume (VAV) box which is controlled using passive infrared sensors (PIRs) located in all the rooms [9]. The central atrium, with a large fixed glazing facing the west, also works to provide stack ventilation that assists the active system by collecting passive solar and occupant gains that are extracted via the plant at the roof top of the atrium. As the RAD building had been occupied for just over a year at the time of this study, it presented a valid choice for the POE study. A large fixed skylight is located above the atrium to the west of the building.

3. METHODOLOGY

To evaluate the IEQ of the RAD building, the authors collected a combination of data via an occupant survey and on-site measurements. This process was undertaken during a three-week period, from the end of winter to the start of springtime (March-April) - a period when signs of overheating might potentially be identified. On-site data was collected from four rooms (see Figures 3 and 4). These rooms were selected based on their glazing orientation/exposure and by virtue of housing of key building uses. The selected rooms consisted of 2 labs, 1 open plan office and a meeting room as seen in Figures 3&4 showing the glazing orientation. The building's main façade is mainly oriented towards the west - putting rooms located along it at higher risk of overheating in the warmer months.

As the building was not fully occupied during the study period, only rooms that were occupied (A08, B18, B20) or in regular use (B05) were selected for this evaluation. A questionnaire was administered to establish occupants' perception of visual and thermal comfort. In addition, spot measurements of illuminance, temperature and relative humidity were taken in the aforementioned rooms. Further, to obtain longer-term data, both temperature and relative humidity data was collected using data loggers during the set three-week period.

Figure 3: Ground Floor plan showing room A08.

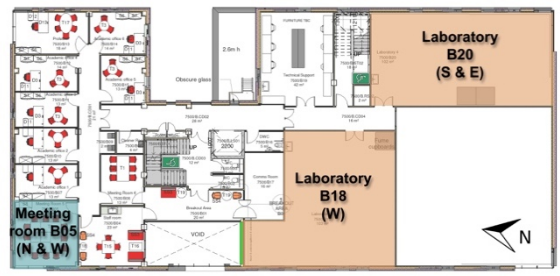


Figure 4: First Floor plan showing rooms B05, B18, B20.

3. RESULTS AND DISCUSSION

3.1 Occupant survey

The questionnaire was filled out by 18 occupants. Findings on occupant perception of thermal and visual comfort and their level of satisfaction with the thermal and visual experience within their workplace are presented in Figure 5. Overall, most of the respondents indicated that they were satisfied with the quality of their workspace. This majority did not directly translate to their satisfaction with thermal or daylighting conditions. This could be explained by the fact that most respondents were dissatisfied with the lack of opportunities offered to occupants in adjusting indoor environmental conditions to enhance their thermal (78%) or visual comfort (55%). For example, the respondents expressed dissatisfaction with the small openable window area which did little to help control thermal comfort. On a more positive note, most respondents were satisfied with their views to the outside (66%) and the impact of artificial light improving lighting conditions (78%).

Question	Very Satisfied		Neutral		Very dissatised
Overall quality of your room	22%	67%	11%	0%	0%
Overall satisfaction of thermal condition in the workspace	56%	0%	22%	11%	11%
Ability to alter temperature to meet your needs (opening windows, turning heater on/off, etc.)	0%	0%	22%	56%	22%
Overall quality of light in your workplace (artificial and natural combined)	11%	33%	33%	6%	17%
Amount of natural light in your workspace	11%	0%	44%	33%	11%
Amount of artificial light in your workspace	22%	56%	22%	0%	0%
Views to outside from your workspace	33%	33%	11%	22%	0%
Ability to adjust artificial light levels to meet your needs	11%	33%	22%	22%	11%
Ability to adjust natural light levels to meet your needs	0%	0%	44%	33%	22%

Figure 5: Questionnaire results showing user perception of thermal and visual comfort and related satisfaction rates.

3.2 Visual Comfort

Firstly, an evaluation of the building was undertaken to establish if it met CIBSE and Passivhaus standards for daylighting. Two of the selected rooms, rooms B05 and B20 (Table 1), were found to have more than the recommended glazing area of 15-20% and daylight factor of 2% [10]. Lab B20 also has a south facing glazing area of 34%, which is more than the maximum of 25% advised by Passivhaus [11]. Also, the high window to floor ratios in B05 and B20 were found to put the rooms at higher risk of overheating as a result of solar gain (Table 2).

Secondly, spot measurements were collected on both overcast and clear sky days to assess the illuminance levels in the different rooms of different orientations. This data was collected at three key times to represent key solar times (9am, 12pm and 3pm) and which are relevant to occupancy patterns. According to CIBSE [10], office and laboratory spaces should have an illuminance levels ranging from 300-500 lux and 300 lux, respectively. The illuminance levels in the all the selected rooms were found to be mainly above the acceptable range, this often caused discomfort such as glare to some of the respondents that were located next to a window.

Table 1: Window to floor ratio of the four selected rooms

ROOM	WINDOW AREA	FLOOR AREA	WINDOW TO FLOOR RATIO
A08-OFFICE	18.6m^2	95.7m^2	19.4%
B05-MEETING	14.7m^2	24.7m^2	59.4%
B18-LAB	20.2m^2	101.7m^2	19.9%
B20-LAB	43.7m^2	101.8m^2	43%

Table 2: Daylight factor of the four selected rooms

ROOM	W (NET WINDOW AREA)	A (AREA OF ALL SURFACES)	DAYLIGHT FACTOR
A08-OFFICE	18.6m^2*0.9= 16.7m^2	371.9m^2	2.7%
B05-MEETING	14.7m^2*0.9= 13.2m^2	125m^2	6.3%
B18-LAB	20.2m^2*0.9= 18.2m^2	476m^2	2.3%
B20-LAB	43.73m^2*0.9= 39.4m^2	466.5m^2	5%

Figure 6: Direct sunlight entering A08 open plan room on a sunny afternoon at 3:00pm

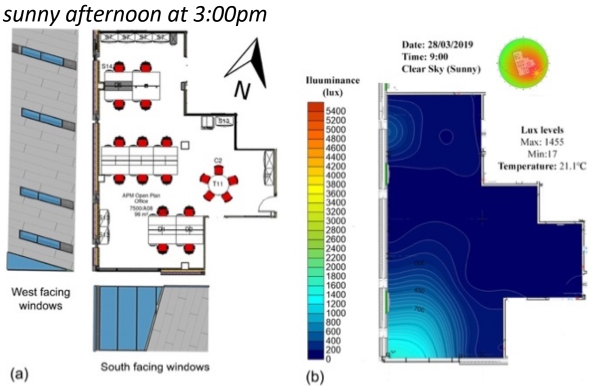


Figure 7:(a) Window distribution, room A08. (b)Illuminance distribution, room A08 at 9 am on a sunny day.

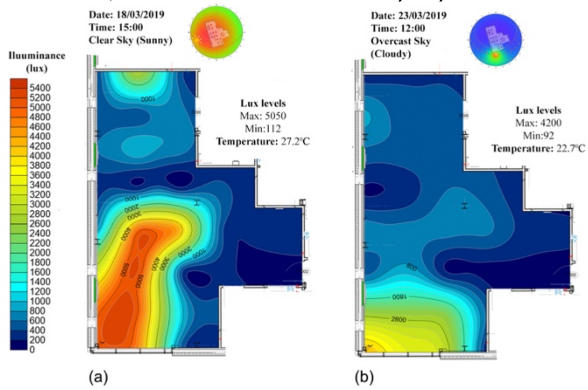


Figure 8: (a) Illuminance distribution in room A08 at 3 pm on a sunny day. (b) Illuminance distribution in room A08 at 12 pm on an overcast day.

In room A08, an open plan office, the illuminance level fluctuated greatly during the 3 key times of measurement. As seen in figures 7 & 8, the lux levels are higher the acceptable range. In addition, in the afternoon of a selected sunny day, direct sunlight is seen to fall on the workspace surface and cause glare. Also, recorded spot measurement of the temperature at that time was quite high reaching up to 27°C which is significantly higher than the maximum indoor temperature prescribed by Passivhaus [11]. Considering that this data was collected during a relatively cooler period of the year (March - April), it was concerning to note what might happen at warmer and full building occupancy times.

Room B05, a meeting room, was found to have a large window to floor ratio (59.4%) and a high daylight factor too. As revealed in the lux mapping shown in Figure 9 and 10, there was a significant amount of direct sunlight entering the room on the sunny afternoon day. As with room A08, the spot temperatures recorded in B05 were significantly high reaching up to 28°C. These high temperatures were recorded when the room was empty therefore discounting the impact of internal gains brought on by occupants and equipment.

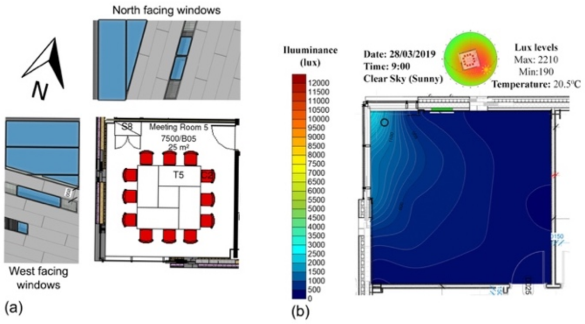


Figure 9: (a) Window distribution of room B05. (b) Illuminance distribution in room B05 at 9 am on a sunny day

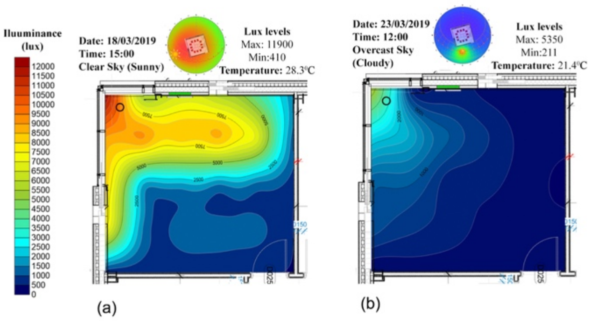


Figure 10: (a) Illuminance distribution in room B05 at 3 pm on a sunny day. (b) Illuminance distribution in room B05 at 12 pm on an overcast day

In rooms B18 and B20, laboratory spaces, illuminance levels were also higher than the range specified by CIBSE [10] with lux levels reaching up to 12000 and 18000 lux. The high window to floor ratios, window design (height spanning from the ceiling to the floor slab) and window placement (significant western exposure) were found to enable direct sunlight to fall on the work benches and cause glare discomfort at different times of day. Unlike B18, B20 didn't have very high temperatures recorded in it since its oriented towards the south-east and had direct sunlight in the morning.

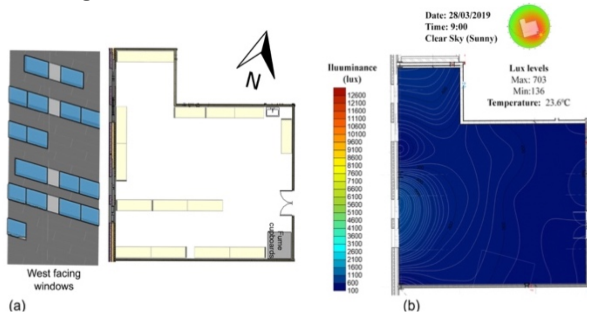


Figure 11: (a) Window distribution of room B18. (b) Illuminance distribution in room B18 at 9 am on a sunny day

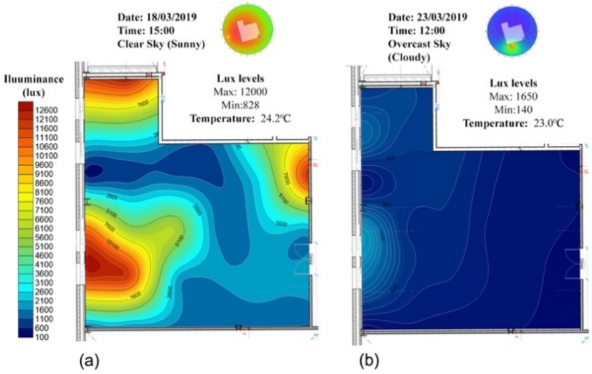


Figure 12: (a) Illuminance distribution in room B18 at 3 pm on a sunny day. (b) Illuminance distribution in room B18 at 12 pm on an overcast day

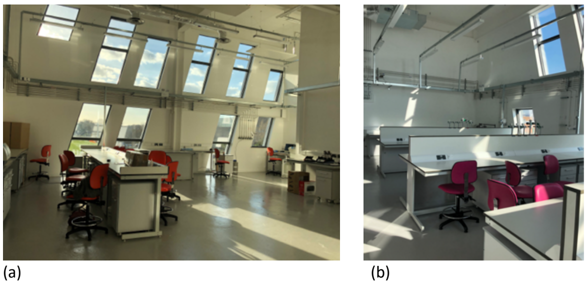


Figure 13: (a)Distribution of direct sunlight within the B18 laboratory on a sunny afternoon at 3:00pm. (b) Distribution of direct sunlight and daylighting within the B20 laboratory on a sunny morning at 9:00am

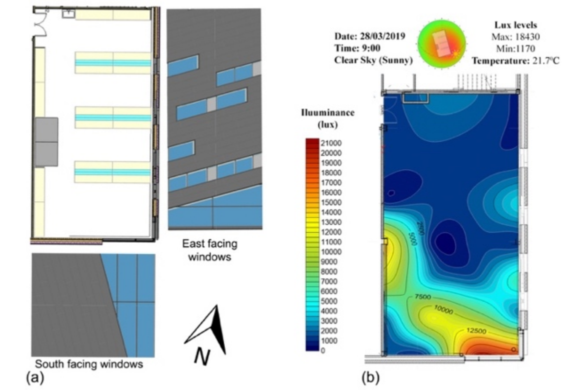
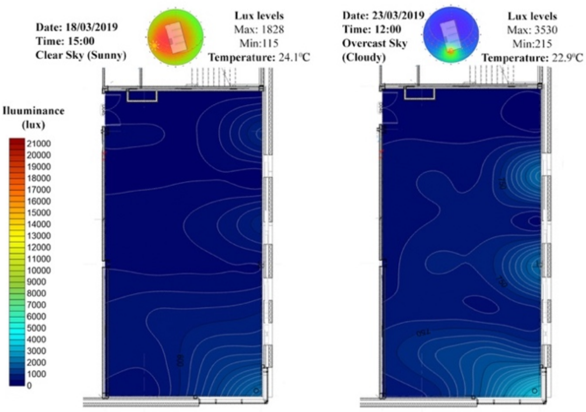


Figure 14: (a) Window distribution of room B20. (b) Illuminance distribution in room B20 at 9 am on a sunny day



(a) (b)

Figure 15: (a) Illuminance distribution in room B20 at 3 pm on a sunny day. (b) Illuminance distribution in room B20 at 12 pm on an overcast day

3.3 Thermal Comfort

According to CIBSE [10], temperatures should range within 21-23ºC (winter) and 22-24ºC (summer) in offices and 19-21ºC (winter) and 21-23ºC (summer) in laboratories. Passivhaus standards stipulate that rooms must not exceed 25ºC for more than 10% of the time annually and with or without occupancy) [11]. In 2018, a thermal comfort analysis of the RAD building was conducted to establish if the building would be able to achieve comfort temperature in the summertime. An average for the year was calculated for all the rooms including the rooms chosen for this study and all were found to meet the Passivhaus overheating criteria, with some on the border just at above 10% [9].

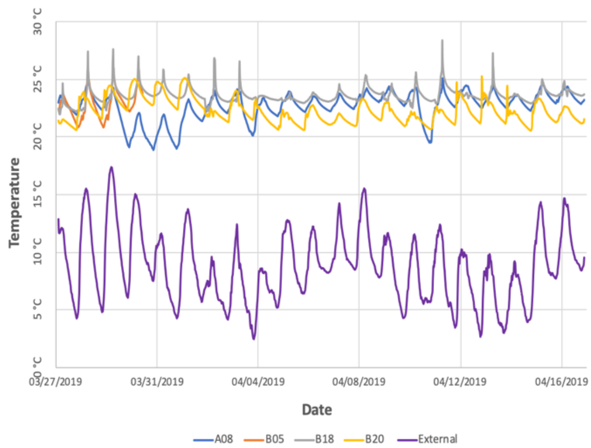


Figure 16: Temperatures recorded over the 3-week period in the 4 rooms and externally.

During this study, data loggers placed in the 4 rooms recorded temperature and relative humidity values for the 3 weeks period. Analysis of this data shows that the indoor temperatures reach above 25ºC, and that this occurred when the outdoor temperature reached a maximum of approximately 18ºC. The indoor temperatures reached a maximum of 28.4°C and were above 22°C, and this occurred for 14% of the entire time, and during working hours. These findings matched temperature values recorded during the spot measurement period. In some cases, the temperature recorded was more than 22°C. This occurred in rooms that had West facing windows (A08, B05 & B18) at 3pm on a sunny day - locations where solar gain is expected to have the significant impact on overheating. Given that the MVHR system is set to maintain temperatures within 18-22ºC and that this study was conducted during a cooler period (March - April), this raised concern as to how high the indoor temperature could be during the summer period.

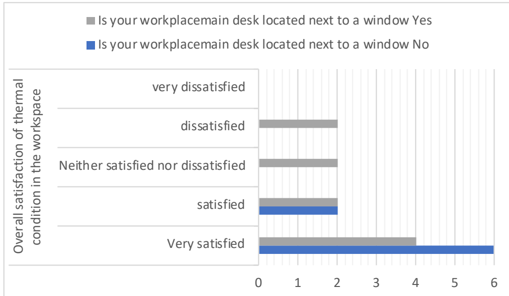


Figure 17: Overall satisfaction with thermal condition

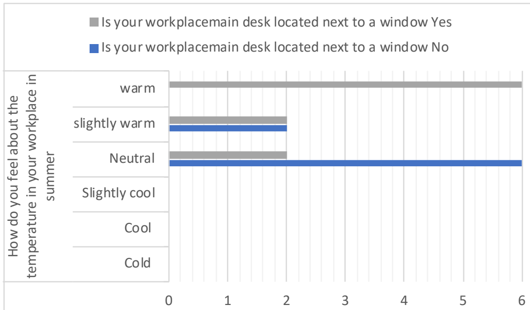


Figure 18: Thermal sensation in summer

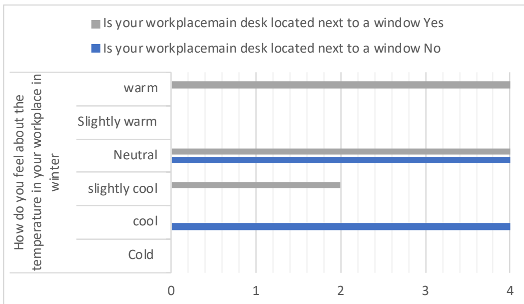


Figure 19: Thermal sensation in winter

Furthermore, most respondents indicated that they found it slightly warm or warm during the summer period. It was also noted that occupant satisfaction with thermal comfort was affected by workspace placement (away or next to a window). Those located next to windows were less satisfied with the thermal conditions of their workplace (Figure 17). It is also clear from the questionnaire that the respondents allocated next to a window felt warmer in both summer and winter than others that weren't next to a window (Figure 18 & 19). This might be due to the fact that they were closer to the source of solar gain. Overall, data collected and analysed indicates that the building is at risk of overheating and especially during the warmer months.

4. CONCLUSION

The uptake of Passivhaus buildings has increased in recent years, its main principle is energy efficiency; this requires careful planning to ensure that suitable indoor conditions are not compromised. In this study, feedback from occupants of the RAD building indicates that they experience issues that impact on their thermal (overheating) and visual comfort (glare and poor distribution of daylight). This has been supported by data collected from spot and long-term on-site measurements. A review of this data and the design strategies employed indicates that more, with respect to the window and façade design, could have been done to reduce these issues.

For instance, whereas the building orientation might have been difficult to alter (owing to plot layout), the designer could have chosen to provide alter the glazing ratio to ensure that there is lower risk of solar gain via glazing and that there are fewer instances of glare and better daylight distribution. As some of the glazing did not abide to Passivhaus standards, with higher window to floor ratios than the recommended, this is thought to have contributed to high indoor temperatures (above 25^{o}C) and poor distribution of daylight that led to occupant discomfort. Further, the RAD building was not found to have any form of external shading. If designed appropriately (e.g. free from the main structure to avoid thermal bridging), shading would have been very useful in not only mitigating solar gain, but could also to better distribute daylight indoors, consequently reducing the need for internal shades and artificial lighting.

Whereas the MVHR would have been expected to ensure indoor conditions are maintained at the required level, more considerate design might have been helpful. For instance, the option of a 'summer bypass' might be useful to allow the air flows to pass through the system without exchanging heat. Such a case would happen when outdoor temperature is lower than those indoors. In cases where summer temperatures are expected to rise significantly (e.g. the current climate change scenario), active cooling might need to be considered. In addition, as occupants reported not being able to find relief from opening windows, it might have been useful to consider providing larger openable widow areas to assist occupants in not only helping purge heat gain but also to help them thermoregulate.

Overall, this study has shown that whereas Passivhaus strategies can be used to enhance energy efficiency there can be instances of performance gaps. In this case, it has been concluded that more could have been done at the design stage to enhance visual and thermal comfort. This is vital aspect of designing buildings - Passivhaus or not. Given key concerns on climate change and its link to increased energy use it is important that building design solutions work to mitigate risk and provide occupants with the opportunities to maintain visual and thermal comfort.

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