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Facilitating responsive interaction between occupants and building systems through dynamic post-occupancy evaluation

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Abstract. Post-occupancy evaluation (POE) is a process that can reveal the interrelations between key building performance factors and successfully integrate indoor environmental quality, thermal comfort, functionality, environmental strategy and occupants' satisfaction. POE has become a prerequisite for several building certification systems and it is often presented as a method to improve the commissioning of buildings and as a user experience feedback mechanism. This paper is based on a POE undertaken through stages at the University of Southampton Mayflower Halls of Residence complex. The first stage included the evaluation of occupant satisfaction, indoor environment quality and energy use. Results from temperature and relative humidity monitoring and an online POE questionnaire were analysed in the context of energy use, thermal comfort and building controls' functionality. The second part of this study monitored the air temperature in a sub-sample of 30 rooms where the residents participated in a thermal comfort survey with a "right-here-right-now" questionnaire and a portable instrument that monitored air temperature, relative humidity, globe temperature and air velocity in the rooms. This paper presents the results of the POE and discusses approaches for the improvement in the buildings' energy performance and the environmental conditions in the living spaces of the students. Results suggest that current use of controls is not always effective, with implications for the buildings' energy use. Large variability was found in occupants' thermal perception and preferences, which points to a need for occupant-centric solutions. In this study, POE is approached as a dynamic process that could be used to facilitate the responsive interaction of occupants with building systems and deliver through their engagement high energy performance and comfort.

1. Introduction

Smart buildings are seen as key in reducing energy consumption and emissions due to their improved operational efficiencies [1]. The prevalence of the Internet of Things and reduced costs of modern sensing technologies heralds the application of such systems to provide real-time, dynamic control and automation in buildings. Clearly, such transformative approaches will also need to be augmented with building occupants' perception of comfort and space functionality to succeed.

New and existing repurposed buildings are required to achieve high energy performance and occupant satisfaction. A commonly used approach, especially in new office buildings, is to design mixed-mode buildings that use passive design strategies supplemented with mechanical systems.



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Residential buildings in Europe were typically free-running with heating as and when required. However, air conditioning has lately become popular as a result of climate change [2], urban heat island [3,4] and modern lifestyle [5]. Low-energy, adaptive buildings will not only have to adapt to the use of space but also to the dynamically changing with time, individual comfort requirements of occupants [6]. Towards this direction, it is important to investigate methods and systems to facilitate responsive interactions between occupants and building systems [7]. Post occupancy evaluation (POE) and continuous feedback can provide some of the tools required to design and manage low-energy buildings [8] with controls and occupants as direct actuators of adaptation.

The majority of the existing (POE) methods are based on questionnaire surveys with different formats according to the aims of the evaluation. One method with widespread use is the BUS Occupant survey [9,10]. The BUS method evaluates the satisfaction of occupants against a number of categories with the use of a seven-point scale. Occupants are asked to rate each category from Very Dissatisfied to Very Satisfied. Similarly, the Probe method questionnaire survey [11] is complemented with visual surveys, focus groups, energy and environmental performance assessments. It focusses on occupant satisfaction, systems' performance and it can be used for benchmarking of the building's overall performance [9,11]. There is evidence however that occupants may use the POE as a medium of complaint and express their dissatisfaction with issues unrelated to building performance [12].

This case study introduced a bespoke "hybrid" diagnostic POE method for the evaluation of the Mayflower Halls of Residence, in Southampton, UK. This "hybrid" POE method uses a combination of questionnaire surveys with data collection and indoor condition monitoring. The observations are analysed in the context of occupants' satisfaction and wellbeing. The aim of this paper is to present the results of the POE and discuss approaches for improvements in the current use of building systems and controls to achieve energy savings and occupants' thermal satisfaction. This POE method is introduced as a constant feedback mechanism to inform building management decisions and facilitate the interaction of occupants with their living space.

2. Case study

The Mayflower Halls of Residence complex is a £70 million building development in Southampton (50.91 °N, 1.404 °W), a port city at the south coast of England. The building development consists of three buildings (Blocks A, B and C in **Figure 1**) that offer a total of 1,104 units for student accommodation, main reception areas, common spaces and facilities, such as laundry and a gym. Block A is a 12-storey building located at the East side of the complex, with main facades of north, northeast and southeast orientation (**Figure 1**). Block B is a 17-storey building (**Figure 1**) with a main facade facing southeast. Block C is a 9-storey building with its long facades facing along the north – south axis.

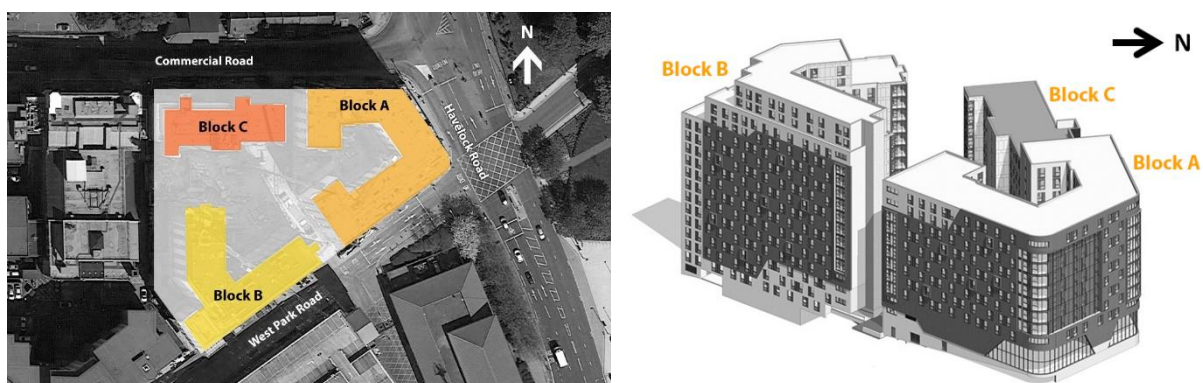


Figure 1. Schematic representation of the site (Left), showing the 3 buildings of the Mayflower Halls complex. (Background image source:[13]). Axonometric drawing of the building complex (Right) (Image adapted from [14]).

There are three types of accommodation provided throughout the building complex: en suite study bedrooms, self-contained studios and one-bedroom suites. The floorplan layout for each accommodation type is the same in all 3 buildings. A diagrammatic plan of the two main typical accommodation units in this study is shown in **Figure 2**.

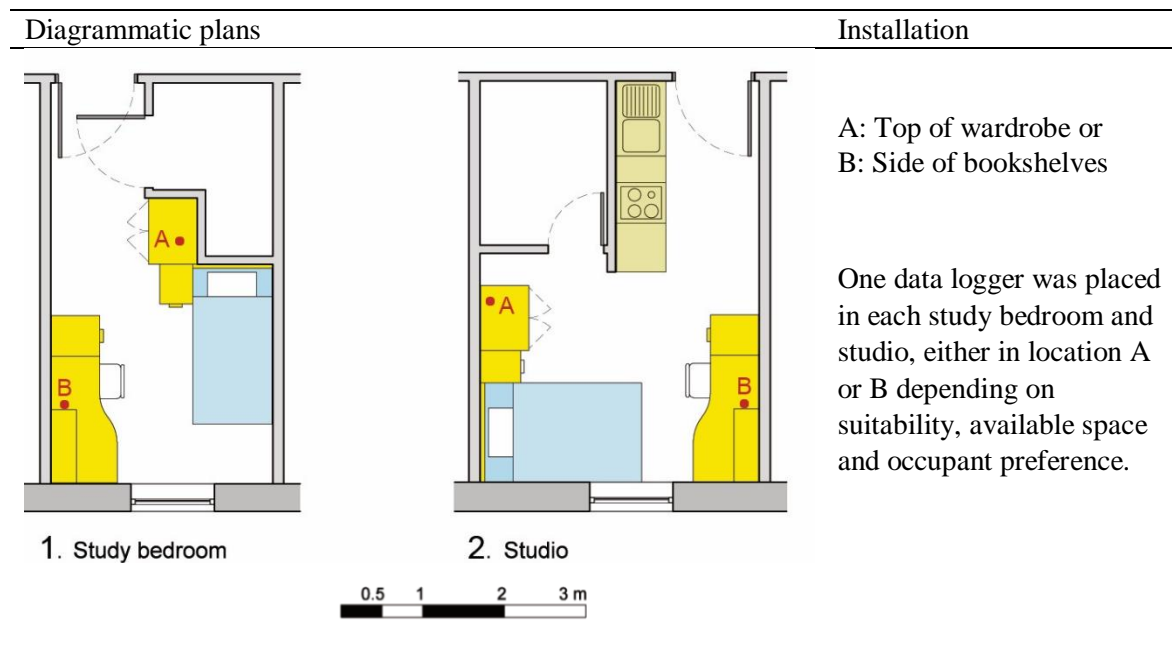


Figure 2. Typical accommodation units and the position of the miniature data loggers.

3. Research design

An in-depth diagnostic review was carried out during the first year of the buildings' occupancy. A post occupancy evaluation usually takes place a year after the beginning of buildings' occupation. There are several existing POE methods that include different techniques and levels of detail [9,12]. The techniques available vary from walkthrough investigation to data collection and workshops.

For the post occupancy evaluation of the Mayflower Halls of Residence a bespoke "hybrid" method has been developed similar to the Probe survey techniques. This diagnostic POE approach uses a combination of questionnaire surveys with data collection and indoor conditions' monitoring. In addition, walkthrough and visual surveys have been conducted inside and outside the buildings.

Student halls are a category of buildings with special characteristics and the method had to comply with the university and halls rules and guidelines and to fit with student timetables. The final format of the questionnaires, the interviews and the planning of the environmental monitoring were influenced by the special characteristics of this building type such as the interrupted occupancy, exam periods and the mix of the different cultural backgrounds of the occupants. The variable occupancy schedule and the cultural background of the students were also key parameters to the analysis and interpretation of the environmental observations and the thermal comfort assessment.

Specifically this paper reports and analyses data from:

1. Web based structured questionnaires (sent out to 90% of the occupants);
2. Air temperature (T_{air}) and relative humidity (RH) observations collected from a sample of accommodation units;
3. Interviews and thermal comfort surveys with a subsample of occupants and the halls' managers;
4. Information from the developer, the University of Southampton and the Halls' management team;
5. Walkthrough observations with the use of scientific equipment (e.g. Infrared camera).

The timeline of the POE study during the first year of occupation can be seen in **Figure 3**.

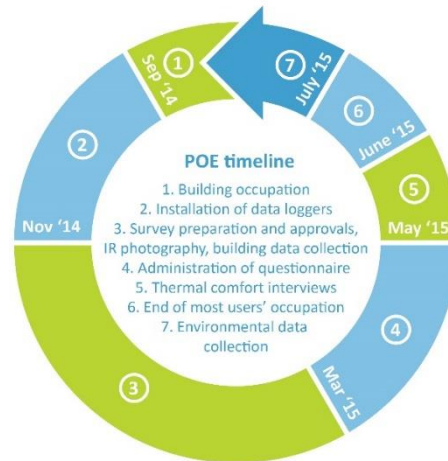


Figure 3. Schematic representation of the different phases of the Post Occupancy Evaluation study.

3.1. Occupant questionnaire survey

An online questionnaire was sent by email to 955 (out of a total 1,029) residents of Mayflower Halls of Residence in March 2015 using the University of Southampton's iSurvey software. The online survey, approved by the ethics review committee of the University of Southampton, consisted of questions relating to the occupants' level of satisfaction with the building in general, their opinion on the indoor environmental conditions in their room and the use of the room system controls such as the thermostatic radiator valves (TRV), window opening, curtains and artificial lighting. The questions distinguish between seasons and were mainly focused on the heating period (i.e. when heating system is in operation). That was dictated by the seasonal occupancy profile with most of the students moving out at the beginning of the summer.

In contrast with the existing POE methodologies that this method has drawn upon, a five-point scale has been used in the questionnaire survey, instead of 7 or more. This was decided based on: (1) clarity / previous experience with questionnaire surveys and interviews; (2) different level of English understanding of respondents; and (3) difficulty and subjectivity to assess thermal conditions. From the initial sample, 298 participants (31%) responded to the survey. The complete, valid questionnaires were 223 (n=223), representing a response rate of 23%.

3.2. Air temperature (T_{air}) and relative humidity (RH) monitoring

Indoor air temperature (T_{air}) and relative humidity (RH) observations were collected from a sample of 95 occupied rooms. In July 2015, data loggers were successfully retrieved from 73 rooms (n=73). Data was collected from rooms distributed across all three buildings and different floors and room (window) orientations. Temperature and relative humidity miniature data loggers [15] (**Figure 4**) were placed in the accommodation units with the permission of the occupants during November and December 2014. A random sample of rooms across the three blocks was selected to represent all locations within the building complex, floor levels and orientations.

The data loggers recorded ambient air temperature (T_{air}) at a 0.01 °C resolution and relative humidity (RH) at a 0.1% resolution every 5 minutes (snapshots, not average); based on logging memory, battery duration and the objectives of this study. The manufacturer stated accuracy is +/- 0.5 °C for T_{air} and +/- 3% for RH. The memory capacity is in the range of 1,000,000 readings per channel and the battery life is 10 years at a 15 minute reading rate [15].

In situ installations had to achieve a balance between being representative of the average ambient room conditions and at the same time ensure easy access, safe and secure placement and limited

disruption to the occupants. The two chosen locations were the top of the wardrobe or the side of the bookcase (marked with A and B in **Figure 2** respectively).



Figure 4. Temperature and relative humidity miniature data loggers used in this study.

The locations where the loggers were installed have been chosen such as to 1) be away from direct internal heat sources (e.g. PC heat sinks and fans, desk lamps, hair dryers, printers etc.); 2) have sufficient airflow and be away from air flow stagnation points and 3) be shaded at all times to avoid incident direct solar radiation.

3.3. Interviews

In addition to the questionnaire survey, thirty separate surveys were undertaken in the form of interviews with occupants who participated in the environmental conditions monitoring. The interview format was an informal 15 minutes discussion with one of our researchers at the occupant's room. During the discussion a questionnaire was filled in. This questionnaire was similar to the one in the email survey. At the same time, portable equipment, specialized for thermal comfort studies, monitored the current room conditions. The 30 interviews were spread across 9 days, during the period from 5- 15 May 2015 and took place at different times during the day (13% between 8:00- 11:00, 27% between 11:00-14:00, 27% between 14:00-17:00 and 33% between 17:00-19:00). Over the 9 survey days, the daily mean ambient environmental temperature was between 10 °C and 12 °C [16].

4. Results and discussion

All room numbers in this section have been coded in compliance with the University of Southampton ethics requirements. The rooms have been ordered according to the building floor level. For example, rooms with a code number of 1 to 3 are at the same or lower floor level than rooms with a code 4 to 6. Similarly, the room with the code 33 is at the highest building floor level available in the sample.

4.1. Overall satisfaction

Overall, there is a high level of satisfaction with the various building spaces, as can be seen in **Figure 5**. The highest percentage of positive votes were reported for the bedrooms/flats, which appear to satisfy the needs of the vast majority of the respondents (89%). The common room (common living space like a shared living room) received a high percentage of 'Neither satisfied nor dissatisfied' votes, which is probably because this space is not used that often and by all the building occupants.

4.2. Indoor environmental conditions

4.2.1. Ventilation

Based on the occupant questionnaire responses, the air flow conditions in the bedrooms/flats were generally perceived as being 'OK' (**Figure 6** (a)). However, 14% characterised the air movement as "too still" and 30% "a bit too still". Given that ventilation is achieved through controllable trickle vents and window opening, these votes are mainly related to the efficiency of these controls. However, based on a few respondents' comments, the window aperture, when open, does not permit enough fresh air to circulate into the room. The interpretation of the responses in combination with the comments suggests that there may be an issue with achieving adequate ventilation rates that would increase air movement

and help regulate air temperature and humidity. Regarding the window aperture, its specifications are set to ensure safety and that the room conditions are not affected by strong gusts, which can be a critical issue in high-rise buildings.

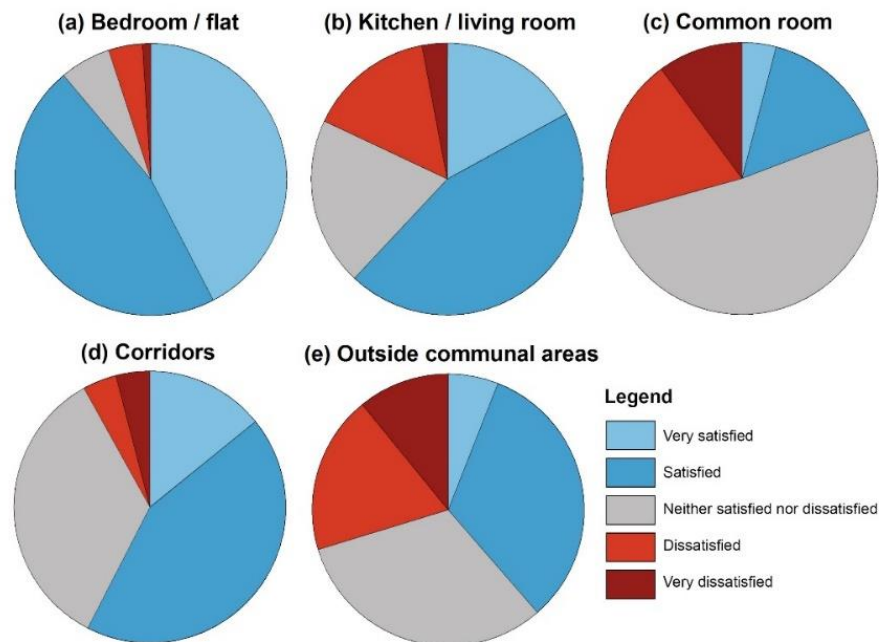


Figure 5. Occupant satisfaction with (a) their bedroom/flat, (b) kitchen, (c) common room, (d) corridors and (e) outside communal areas.

Automatic control of the shower extractor fans and the use of ceiling fans could help to alleviate issues with air movement and increase occupants' satisfaction. The distribution of responses in relation to air movement (**Figure 6 (a)**) is skewed towards the still side. This supports initial evidence that there may be a general issue with ventilation levels in the buildings.

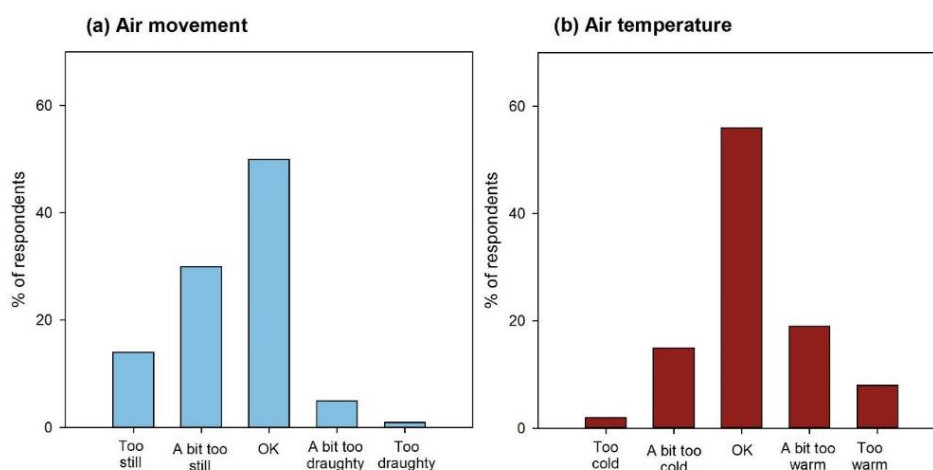


Figure 6. Distribution of occupant responses about (a) the air movement and (b) the air temperature during winter, in their room.

4.2.2. Air Temperature

The air temperature was perceived as being satisfactory by the majority of respondents (56%) (**Figure 6** (b)). However, there were still a number of occupants voting for either side of the thermal sensation (TSV) scale (“too cold”, “a bit too cold” and “too warm”, “a bit too warm”). Furthermore, a number of respondents highlighted in their feedback that the temperature was either too warm or too cold. This suggests that there might be an issue with temperature stability and distribution across some parts of the buildings.

Based on comments from a number of respondents, the warm temperatures are mainly due to direct solar radiation gains. In most of the cases, the opening of the windows was not enough to offset the solar heat gains giving strength to the arguments regarding the low ventilation levels achieved in some rooms. This seems to only affect rooms that receive direct solar radiation and therefore additional shading with blinds or different type of curtains, should be considered for these rooms (there was one comment suggesting that the curtain is not blocking enough sunlight). High quality window films could also form a solution, if it is proven that a large number of rooms are affected. Poor use of the manual radiator controls could also be contributing to the temperature variability issue.

There were a limited number of respondents that found that heating in winter is not sufficient (votes: “too cold”, “a bit too cold”). Given the small percentage of these cases, this is most probably related to individual preference. Specifically in buildings with such large diversity of climatic and cultural backgrounds of occupants, individual preference is expected to have a significant role [17].

During the heating season most of the rooms were heated to internal temperatures well above the 19 °C, which was the design minimum. The box plots in **Figure 7** include the period of the Christmas break when some of the occupants seem to have turned off the radiators while away.

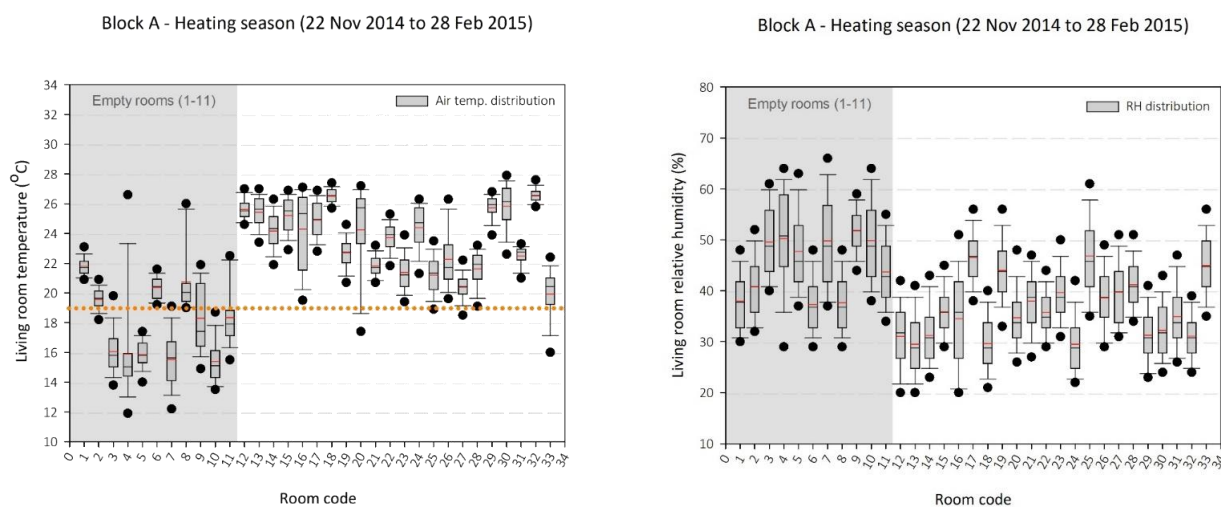


Figure 7. Box plot of the 5 minute temperature (Left) and RH observations (Right) collected from Block A during winter. Rooms 1 to 11 (shaded box) were occupied or heated towards the end of the shown period. The design minimum temperature in winter was 19 °C (shown with orange dotted line).

Results from Block A are discussed here as representative of the total sample. Most of the rooms in Block A that were occupied in September 2014 (room code 1,2,12 – 33 in **Figure 7**) had temperatures above 19 °C during 95% of the measurement period in winter. Rooms coded as 1 to 11 (grey shaded area) are shown as reference for the conditions in the accommodation units when not occupied. These rooms were empty during the first term due to works taking place in Block A. Most of them were occupied or heated after the end of the works which explains the low temperature values and the large range of the observations (**Figure 7**).

There is no evidence that room temperature levels in Block A were affected during winter by the building floor level. In several rooms the variation of temperature is small ($< 4^{\circ}\text{C}$) indicating stable internal conditions at all times. Large variations can be the result of occupants' use of the thermostatic radiator valve (TRV) settings and manual control of the window. In general, high variation of internal temperatures at the Mayflower Halls could be associated with thermal discomfort reported by some occupants. Large variation can also be seen between rooms, with average room temperatures ranging from approximately 21°C to 27°C . Such a range could be due to interpersonal differences, which points to a need for personalized thermal comfort approaches and solutions [18,19].

Almost half of the rooms occupied in September 2014 had a temperature above 24°C in at least 50% of the monitored observations. According to CIBSE Guide A recommendations, an operative temperature of maximum 24°C is the threshold for considering a risk for overheating during winter [20].

Relative humidity (RH) has a negative correlation with air temperature and it is expected to follow the temperature patterns. In general, RH becomes important for thermal comfort during periods of high temperatures when the evaporation of perspiration is hindered [20]. Most of the rooms in Block A have RH levels towards the lower end of the 30% to 60% region (Figure 7).

It is pointed out that the temperature in the accommodation units remains stable over a 24-hour period (Figure 8). The small peaks can be associated with internal heat gains and any troughs with room ventilation and the occupation profile. The rooms with a temperature in the region of 14°C are the unoccupied rooms. There is no evidence that the unoccupied rooms were heated to some extent but the stable conditions show the high level of the buildings' airtightness. The majority of the rooms have temperatures above the internal temperature design target of 19°C . The two rooms (marked with red and dark red lines) with temperature near the 19°C threshold could have these conditions due to the occupants' personal preference.

Block A - Coldest day in January 2015 (20 Jan 2015)

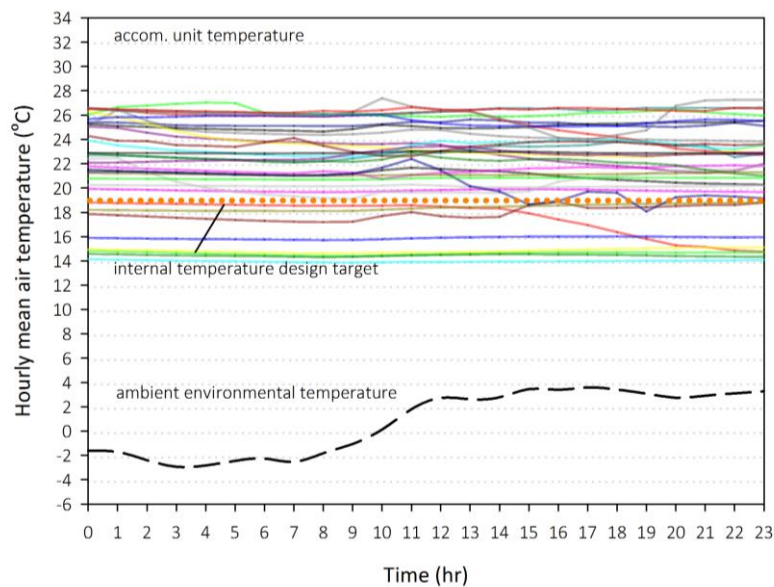


Figure 8. Comparison between the temperatures of the accommodation units (colour lines) in Block A and the environmental temperature (black dash line) for the coldest day in January 2015. The internal design minimum temperature is shown with the orange dotted line.

4.3. Occupant interaction with building controls

Responses to questions on the use of indoor environmental controls, specifically the use of the radiator controls (thermostatic radiator valve settings), window opening, the use of curtains and artificial lighting, show a noticeable diversity in the behaviour of the occupants (**Figure 9**).

In the case of windows and curtains, there appears to be an increased engagement with the controls available. The majority of respondents interact with the windows and the curtains daily or more than once a day. The use of the radiator controls (noted as “Heater”) shows a relatively even spread across all choices, with the majority reporting using the heating controls less than once per month (“never”) (**Figure 9**). This behaviour agrees with the guidance in the Building Log Book [21], which states: “Set thermostats to the required temperature then leave them alone. Do not use them as ON/OFF switches”. However, it is also evident that occupants have not pre-set the thermostatic radiator valves to the required temperature setting. If the TRV setting was turned to maximum and it has never been adjusted then it could explain any complaints and the existence of high room temperatures.

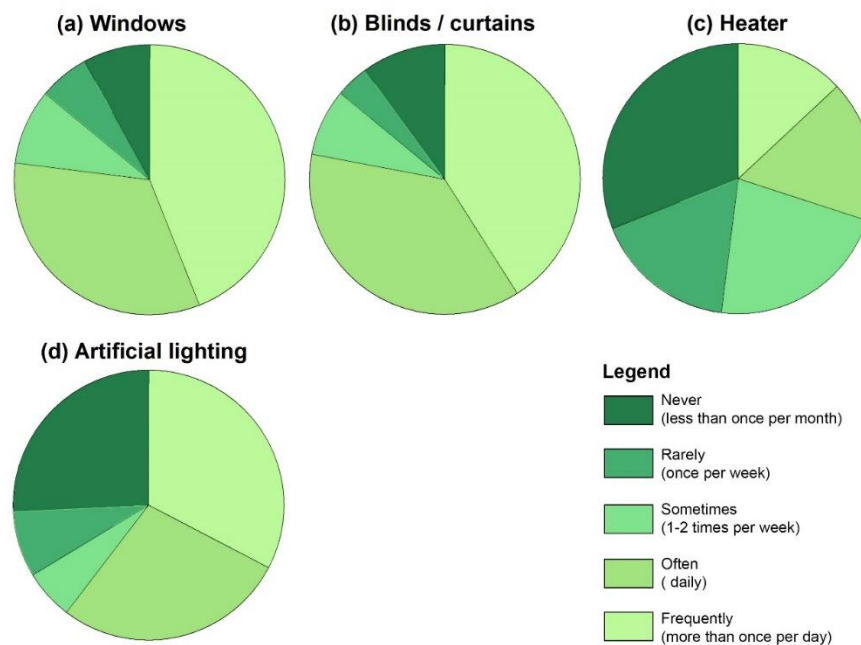


Figure 9. Occupant responses about the frequency of use of indoor environment controls.

4.4. Thermal comfort and interview responses

In the thermal comfort surveys, the most frequently mentioned area of concern for the residents was temperature in the room with 8 respondents reporting the room being ‘too warm’ and 4 participants mentioning specifically lack of air movement or ventilation as the main reason for this. This is further emphasised by the use of fans purchased by the students themselves – one reporting use every night and the other during warmer months only. Additionally, 2 other residents found that the air movement conditions in the room were too still when the window is closed and too draughty when open implying the inevitable variation in air movement levels based on location in the building (orientation and floor level).

The concerns regarding ventilation and temperature mentioned in Section 4.2 were confirmed by the measurement of thermal comfort parameters such as air temperature, radiant temperature, relative humidity and air speed during the interviews. The measured room air temperatures were between 21 °C and 26 °C, with an average of 24.5 °C (standard deviation = 1.2). The two highest readings (26.2 °C and 26.7 °C) correspond to interviews that took place at 10:30 in the morning on sunny days, when the maximum outdoor temperature reached 17 °C. The operative temperature during the interviews was

obtained with a 50 mm globe thermometer probe. The operative temperature provides a realistic measure of a person's temperature perception (feeling) [22]. It is a function of the air temperature in the room, the radiant effects of the structure and air speed [23]. The operative temperatures were compared to the EN 15251 recommended comfort bands and overheating thresholds [24]. These were derived using the exponentially weighted running mean outdoor temperatures for the survey days, calculated from daily mean temperatures. This method applies to buildings in free-running operation such as Mayflower Halls during the interviews.

Figure 10 shows the room operative temperatures against the calculated comfort band and overheating threshold for each of the 9 days of the interview survey. The majority of data points (18 out of 30) lie within the comfort band, 20% are above the comfort band but below the overheating threshold while 20% exceed the overheating threshold. Each data point is the average of 20 half-minute measurements (10 minutes). Given that the interviews took place in the beginning of May with mean daily outdoor temperatures at around 10 °C, the proximity of the operative temperatures to the overheating threshold suggests that there might be a risk of overheating in the building during warmer periods.

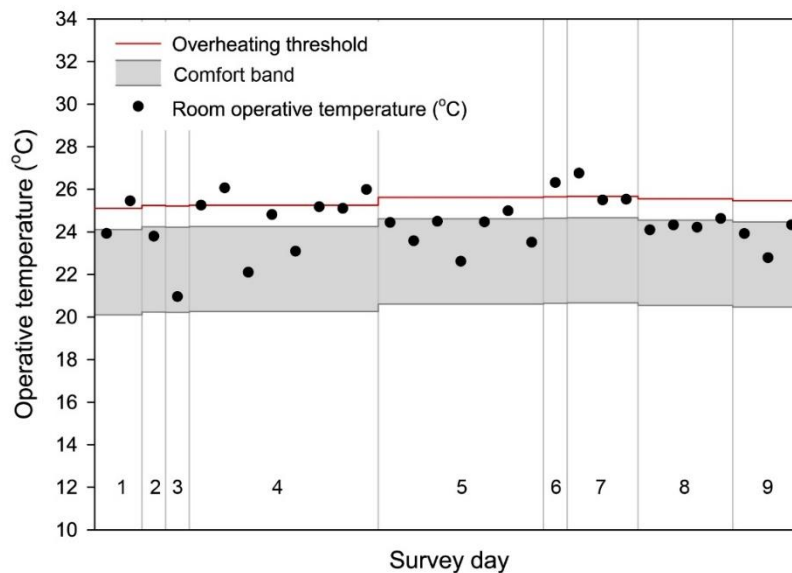


Figure 10. Observed room operative temperatures against the calculated comfort band and the overheating threshold for the 9 days of the interview survey in May.

The radiant temperature during the interviews was almost equal to the air temperature, with an average difference of -0.02 °C (standard deviation = 0.2). The radiant temperature was in most cases slightly lower than the air temperature in the room. On sunny days the opposite was observed; however the difference remained small (max difference = 0.5 °C). This suggests that the building's insulation and surface materials regulate the radiant effect of room surfaces, which can otherwise cause thermal discomfort under cold or hot weather conditions.

The measured air speeds during the interviews were generally very low. In 80% of the sessions the windows were shut and there was no air movement. However, even in the cases where the windows were open, air speeds remained low (less than 0.1 m/s). Although this means that there is a low risk for draughts to occur, such air speeds also indicate that ventilation rates might be insufficient. This was also pointed out by a number of questionnaire responses, results of the environmental monitoring and interviewees, as mentioned in previous sections.

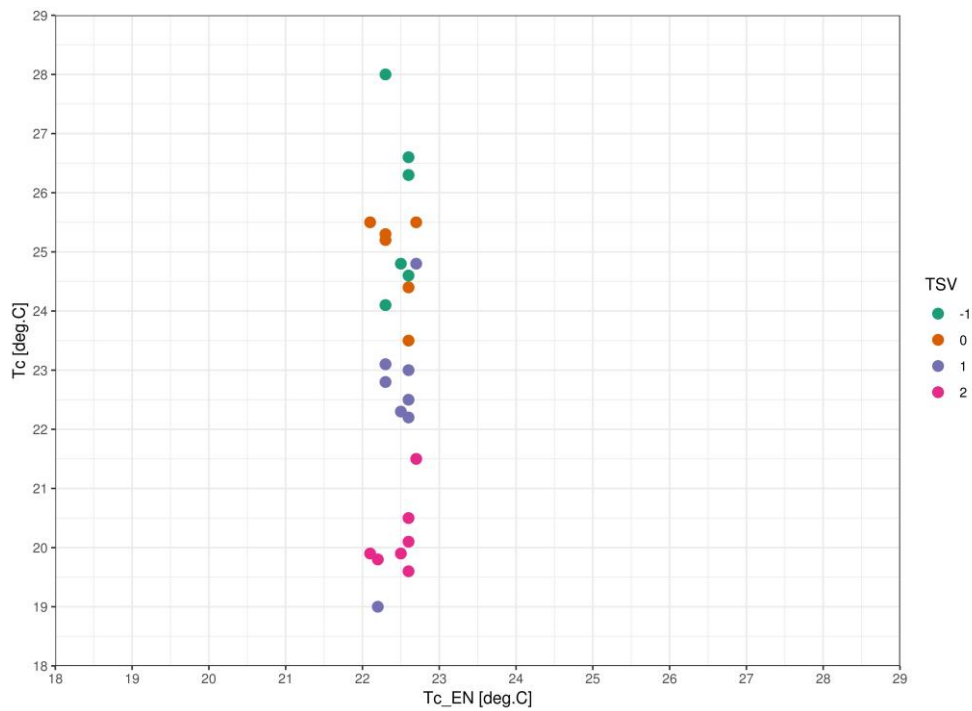


Figure 11. Relation between the comfort temperature estimated with EN15251 (T_{c_EN}) and calculated using Griffiths method (T_c) grouped by the thermal sensation responses (TSV, -2: too cold, 0:neutral,+2:too warm).

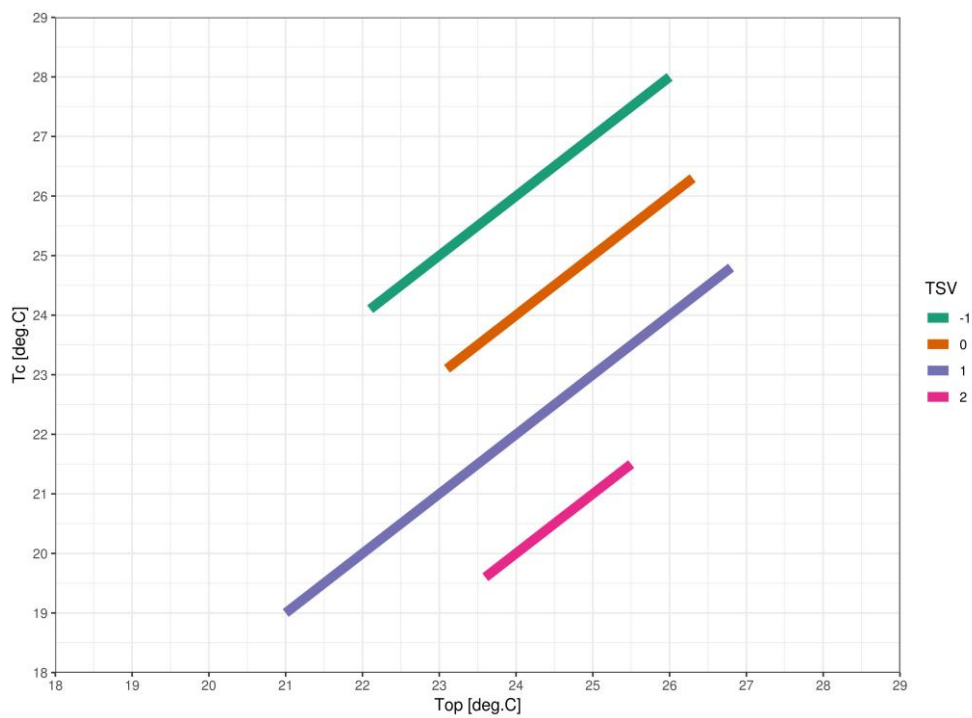


Figure 12. Relation between the operative temperature (T_{op}) during the surveys and the comfort temperature calculated using Griffiths method (T_c) grouped by the thermal sensation responses (TSV, -2:too cold, 0:neutral,+2:too warm).

The comfort temperature (T_c) during the interview – thermal comfort surveys was calculated using Griffiths method with a constant value of $G=0.5$ (Eq.1) [17,23]:

$$T_c = T_{op} - TSV/G$$

where $G=0.5$ is the Griffiths constant.

From Eq.1 it can be seen that the comfort temperature is equal to the operative temperature adjusted for the personal thermal sensation.

In a first step, T_c was compared with the comfort temperature estimated using EN15251 (T_{c_EN}) [24]. **Figure 11** shows the relation between the two comfort temperature calculation methods grouped by the thermal sensation votes (TSV) of the participants. As can be seen, the T_{c_EN} has a very small range from 22 °C to 23 °C due to its dependence on outdoor temperature that did not vary much over the 9 survey days. However, the T_c , which depends on occupants' actual responses (see Eq.1), ranges from 19 °C to 28 °C. In order to better understand the interaction of occupants with building controls it is necessary to understand the relation of individuals' T_c to objective measures such as T_{op} and subjective factors which could explain the large variation in thermal preference.

Figure 12 shows this relationship between comfort temperature (T_c) and the operative temperature for different groups of TSV. The common operative temperatures for the different TSV clusters and the range of T_c is an indication of the diversity of individual thermal sensation and the interaction of psychological and contextual factors [25].

5. Conclusions

This study reports and analyses the observations from a hybrid, diagnostic POE approach towards the understanding of the dynamic interaction of occupants with the building's controls in free-running buildings. In addition, it demonstrates the challenges of designing, managing and evaluating the performance of buildings with occupants from a diverse cultural and climatic background and a highly variable occupancy profile.

While it is important to acknowledge the concerns of the residents as highlighted by the in depth interviews it should be noted that the number of concerns was small which indicates, as do results from the structured questionnaire, overall satisfaction with the living environment. Overall, there is a high level of satisfaction with the buildings' space layout and facilities. The building scored very well with regards to its location and the proximity to the city centre and the railway station. Artificial lighting and daylighting levels were found to be adequate and most of the occupants are satisfied with the lighting conditions.

The questionnaire responses pointed out that the majority of the occupants are satisfied with the air temperature in the rooms. However, there are 30% who find the temperature "a bit" or "too hot". These responses are supplemented by comments on limited ventilation rates and air movement. Overall, the percentage of those that voted "too still" is quite low (14%) to suggest that there is a general, large problem with ventilation in the buildings. High temperatures in summer were explicitly associated with direct solar radiation and solar heat gains. The considerations on air temperature and air change rates have been confirmed by the environmental monitoring results. The observations show several cases with high internal temperatures for prolonged periods both in winter and in summer.

During the heating season, most of the rooms were heated to internal temperatures well above the 19 °C that was the design minimum requirement. Almost half of the monitored rooms had temperatures above 24 °C for at least 50% of the observation period. According to EN15251 standard [24] recommendations an operative temperature of maximum 24 °C is the threshold for considering a risk of overheating during winter. That has the meaning of increased discomfort for the occupants. It has been pointed out that the occupants of this type of buildings such as the Mayflower Halls have a very mixed climatic background and diverse perception of thermal comfort conditions [17]. The high degree of satisfaction with temperature (~60%) can mean that occupants prefer the temperature at these high

levels. The negative responses in winter can only be attributed to improper control of the thermostatic radiator valve (TRV) and poor understanding on how the radiators work. In addition, the proper function of the thermostatic control needs to ensure unobstructed airflow through the TRV head. Lastly, thermal imaging in winter revealed excessive heat losses through open windows at night that could be attributed to increased discomfort due to the high temperatures measured in several cases.

The results from the thermal comfort assessment in the interviews show that the majority of rooms in this small sample (18 out of 30 rooms) lie within the comfort band, 20% are above the comfort band but below the overheating threshold while 20% exceed the overheating threshold. Given that the interviews took place in the beginning of May with mean daily outdoor temperatures around 10 °C, the proximity of the operative temperatures to the overheating threshold suggests that there might be a risk of overheating in the building during warmer periods. Rooms towards the top floor have a higher mean temperature than the rooms in lower levels. Similarly, the comparison between south and north orientated rooms shows that the temperature in rooms with a south orientation is more sensitive to the room's floor level than it is for a north orientated room. The effective air change rates achieved by the open windows in summer are estimated to be at the region of 0.6 air changes per hour (ACH) [26]. The extractor fan could increase the ventilation rates to 2.5 – 3 ACH but this rate is still quite low to achieve effective natural ventilation night-time cooling of the building and avoid high temperatures during daytime.

The evaluation of thermal comfort and adaptive opportunities in the context of this study leads to the following three main conclusions.

First, it is pointed out that there is not a single-point temperature setting that would satisfy all the participants in the study. In free-running, residential buildings, the indoor environment related adaptive opportunities of individuals rely on the accessibility and functionality of manually operable systems, mainly the windows and the curtains/blinds. If the designed function of these systems fails to regulate the indoor conditions to meet the occupants' preferences then it is highly likely that the occupants' will resort to actions with possibly adverse effects on energy consumption.

Second, this study showed a large variability in comfort temperature that is associated with the diversity in individual thermal perceptions due to the complex interactions amongst physiological and psycho-contextual factors [25]. The results support existing literature on the need for person-centric comfort profiles and their integration into building design and heating, ventilation and air-conditioning strategies.

Finally, dynamic POE could be used as a resilience mechanism by introducing occupant-centered measures that could improve the energy performance of the building and occupants' satisfaction through proactively adapting the indoor conditions and through data informed facility management. The results indicate that the presented staged approach can inform technology innovators, building developers and facility managers about the user controls design and the occupants' response to the indoor environmental conditions. Future research will look further into the generation of personal comfort models and the use of POE feedback for the generation of local specific, occupant centric indoor microclimates.

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