A Sociotechnical Perspective on Winter Window Opening and Heating Controls in Purpose-Built Student Accommodation

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Abstract

There has been significant investment in purpose-built student accommodation (PBSA) across the UK. A case study research design was used to investigate the in-use performance of two recently built PBSA developments by monitoring indoor environmental quality, radiator use, and window opening, alongside semi-structured interviews with the building's residents. The results showed that during the heating season the study participants typically controlled the conditions in their bedrooms by opening their windows regularly, often for long periods, and frequently whilst the heating was on. Five behavioural causes of consistent winter window opening were identified. These were to prevent overheating, inadequate ventilation, poor understanding of the controls, lack of responsiveness of the heating system, and lack of financial implications. Important lessons for the future design of PBSA are identified.

Keywords
Student accommodation; overheating; indoor air quality; window opening; heating controls; occupant behaviour.

1 Introduction

The release of greenhouse gases (GHG) from human activity is increasing global average surface air temperatures, disrupting weather patterns, and causing ocean acidification [1]. The UK faces increased risks from a warming climate that are widely considered to be significant [2]. As part of the global effort to decrease GHGs the UK Government is statutorily committed to delivering net zero GHG emissions by 2050 [3].

In the UK buildings have been estimated to account for 47% of total GHG emissions [4]. As such, the decarbonisation of the built environment has been described as a “strategic environmental and infrastructure goal to which there is no obvious alternative” [5]. Therefore reducing energy usage in buildings is widely agreed to be a fundamental component of any realistic scenario to achieve net zero [2].

However, there is a often a gap between anticipated energy usage in new buildings, and the as-built reality [6, 7, 8, 9, 10]. Meanwhile there is also growing evidence that some of the design strategies that have been pursued to minimise thermal losses in buildings may be causing unwanted indoor environmental quality (IEQ) issues, such as overheating [11], and indoor air quality (IAQ) problems associated with restricted ventilation [12].

One method for examining whether the pursuit of low-energy building design is leading to IEQ issues and unintended behavioural responses is to conduct post-occupancy evaluation (POE) studies i.e. to investigate how real buildings are performing in practice. This evidence is essential for feedback purposes; allowing performance successes to be built upon, and repeat mistakes avoided [13].

One building type that may be particularly suitable for POE is purpose built student accommodation (PBSA). This is due to three characteristics of the stock; high development rates [14, 15], relatively homogeneous designs [16], and the suggestion that the current designs of PBSA may be leading to overheating issues [17, 18], and wasteful energy practices [19, 20].

However, critical knowledge gaps exist regarding the operational performance of PBSA. For example, it has been suggested that unintended IEQ issues may be causing “the common problem of students opening their windows because residences are being over-heated” [20]. Yet in a comprehensive review of the previous PBSA POE literature no actual evidence (e.g. field-trials) was found to support this statement [20, 17, 21, 22, 23, 18, 19, 24, 25].

As such, suggestions about how PBSA occupants may have been using their windows during the winter months could not be validated. Indeed, it has been suggested that there is a lack of understanding more generally regarding “the dynamics of the relationship between indoor environment, occupant behaviour and energy consumption” [26] in buildings.

Therefore the aim of this study is to address the research gap around winter window opening in PBSA. In the process of investigating this topic, this paper also aims to explore whether occupants can adequately control the indoor conditions in PBSA bedrooms, and what effect their behavioural actions has on the internal environment.

2 Main Content

This paper is split into the following sections. The first section describes the case studies investigated in this paper, while the second section briefly outlines the data collection methods. The third section looks at how the participants controlled the windows during the winter months, while the fourth section investigates the causal factors for the participant's control strategies. The fifth and final section assesses the adequacy of those controls. This is followed by a conclusion that summarises the results, and makes design recommendations for future PBSA.

2.1 The Case Studies

Two PBSA have been monitored in this study. Case Study A (CSA) is a dense, high-rise PBSA, located in central London. Case Study B (CSB) is in a suburban area in South-West England; it is medium rise and contains separated accommodation blocks. Both PBSA have similarities including high fabric efficiency standards, wet heating systems and top-hung (restricted opening) windows.

However, they also have several key differences. This includes the ventilation strategy. CSA has a mechanical ventilation heat recovery (MVHR) system, while CSB has mechanical extract ventilation in the clusterblocks, and natural ventilation in the townhouses. The heating controls also differ, with CSB having fully adjustable thermostatic radiator valves (TRV), and restricted heating availability according to a centrally controlled timer. Whereas in CSA the TRVs are pre-set and heating is available continuously throughout the cooler periods.

2.2 PBSA Monitoring

The monitoring of the PBSA took place between November 2017 to August 2018 (CSA) and between November 2017 to June 2018 (CSB). This paper will cover the conditions in both buildings between November 2017 to May 2018. After May the heating was switched off in nearly all of the monitored rooms. There were eleven participants in CSA, and nine in CSB. Each participant's rooms was monitored for air temperature, CO_2 and Relative Humidity (RH), alongside radiator use, and window opening.

The air temperature, CO_2 and RH conditions in the room were monitored using an iBEM B3 device, which is an integrated environmental quality sensor developed by *Tsinghua University* [27]. The specification for each of the sensors can be found in the Appendices. The data was recorded at 1-minute intervals. The devices were attached to the walls of the bedroom, and were positioned to avoid heat sources and out of direct sunlight.

HOBO temperature sensing devices were magnetically attached to radiators in the participant's bedrooms. These were used to infer space heating patterns. They could not quantify the actual radiator temperature, or the amount of energy used. This method was selected because it would have been disruptive and expensive to meter the flow of heat into the radiators in individual bedrooms.

An algorithm was used to determine heating usage based on the temperature profile of the data. This method has been shown to provide usable data in previous studies that have investigated occupants control of heating, see for instance [28, 29, 18].

Window opening was monitored using state loggers, with magnets situated on the window and the frame. These were binary devices, recording only the time at which the window is opened or closed, but not the degree to which it is open. In addition, hourly external temperature and RH data was collected from the nearest met office station for each site.

The participants were also interviewed twice during the winter period. The interviews were used to help understand the participant's perspective on the internal conditions and their behaviour. Semi-structured interview guides were drafted with the specialist help of social scientists within the researcher's department. These were produced to allow questions and prompts to be prepared ahead of time so that all the key content was covered.

A semi-structured approach was selected to provide "reliable, comparable qualitative data", whilst allowing the participants the freedom to "express their views in their own terms" [**?**]. They also allow for "probing", which can provide for "clarification of interesting and relevant issues raised by the respondents" [**?**]. It was felt that fully structured interviews would be too restrictive, and limit the richness of the interview data.

2.3 Indoor Conditions during the Heating Season

The section below examines the internal conditions over the November to May period. The average temperature across the monitored bedrooms is shown below in Figure 1. The faded band represents the inter-quartile range of indoor temperatures.

Figure 1 shows that the average weekly temperature across the monitored rooms in CSA is approximately 25°C, and tended to be both stable, and relatively unaffected by the external air temperature. Whereas in CSB the average weekly temperature varied between

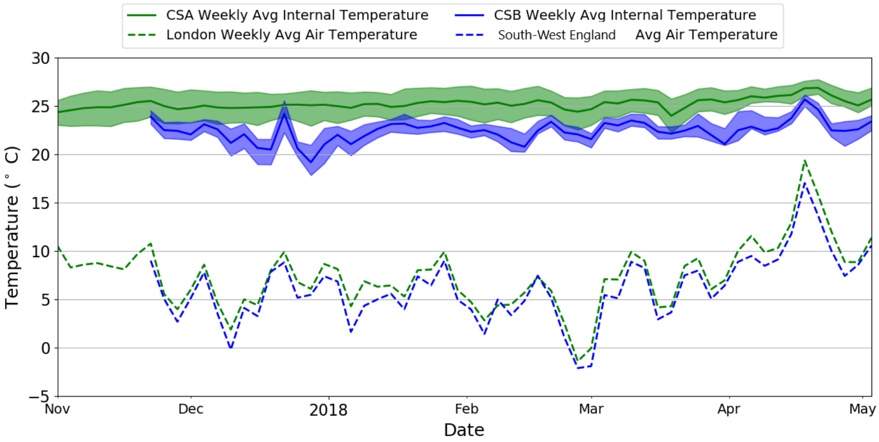


Figure 1: Mean weekly average internal and external temperatures at the case study locations

20°C to 25°C, showed greater fluctuations, and was more responsive to external air temperature.

Figures 2 & 3 show the distribution of hourly average temperatures in all of the monitored rooms over the monitoring period.

In CSA (Figure 2) many of the rooms remained warm for the majority of the period; for instance, 8 of the bedrooms are above 24°C for 80% of the time. In comparison in CSB (Figure 2) many of the rooms were notably cooler, staying within 18°C to 24°C for the majority of the period.

In terms of IAQ, the main area of concern was the naturally ventilated CSB townhouse bedrooms (B1, B2, B3 and B5). High CO_2 concentrations were observed in all of these rooms; the effect was most pronounced at night. Example CO_2 profiles for the CSB bedrooms are shown below in Figure 4.

Figure 4 shows how the CO_2 concentration tended to rise during the night, and then drop in the morning as the participant's opened

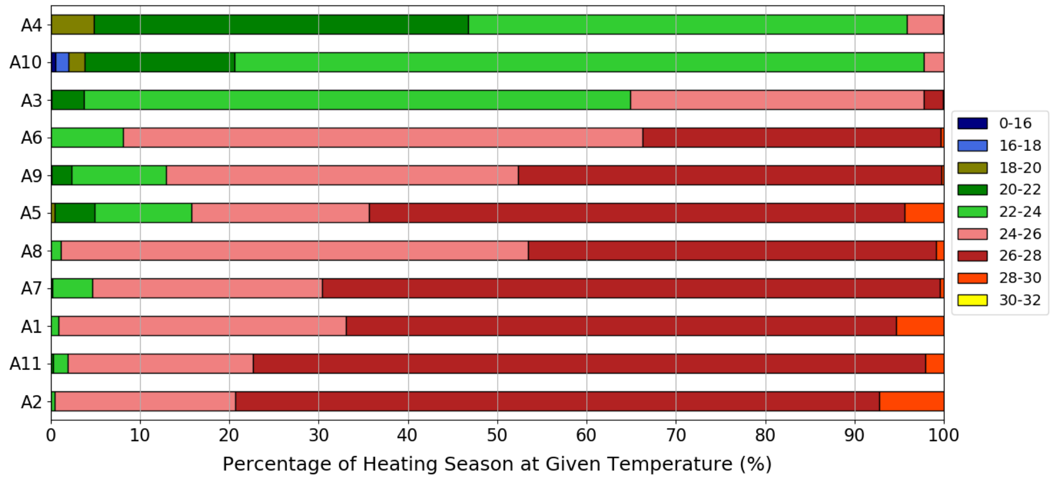


Figure 2: The distribution of temperatures in the monitored bedrooms in CSA over the heating season.

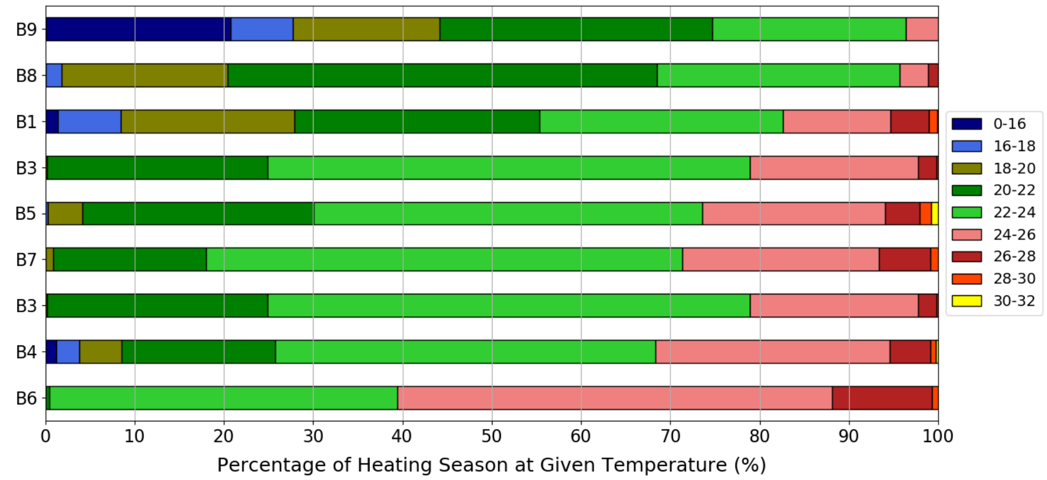


Figure 3: The distribution of temperatures in the monitored bedrooms in CSB over the heating season.

their windows, or vacated their rooms. The precise occupancy of the rooms during the monitoring period was unknown, however during the interviews the participants confirmed that they generally socialised in the communal spaces rather than their bedrooms.

The overnight concentrations in certain CSB rooms were also

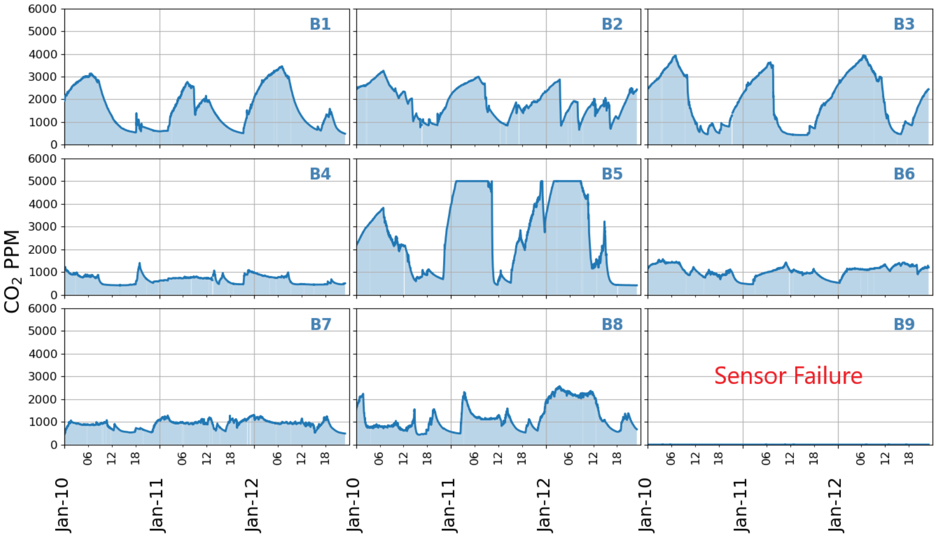


Figure 4: The CO$_2$ concentrations (PPM) in CSB rooms over a 3-day period

consistently high throughout the heating season. This is shown below in a distribution plot (Figure 5). This shows the percentage of nighttime hours (23:00-07:00) during which the CO$_2$ concentration was within a particular band over the November to May period.

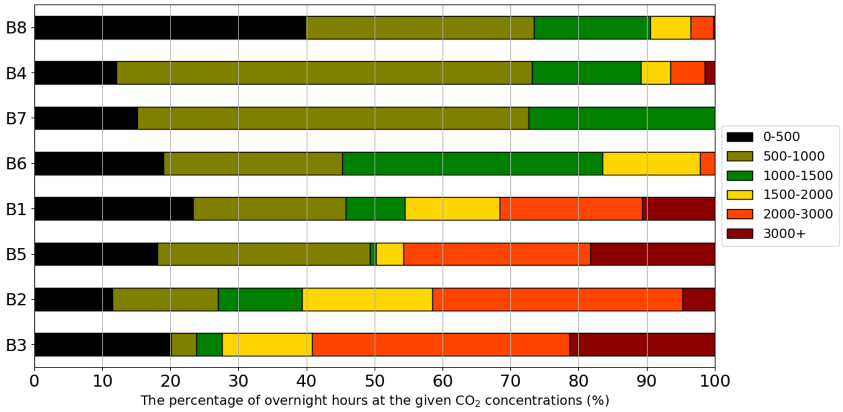


Figure 5: The percentage of overnight hours (23:00-07:00) at a given CO$_2$ concentration (PPM)

Figure 5 shows that 5 of the rooms were above 1000PPM for over

50% of the nighttime hours, while 4 of the rooms are above 2000PPM for 30% of the nighttime hours. The results indicate that the overnight environment in these rooms is likely to have been excessively stuffy, and therefore that ventilation was an issue.

2.4 Participant Feedback on the Conditions

The participants were interviewed twice about the indoor conditions during the heating season. In CSA the main response from the participants was that they were generally comfortable during the heating season. Comments such as “Yeah... it’s been fine... it’s pretty comfortable” were common.

However, several participants did opine that the temperatures were often fairly warm “yeah I do think sometimes in the morning when I wake up it can be a bit hot”, and that this tended to occur during the night “yeh well it can get a bit hot at night, because if you close the window when you want to sleep it’s too hot”.

In CSB the participants also reported being generally comfortable regarding the temperature. However, all of the residents in the CSB townhouses complained vociferously of stuffy conditions in their bedrooms. The comments included “well basically if I ever close my window it will get stuffy”, and “so stuffy, just so, so stuffy” and “it can get very stuffy in here, yeah, like really bad”.

Several of them also commented on how they felt these conditions affected their ability to study “yeah well the air isn’t fresh enough so you get a bit agitated, and then I find it kind of hard to concentrate and study in my room”. Furthermore, many indicated how counteracting stuffiness was also the primary driver of winter window opening (see Section 2.6.2 below).

To summarise, there were two clear trends observed over the November to May monitoring period. Firstly, indoor temperatures were generally warm, and that secondly, most of the study participants reported being comfortable. However, the CSB townhouse participants were extremely dissatisfied regarding the stuffy conditions in their bedrooms. Now that the conditions have been summarised, the rest of the paper will focus on the control of the conditions.

2.5 Winter Window Use

Across both case studies, it was observed that windows were opened regularly, often for long periods, and frequently whilst the heating was on. The quantitative evidence for this can be found from observing window opening and heater usage in the participant's bedrooms.

The percentage of time the windows were open or closed over the November to May period is shown in Figure 6 for CSA and Figure 7 for CSB. The charts also show the total amount of time (in days) that this percentage equates to for a sample of rooms.

Figures 6 and 7 show that in both case studies windows were often open for substantial periods. Indeed, in a quarter of the rooms (across both case studies) the windows were open more than they were closed. Yet, the results also showed significant variation in window opening habits. For instance, in CSA the window opening varied from just 4% of the heating season (A3) to 66% (A7).

2.5.1 Diurnal Variation

The opening of windows occurred throughout the November to May period i.e. it was not just limited to warmer periods. For example,

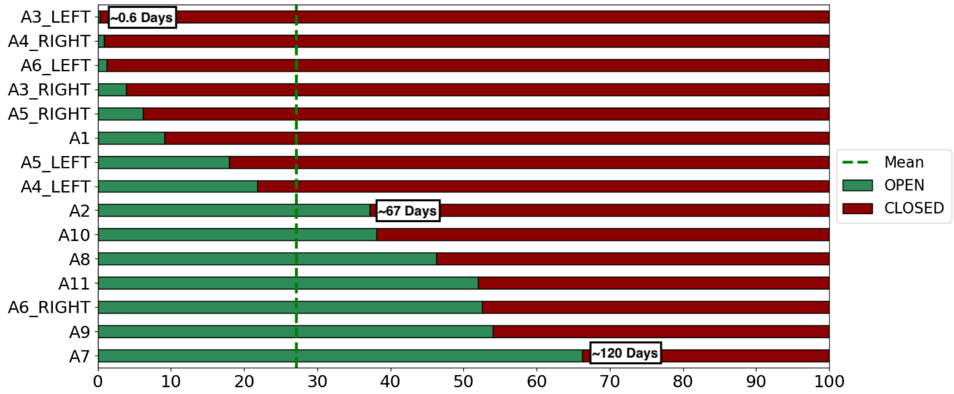


Figure 6: The percentage of the heating season in which the windows were open in the monitored rooms in CSA

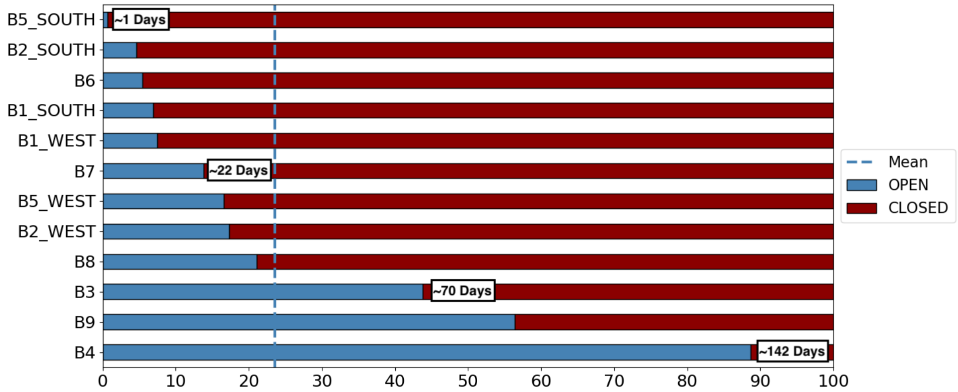


Figure 7: The percentage of the heating season in which the windows were open in the monitored rooms in CSB

the diurnal patterns of window opening are shown below in Figure 8. This chart shows the average percentage of windows open in each case study over a 24-hour period for each month.

Figure 8 shows there to be a clear diurnal pattern to window opening i.e. the likelihood of windows being open increases during the daytime. Yet there is limited variation between the different months.

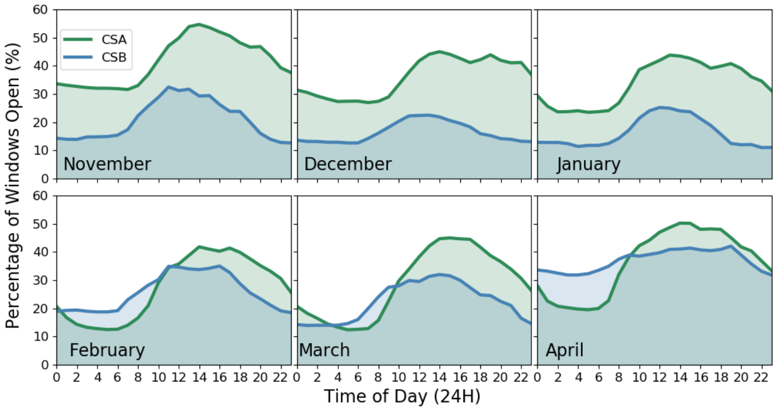


Figure 8: Monthly diurnal window opening profiles. The chart shows the average percentage of windows open in each case study during a 24-hour period

Indeed, in CSA between 2-6PM on average 40% of windows were open throughout the period. This suggests that regular window opening occurred irrespective of the external conditions.

2.5.2 Frequency & Duration of Openings

Alongside determining the total amount of time the window is open, it is important to understand both the frequency (i.e. how often are windows opened or closed) and the duration of the opening events. Therefore Figure 9 shows the number of opening events that fall within particular time bands, while Figure 10 shows the total cumulative time in hours that the window is open within those same time bands.

Figure 9 shows that a significant proportion of all window opening events occur for relatively short periods. For example, in both case studies approximately 50% of all window opening events occur for an hour or less.

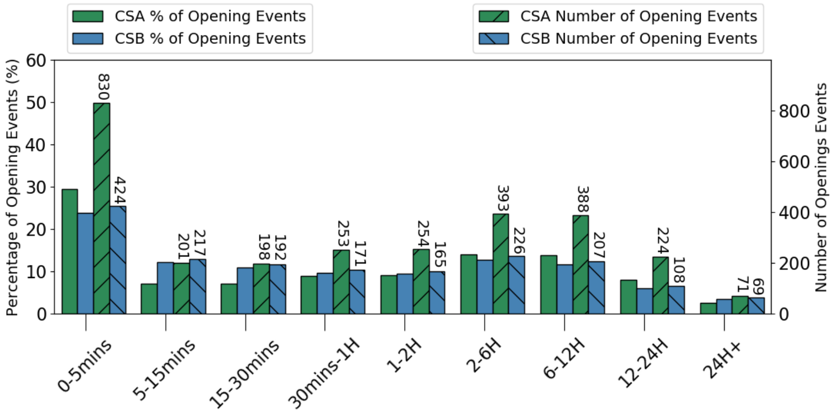


Figure 9: The frequency of window opening events for different time bands

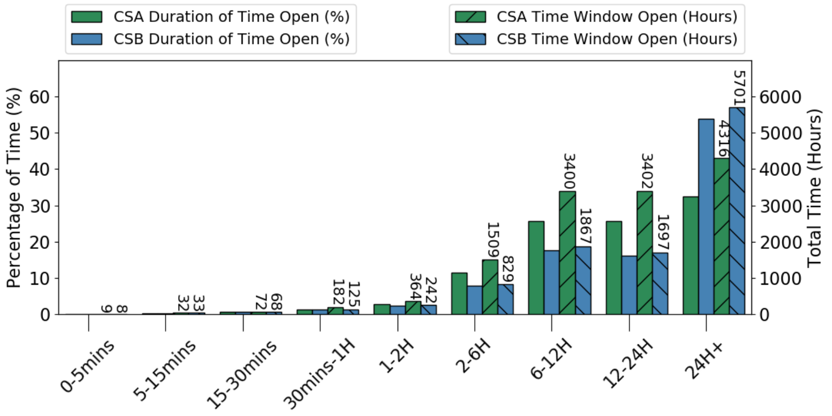


Figure 10: The cumulative duration of the time the window is open for different time band (calculated by summing window opening events within the same time bands)

However, as shown in Figure 10, it is the relatively infrequent longer duration events that cumulatively amount to a large proportion of the total time the window is open. For instance, although events longer than 24 hours make up just 3.6% of all window opening events in CSB, they are responsible for 56% of the cumulative time the windows are open. In other words, while most window openings are short, it is the longer duration events that make up a large proportion of the total time the window is open. This finding has a number of important implications.

Firstly, it shows that for many of the participants maintaining comfortable conditions in their bedrooms was dependant upon having their window open consistently, and not just for short purge events. This is the result of many rooms being persistently overheated (see Figure 2), under-ventilated (see Figure 3) or both. Indeed, many participant's expressed how closing their windows would rapidly lead to poor IEQ.

Secondly, assuming that the ventilation and heating control can be improved, these results suggest that targeting long duration window opening events could be an effective method for limiting thermal losses through open windows. For instance, window opening events of longer than 12-hours were responsible for approximately 65% and 70% of the total time the windows were open in CSA and CSB respectively

2.5.3 Heating On and Window Open

HOBO temperature sensing devices were magnetically attached to the surface of radiators in the participant's bedrooms. Space heating patterns were then inferred using an algorithm developed in similar monitoring studies that have also used radiator surface temperatures to determine heating usage [28, 29]. This method could not quantify the actual radiator temperature, or the amount of energy used, but did indicate whether the heating was likely to be on or off.

Therefore the amount of time during which the participant's had their window open and heating on could be calculated. This is shown in Table 1 for CSA and CSB. For the rooms with two windows the percentage of time that the heating was on and at least one window was open has been calculated.

Room	Total Time Heating on & Window Open in Days (and as % of monitoring period)
A1	11.4 (4.5%)
A2	92.0 (36.0%)
A3	4.7 (1.8%)
A4	41.5 (16.3%)
A5	27.0 (10.6%)
A6	123.9 (48.5%)
A7	183.9 (72.0%)
A8	99.7 (39.0%)
A9	105.4 (41.3%)
A10	71.2 (27.9%)
A11	123.3 (48.3%)

(a) CSA

Room	Total Time Heating on & Window Open in Days (and as % monitoring period)
B1	2.5 (1.6%)
B2	22.3 (14.0%)
B3	23.8 (15.0%)
B4	39.8 (25.1%)
B5	16.9 (10.6%)
B6	1.1 (0.7%)
B7	7.3 (4.6%)
B8	0.4 (0.2%)
B9	14.5 (9.1%)

(b) CSB

Table 1: The total amount of time in days (and as percentage of November to May period) the window was open and the heating was on at the same time in the participant's bedrooms

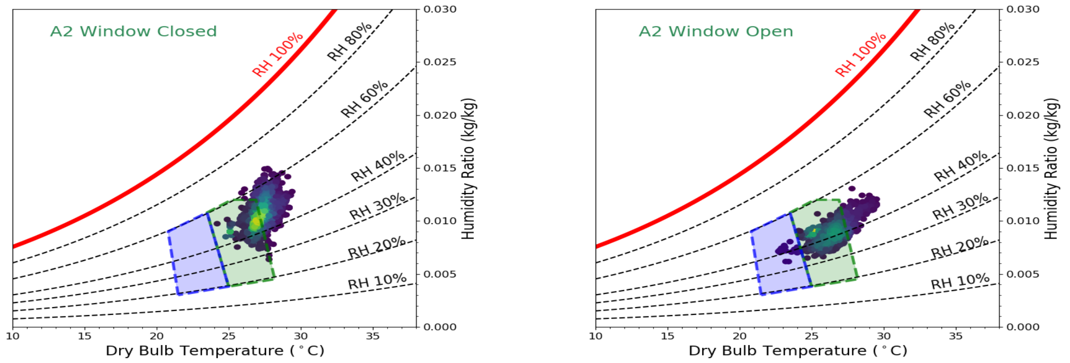
Table 1 shows many participants spent significant periods of the heating season with the heating on and their windows open. The behaviour was more pronounced in CSA in which participants could not turn their heating off (although the TRV set-point should have been restricting flow beyond a certain internal temperature). Therefore the results suggest that, rather than windows being used as a means of last resort for thermal control (in which case you would have expected to see the heating switched off before the windows were opened), they were often used as the primary means of thermal control.

2.6 Thermal Control Causal Factors

As outlined above, many participants used their window routinely during the winter, and often for extended periods. The next section will describe the causal factors that lay behind this behaviour.

2.6.1 Preventing Overheating

In CSA, in which occupants could not control the heating, windows were used to prevent bedrooms from becoming overheated. This can be clearly shown using psychometric charts; separating the times during which the window was open from when it was closed. An example is shown in Figure 11 for room A2.



(a) Window Closed

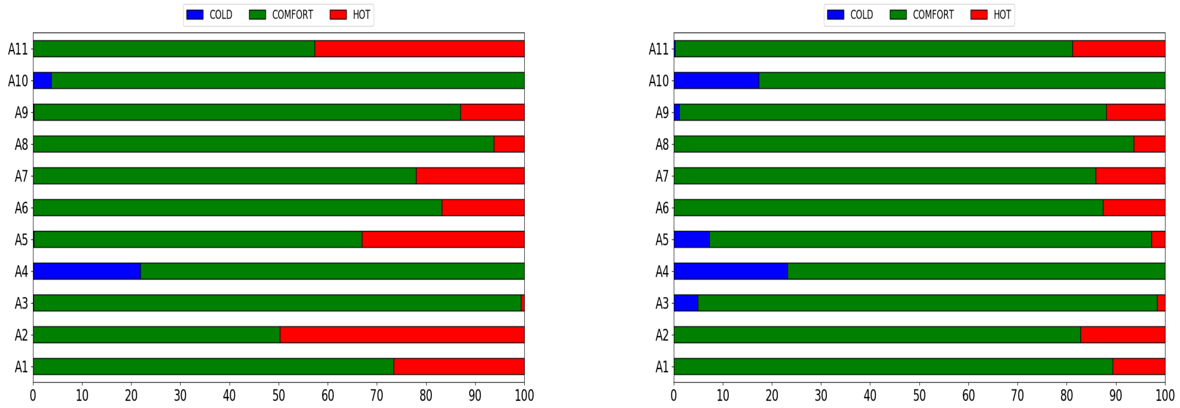
(b) Window Open

Figure 11: Psychometric charts showing the conditions inside room A2 over the period for differing window states. Green area = 0.5 clo comfort band. Blue area = 1 clo comfort band.

Figure 11 shows that the amount of time the conditions are within the comfort bands is greater for when the window is open. Furthermore, according to the participants, clothing levels equating to roughly 0.5

clo were common nearly all year round. Figure 11 shows why this is likely to have been the most comfortable option.

The psychometric charts were used to calculate the percentage of time in which the conditions were within the 0.5 to 1 clo comfort bands when the windows are either open or closed. The results and are shown in Figure 12 for CSA.



(a) Window Closed

(b) Window Open

Figure 12: Charts showing the percentage of time over the monitoring period in which the internal conditions in the CSA bedrooms were within the 0.5 to 1 clo comfort bands for different window states

Figure 12 shows that the majority of the monitored rooms in CSA spend a greater percentage of their time within the comfort band area when the window is open, rather than closed. Thus showing that for many participants the pursuit of keeping their rooms comfortably cool during the heating season depended upon opening their window regularly.

In addition to the empirical data there is also a large amount of supporting qualitative evidence from the interviews. In fact, the majority of participants in CSA expressed how they had to open their windows regularly to prevent winter overheating. For instance, “I have to have my window open or it gets far too hot", and "I mean, if I close my window then it does get hot and it gets hot fast", and "if I shut the window then it gets hot... like really hot".

2.6.2 Inadequate Ventilation

The second causal factor, which affected the CSB townhouse rooms most acutely, was inadequate ventilation. In this case, participants felt that they had to open their windows in order to prevent their rooms becoming overly stuffy. On some occasions, this was despite the thermal discomfort that it caused them. In other words, they prioritised fresh air over some thermal discomfort. The stuffy conditions in the CSB townhouse rooms have been shown above in Figure 3.

The desire to open windows in order to prevent stuffiness, and the corresponding effect on the conditions in the room (and the radiator's response) can be seen by combining multiple variables onto one chart. This is shown below in Figure 13 for room B3 during a period in mid February 2018.

In Figure 13 window opening is shown at the top. The window is open if the area is shaded. CO_2 levels are the shaded area at the bottom of the chart, and are shown on the right y-axis. Internal temperature, radiator surface room temperature, and external temperature are shown on the left y-axis

Figure 13 shows that during the night (when the window is shut) the CO_2 concentration rises to approximately 4000PPM. Therefore during the day, when this participant liked to study in their room, they opened the window to provide more fresh air. The opening of the window then causes a response from the radiator (as the air temperature in the rooms drops the TRV valve opens up to provide

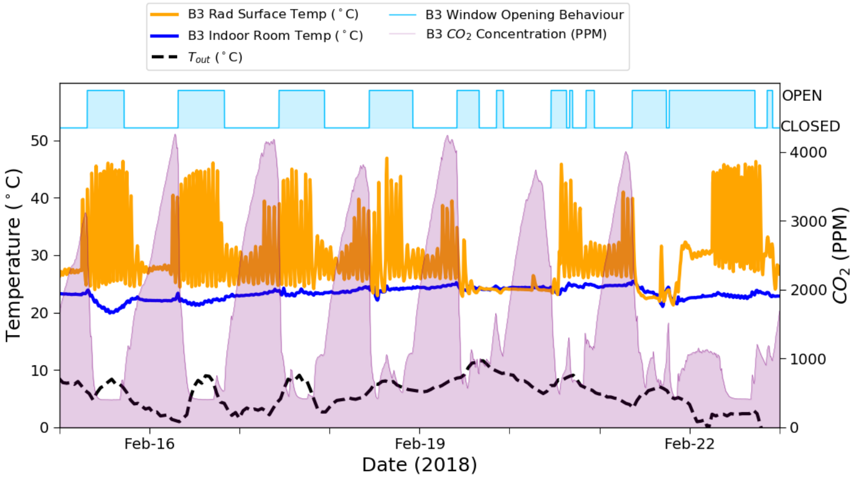


Figure 13: Chart showing frequent window opening, heating usage and stuffy overnight conditions in room B3 during a cold period in February 2018.

heat to the radiator).

In some cases (e.g. February 15th), despite the radiator turning on it is still not sufficient (for a time) to prevent the internal room temperature from dropping. Thus Figure 13 shows how inadequate ventilation is leading to window opening, which in turn necessitates the need for heating to maintain the internal room temperature.

Once again, the opening of windows due to inadequate ventilation was raised frequently during the interviews. For example, “if I don’t have my window open then it gets very stuffy, so I try and have my window open to get fresh air in when I’m in here, but then this can get a bit chilly when I’m working because of the draft, but it’s not too bad”.

2.6.3 Poor Understanding

There is evidence from the interviews that occupants did not properly understand the heating system. In short, in CSA occupants did not know whether they could adjust their heating, whereas in CSB occupants did not know the heating timing schedules, or how their TRVs worked. Thus comments such as “I don’t know how the control thing works and I don’t know what it does” were common.

Another factor that seemed important to residents in CSB was to make sure they received heat when it was available. Hence “well I keep my radiator on all the time because I don’t know when it comes on... and I don’t want to miss out on it in case my room gets too cold”. Thus it seemed for many participants that leaving the heating permanently on felt like the no-lose option. It was the best option for ensuring your room was sufficiently warm, and if it became too warm, then you could just open the window.

2.6.4 Responsiveness

Many participants expressed how they wanted instantaneous thermal change within their bedrooms, and that it was opening the window that provided this. For example, “I use the window to control the temperature because it is just so instant, whereas I turn the knob on the radiator and nothing really seems to happen”.

As such, the behaviour shown in Figure 14 was common i.e. the window being used regularly to adjust the temperature. It can be seen how the temperature decreases when the window is open, but also how quickly it returns to the residual temperature of 27℃ once the window is closed.

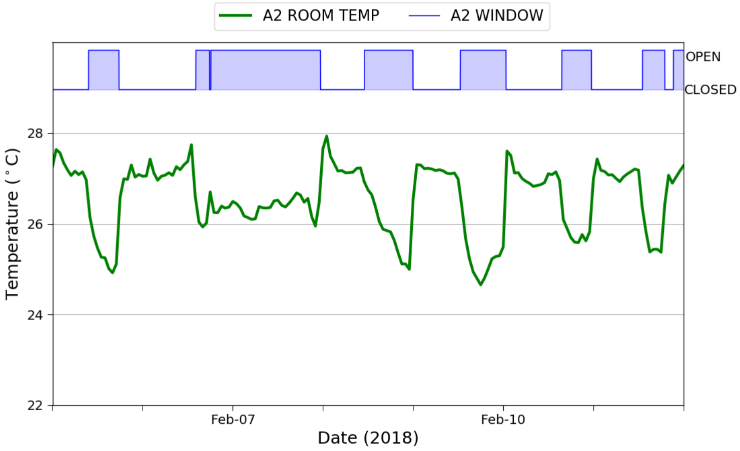


Figure 14: Chart showing the reduction or increase in internal temperature in room A2 during window opening or closing events respectively

2.6.5 Financial Implications

An additional factor that appeared to influence behaviour is the fact that there is no financial incentives (or penalties) for different heating practices. In these PBSA the occupants rental costs are fixed regardless of their energy usage.

The majority of residents were clear that they thought their behaviour would change if they were paying for their energy directly (rather than it be included in the rental fee). For example, “I think if I was paying for my heating that would change my behaviour. Definitely, yeah”.

This can be clearly shown during the occasions in which participants left their rooms unoccupied for extended periods with the window open, and the heating on. An example is shown below in Figure 15.

In Figure 15 the room was unoccupied between the 15th February to midday on the 19th February. This can be seen from the CO_2 concentration, but was also confirmed during the interviews. Over this period the occupant had left their heating on and one of their

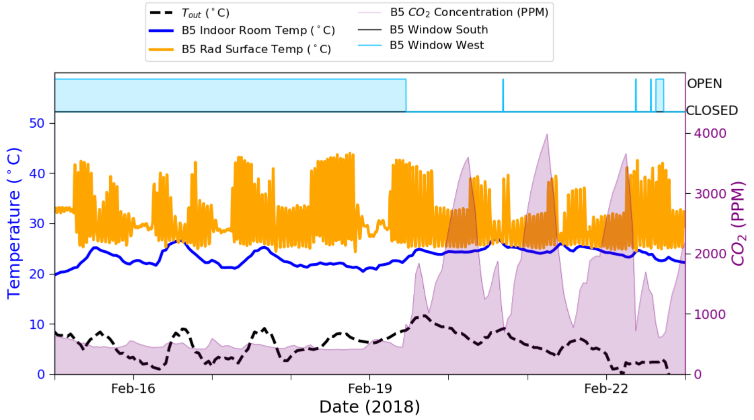


Figure 15: Chart showing the heating on and window open in room B5 while it is unoccupied during the heating season

windows open. Yet there is no financial impact for this behaviour. Similarly, Table 1 shows how frequently the participants left their windows open and had their heating on.

This paper has identified five interacting factors that were the main drivers of the window opening in PBSA. These were to prevent overheating, inadequate ventilation, poor understanding, the desire for responsiveness, and a lack of financial implications.

2.7 The Adequacy of the Controls

This paper has identified a common control strategy that was widely adopted by the participants in both case studies. This was to use windows regularly as a means of both thermal and air quality control. In general the participants suggested that, purely from a comfort perspective, the control strategy was broadly acceptable during the daytime. However, several did suggest that using such a strategy meant that they were frequently choosing between being too warm (with the window closed), or too cool (with the window open).

However, the main problem with this strategy (excluding energy usage implications) was that it did not work for the participants overnight. This was because the majority of occupants did not like to open their windows overnight. This was primarily because of noise, for example “although I find the train is noisy if I open the window. So I have to choose between being hot or having the train noise”. However, there were also other issues raised regarding window opening at night, including insects, pigeons and security concerns.

The other issue was that the windows could not be adjusted whilst sleeping. Therefore many felt that they had to choose between being too hot, or too cold whilst they slept. For example, “well I’m either too warm with it shut or too cold with it open, so I shut it just before getting into bed and hope I fall asleep before it gets too hot”.

There was also near unanimous consensus across both buildings that the participants wanted greater control over the heating system in their rooms. In CSA the complaints were primarily focused on gaining even limited control over the heating system “firstly I would just like to control the temperature a bit. You know when to switch it on and when to switch it off. Particularly when to switch if off”. While in CSB the complaints were primarily focused on the heating schedule and getting too much heat at certain times, whilst receiving insufficient heat at others, e.g. “you are always worrying about what time it turns on and off and then timing it correctly to heat up your room at the right time”.

In addition, when asked how greater control would affect their heating usage, the majority of the participants suggested they thought they would use less heating. For instance, “I would definitely turn it off during the day, so then I wouldn’t have to leave my window open to not return to a sauna”, and “I would use less heating because if I went out for a long time then I would turn the heating down, or even off".

To summarise, analysis of the interviews highlighted several clear themes, such as the preference for more control, confusion at how the controls work, the unfairness of centrally controlled systems, and that using the window for thermal control was an ineffective strategy overnight.

2.8 Conclusions

In previous studies there have been assertions made about how occupants may use their windows regularly during the heating season in PBSA e.g. [23, 20]. Yet this has never been validated. This study confirms that in these two particular PBSA case studies the majority of participants used their windows regularly, and for long periods throughout the heating season.

The findings suggest this was primarily done for two main reasons; to prevent overheating, or to provide sufficient ventilation to achieve adequate IAQ. There were other aspects that also were also important, such as responsiveness, confusion and lack of financial implications.

All these factors appeared to confound one another, leading many participants to simply give up on interacting with their heating system altogether. Instead, they opted for the simplest strategy; leaving the heating on one setting, then adjusting the temperature via the window. Indeed, in the case of CSA, there was no obvious alternative to this strategy.

The study suggests that centrally controlled wet-heating systems with TRVs in individual rooms did not provide adequate thermal control for either occupant satisfaction, or efficient use of space heating. This was evidenced by the fact that participant satisfaction with the controls was low, and the majority of the rooms were over heated during the heating season. There were also examples of rooms being heated for extended periods (i.e. multiple consecutive days) while they were unoccupied.

Although energy usage implications were not directly quantified in this study it is likely that the observed window opening behaviour had a negative impact on the thermal performance of the PBSA. It is also likely that this may negate some of the efficiency gains from fabric improvements; for instance there is limited benefit in a “fabric first” approach if the fabric is routinely opened.

Overall, the results suggest that heating controls in PBSA need to provide a number of key characteristics, and that the heating systems in these particular case studies (i.e. wet-heating systems with TRVs) often failed to deliver these. Firstly, the results suggest that the individual heating systems in new PBSA, built to modern energy efficiency standards with small study bedrooms, do not need to deliver lots of heat (providing windows are not used regularly). For instance, bedrooms in which heating was rarely used did not see significant falls in temperature.

The findings from the interviews also suggested that the heating system should be responsive (occupants reported wanting instantaneous change), easily understandable (the majority of participants did not fully understand their heating system), and capable of switching off to prevent overheating. In addition, preferably the controls should help conserve energy by preventing the heating of spaces which are unoccupied or where windows are open.

It is this author’s view, that the characteristics required of the space heating systems in PBSA would be best served by relatively small resistance heaters (e.g.1-2 kW). These would be linked with individual thermostats in each room to control the heating at a certain internal temperature set-point (e.g. 22℃). More localised controls should help reduce the amount of winter overheating, as was shown to affect CSA in particular.

These heaters should also be installed with timers. These would turn-off the heater after a certain time period, unless the occupant chooses to re-activate it. This should help to prevent the heating of unoccupied spaces for long-periods, as was shown to occur in Figure 15. In addition, as long as the ventilation is adequate, the heating controls could also be linked with automatic relays in the windows. These would prevent the window from being open and the heating being on at the same time, as occurred regularly in these two case studies (see Table 2.5.3).

Finally, electric resistance heaters would also reduce the amount of hot water pipework in the buildings. This should help to conserve energy, while simultaneously helping to address both winter and summer overheating. The elevated bathroom and corridor temperatures throughout the monitoring period suggested that high internal gains were an issue. Furthermore, as renewables continue to constitute a greater proportion of electricity generation over the coming years [2], the carbon emissions of electrically heated buildings should continue declining relative to gas (providing that they are well-maintained and managed).

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2.9 Appendices

2.9.1 Monitoring Equipment Specifications

Table 2: iBEM Temperature Sensor Parameters

Measurement Range	Dry-bulb temperature: -40 $\sim$ 80°C
Measurement Accuracy	$\pm 0.3^{\circ}$C
Resolution	0.01°C
Response Time	5s

Table 3: iBEM Humidity Sensor Parameters

Measurement Range	Relative Humidity: 0 $\sim$ 99%
Measurement Accuracy	± 5%
Resolution	0.04$\%$
Response Time	5s

Table 4: iBEM CO^2 Sensor Parameters

Measurement Range	400 $\sim 5000PPM$
Operating Temperature	0 $\sim 50^{\circ}$C
Measurement Accuracy	$\pm(70PPM \pm 5$%$)$
Resolution	1PPM
Response Time	2 minutes

Table 5: HOBO Temperature Sensor Parameters

Measurement Range	Dry-bulb temperature: -20 $\sim$ $70°$C
Measurement Accuracy	$\pm 0.35°$C
Resolution	0.03°C
Response Time	6 minutes

Table 6: Window opening state logger parameters

Specifications	**Value**	**Units**
Time between events	200	ms
Time between state changes	500	ms
Time between event counts	50	ms
Timing accuracy	± 3	secs per 24hr
Operating temperature range	-35 to 80	°C
Typical Battery Life	1	year