PLEA 2017 EDINBURGH
Design to Thrive

Thermal comfort and overheating investigations on a large-scale Passivhaus affordable housing scheme

Andrea Botti[1]
[1] Centre for Environment and Sustainability, Faculty of Engineering and Physical Sciences, University of Surrey, Guildford, UK, a.botti@surrey.ac.uk
PRP, Lindsey Street, London, UK, a.botti@prp-co.uk

Abstract: The uptake of the Passivhaus standard has rapidly increased in the UK during the recent years, in line with the improvements in the energy efficiency standards for new dwellings.
This paper builds upon a recently completed post-occupancy study for a Passivhaus-certified large-scale affordable housing development, specifically focusing on summer thermal comfort. Assumptions and predictions of overheating risk made at the design stage are analysed and compared with the indoor temperatures measured during summer 2015.
In this study, interviews and questionnaires are overlaid with quantitative data in order to explore occupants' comfort perception and improve the understanding of the inter-relationships between aspects of building design, occupant behaviour and the risk of overheating.
The analyses showed a high frequency of overheating, diverging significantly from the estimates made using the PHPP tool. This is due to a combination of factors, such as higher internal heat gains arising from higher occupant density and usage of internal appliances and, in some cases, insufficient reliance on natural ventilation to purge excess heat. Given the difficulty in predicting in-use occupancy patterns at the design stage, a more robust design strategy is recommended, which could include measures to minimise summer overheating and future-proofing against a changing climate.

Keywords: passivhaus, PHPP, overheating, monitoring, post-occupancy-evaluation

Introduction

There has been an increasing up-take of housing schemes built to Passivhaus standards in recent years, in line with Government policy trends that have encouraged improvements in the energy efficiency standards for new-build developments. In an effort to tackle fuel poverty, which still affects 10.6% of English households (DECC, 2016), social housing developers are expected to be the frontrunner for building energy efficient for their social renters (McManus et al., 2010).

Buildings designed and built to Passivhaus standards are considered to be highly energy efficient, due to a highly insulated and airtight building envelope, as well as to the optimisation of passive solar gains and heat generated from building occupants (McLeod et al., 2011). While these measures can significantly reduce the energy use as well as improve thermal comfort in the winter months, a growing body of literature suggests that unintended consequences may arise during the summer months, contributing to the risk of indoor overheating (Dengel & Swainson, 2012; McLeod et al., 2013; Jones et al., 2016).

Despite the recent adoption of the Passivhaus standard in the UK (Passivhaus Trust, 2016), a growing number of research studies are focusing on the overheating assessment of

Passivhaus buildings, by means of both thermal simulation modelling and of in-use data monitoring (McLeod et al., 2013; Sameni et al., 2015). The risk of summertime overheating has been documented for Passivhaus buildings in Northern Europe (Larsen & Jensen, 2011), and it has the potential to be severe in the UK as a result of climate change (Jenkins et al., 2009). For Passivhaus built in urban locations, McLeod et al. (2013) warned that active cooling may become a requirement in the near future, unless the minimisation of future overheating risk becomes a key design objective.

In order to obtain Passivhaus certification, designers have to consider summer thermal comfort and are required to provide evidence the risk of overheating is minimised. However, the assumptions made in the PassivHaus Planning Package (PHPP) design tool are often standardised, thus they may not accurately reflect the conditions observed in reality. Opening windows for purge ventilation may be limited or not at all possible in urban locations. Furthermore for certain types of occupancy, such as social housing tenants in the UK, research has suggested that occupant density and internal heat gains may be significantly higher than the standardised assumptions included in the PHPP (McLeod et al., 2013). As it has emerged in the recent years, building overheating is a complex issue and there is a lack of conclusive evidence on how the risk predictions produced using simplified methodologies compare to the in-use performance (ZCH, 2015).

Methodology

Case study

This paper builds upon a recently completed POE project carried out for an affordable housing scheme, located in the London Borough of Havering and completed in 2015. The scheme is one of the first large-scale 100% affordable Passivhaus-certified housing developments in the UK, with a total of 51 dwellings, comprising one-bedroom and two-bedroom flats, and three-bedroom and four-bedroom terraced houses.

The study involved monitoring a sample of 9 homes during the first year of occupancy (Table 1), in order to gain an understanding of residents' experiences and behaviour. Both quantitative and qualitative methods were used, where environmental data was collected from the main rooms and questionnaires were prepared for the purpose of conducting in-depth interviews with the residents. By overlaying the two information sets, a rounded understanding of the relationship between building performance and occupant behaviour was gained, including how far different behavioural patterns deviated from the typical design assumptions. This paper narrows down the broad focus of the POE project to look more specifically at summer-time thermal comfort. The extent of indoor overheating is assessed for monitored temperatures and compared to the predictions made at the design stage, allowing to quantify the performance gap and to identify the main causes for it.

Table 1. Total units and sample units selected for the POE study

Block	Unit types	Total no of units	No units in POE study	Short names
Block A	1B, 2B flats	16	4	A08, A10, A11, A16
Block B	4B house	13	0	
Block C	3B house	8	2	C01, C06
Block D	4B house	13	3	D11, D12, D14

Thermal comfort assessment criteria

Buildings seeking to achieve Passivhaus standard have to be modelled using the PHPP design tool developed by the Passivhaus Institut (PHI). For summer thermal comfort, the PHPP sets out a maximum temperature threshold, intended as a comfort limit, and using steady-state calculations it predicts the frequency which temperatures are expected to exceed it. Such overheating risk is expressed as a percentage of the occupied year, which for a dwelling is taken as 365 days (Passivhaus Institut, 2014).

$$T > 25°C \; (= T_{max}) \; for \; more \; than \; 10\% \; annual \; occupied \; hours$$

While meeting the 10% target is mandatory in order to achieve the Passivhaus certification, the guidelines recommend that the frequency of overheating does not exceed 5% in order to guarantee high summer comfort in a changing climate (McLeod et al., 2011).

Review of the design assumptions in the PHPP

While a comprehensive in-depth review of the PHPP as a design tool is outside the scope of this paper, the present study follows two lines of investigation:

a) how different are the risk estimates made for the different unit types at the design stage, and why;
b) how far the risk estimates are reliant on assumptions of in-use occupant behaviour.

As such, for the purpose of this study only the factors leading to different estimates are reported (Table 2). In terms of heat gains, this means solar gains resulting from different block orientations and internal gains from different assumptions on household size. With respect to heat losses, including natural ventilation by means of window opening.

Table 2. Factors defining heat gains and losses during the summer as calculated through the PHPP tool (v8.5)

PHPP v8.5				Heat Gains			Heat Losses		
				Solar Aperture (for solar gains)		Int. heat gains	Ventilation (ach)		
	TFA (m^2)	No units	No occupants	total (m^2)	(m^2/ m^3)	Specific power (W/m^2)	via MVHR	Via windows	OH Risk
Block A	1311	17	37.5	35.6	0.03	2.9	0.34	0.0	2.6%
Block C	639	8	18.3	22.5	0.04	2.3	0.30	0.1	2.3%
Block D	1476	13	42.2	68.4	0.05	3.5	0.40	0.2	8.3%

Quantitative data collection: monitoring equipment and external weather

Monitoring of indoor environmental conditions was carried out using HOBO UX100-003 Temp/RH 3.5% data loggers to record indoor temperature and relative humidity (with ±0.2°C accuracy) and HOBO UX90-001 State/Pulse/Event to record window opening. The UX100-003 loggers were calibrated in an indoor environment, revealing a ±0.15°C difference which was deemed acceptable for the purpose of the study. The UX100-003 loggers were placed on top of door frames, away from sight, direct sunlight and active heat sources and data was recorded in 15-minute intervals. HOBO UX90-001 were fixed onto window frames.

The focus period chosen for this paper ranges from 21st June to 21st September 2015, herein referred to as 'summer 2015'. During this period a short 'hot-spell' was experienced, from 30th June to 2nd July, with temperatures exceeding 30˚C on two days.

External weather data was obtained from Gravesend-Broadness weather station, using the MIDAS data archive system (Met Office, 2012). A comparison between the monthly weather data used in the PHPP calculations with mean monthly values calculated for the Gravesend-Broadness weather station (Table 3) shows no significant difference other than for the month of July, partly due to the hot spell. While it is likely that had an impact on the 25C exceedance, this assessment has not been the focus of this research, as all units were impacted in a similar manner.

Table 3. Monthly data for design weather, compared with mean values recorded during summer 2015

Location / type of data	Distance from site	Jun	Jul	Aug	Sep
Hemsby (East Anglia) / generated from historical data	~100 miles	15.2	16.7	17.4	14.9
Gravesend-Broadness (Kent) / calculated from data collected during summer 2015	~10 miles	15.9	18.1	17.7	13.6

Qualitative data: occupant perception and behaviour

The broader study relied on questionnaires and one-to-one interview, including both ranking and open questions, to collect background information about the household composition, occupants' background, perceptions of their thermal environment and interaction with it. For the purpose of this paper, an extract of the questionnaires for the summer period was considered, particularly the section exploring thermal comfort perception, when asked "H*ow has your home been over the summer?"* participants could choose from: "*comfortable"*, "*sometimes too hot"*, "*always too hot"*. As for window opening behaviour, when asked "*When did you open windows?*" they could indicate "*never*", "*out of habit*", "*when too warm*", "*all day*" for day-time and "*never*" and "*always*" for night-time.

Results

One of the early findings of the POE project was the discrepancy between the standard occupancy assumptions and those actually observed, in terms of both size of households and occupancy patterns. Table 4 provides a summary of such patterns, indicating the typical pattern for the adult (block A) or the adults (blocks C, D) for each households.

Table 4. Comparison between actual size of households and PHPP assumptions

		Household size		Occupancy pattern	
Block	Unit	Actual	Assumed	Actual	Assumed
Block A	A08	2	2.2	works part-time	standard
	A10	2		home most days	
	A11	2		works part-time	
	A16	2		works part-time	
Block C	C01	4	2.3	both home most days	standard
	C06	5		partner home most days	
Block D	D11	6	3.2	both home most days	standard
	D12	5		both home most days	
	D14	5		both work full-time	

Internal temperatures were very high during the whole period, with median often above 25°C, as shown in Figure 1. However, different building unit types showed different temperature distributions: most notably, much greater ambient temperatures swings were observed in the houses' (block C and D) if compared to the flats (block A), which were mostly ranging between 24°C and 26°C.

The occurrence of overheating for the summer period, i.e. a 25°C exceedance expressed as a percentage of annual occupied hours is shown in Figure 2. The chart provides a comparison between the predicted risk of overheating (black bar), expressed as a summary figure for a whole block and calculated using monthly average values, and the much more granular data - logged sub-hourly - for individual rooms in each unit. This approach can reveal the limitations of using simplified tool when trying to capture a complex phenomenon such as indoor overheating.

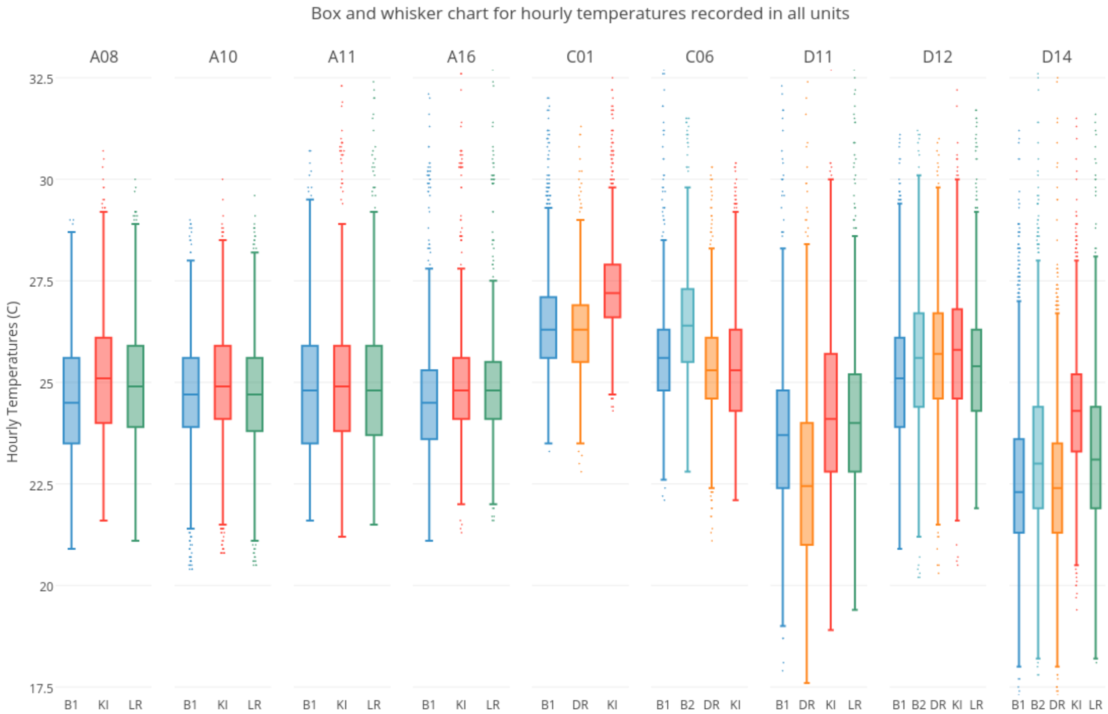

Figure 1. Box and whisker chart of indoor temperature observed during summer 2015, colour coded based on room type (i.e. blue=bedroom1, cyan=bedroom2, red=kitchen, yellow=dining room, green=living room)

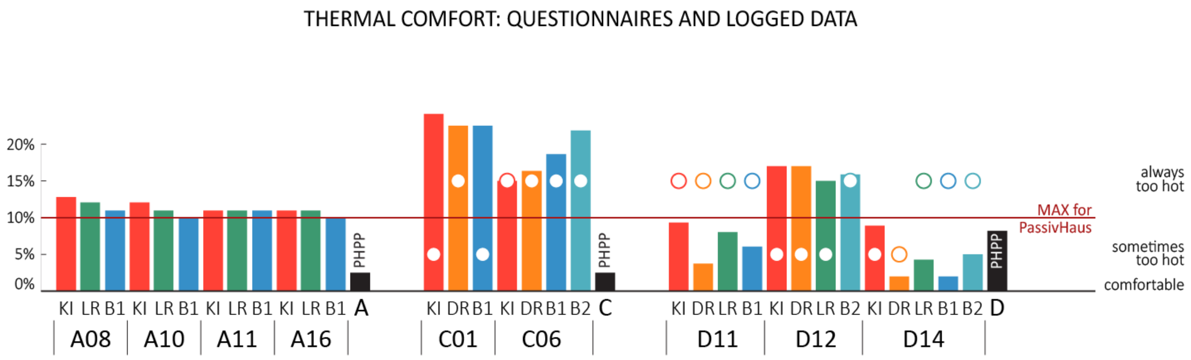

Figure 2. Number of occupied hours above 25 ºC for all monitored rooms, expressed as a percentage of total occupied hours during the period (right) as well as for a whole year (left).

While all flats (block A) failed the overheating criterion and greatly exceeded the PHPP predictions, their thermal performance was fairly homogeneous. On the other hand, a notable difference could be observed for the houses, suggesting the impact of occupants' behaviour, both in terms of internal heat gains and natural ventilation. Previous research has highlighted how using fixed W/m^2 internal gain figures for each building type, while convenient as a design aid, can lead to anomalies at extremes of building size and occupancy (Grant & Clarke, 2014). Given assumed internal gains are largely proportional to occupancy, the discrepancy between those and the actual figures is a key factor behind the gap displayed in Figure 2.

Window opening behaviour

An indication of the impact of building occupancy on thermal performance for all units was obtained by combining residents feedback included in questionnaires with window opening captured by data loggers. This allowed a reciprocal validation of the two data sets. As shown in Figure 3, data showed heavy reliance on natural ventilation for household D11, where windows were mostly open at day and night and, to a lesser degree for D14, where the rooms at ground floor level where only ventilated during the day and rooms at the upper floors both at day and night. C01 and C06 opened windows during the day and kept them closed at night, whereas D12 only appeared to be opening those in the main bedroom (B2).

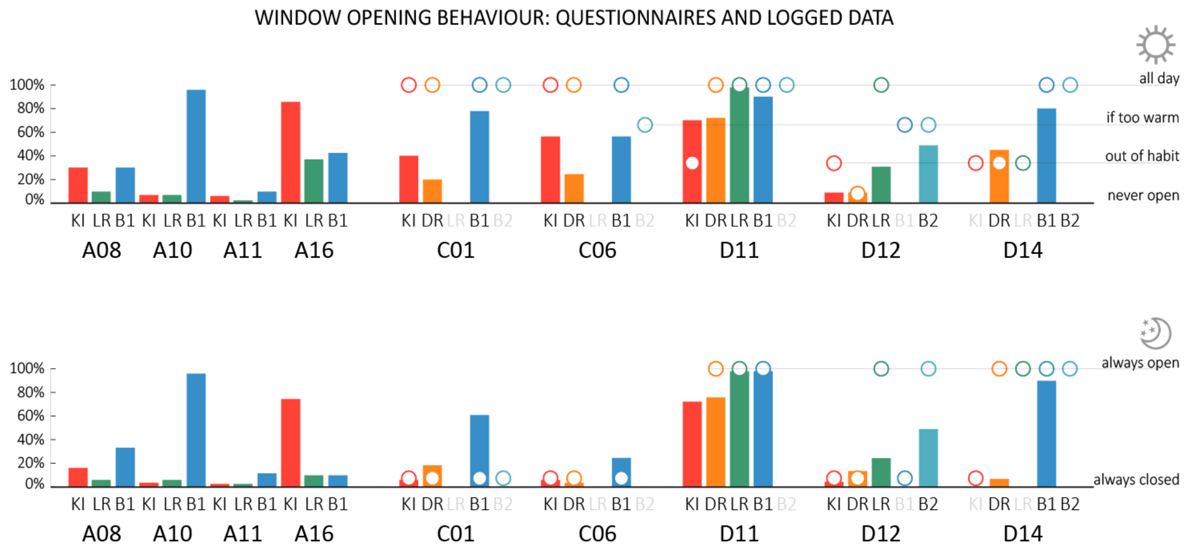

Figure 3. Reponses from residents' questionnaires (circles) and monitored data (bars) for window opening during day-time (above) and night-time (below)

Discussion

Discrepancies were found between different properties under study, and between measured and predicted summer thermal performance for nearly all of these. This was due to a combination of design aspects and, most crucially, occupant-related factors that were not predicted – or could not be predicted – at the design stage.

Solar shading

The estimated solar gains, as indicated in Table 2, where much greater for block D than block C (ca.133 vs 91 kWh daily solar load). However, it was observed that properties in block C made little or no use of internal shading (e.g. internal curtains or blinds), even during the warmest days, as opposed to households D11 and D14, were dark curtains were used. The discrepancy between different households in block A was less noticeable, given they all benefitted from solar shading provided by balconies on the south façade. In this regard, occupant behaviour could help justify the different performance observed among the households, as no discrepancy with the PHPP estimates was found.

Internal heat gains
A significant difference was found between what assumed at the design stage and what observed in reality. While the PHPP assumed values for the houses in block C (2.3 W/m^2) to be nearly 35% than those in block D (3.5 W/m^2), information gathered in one-to-one interviews suggested this was not the case. C06 made extensive use of energy-intensive plasma screens throughout the summer, to watch TV on the main living room and to play games console in bedroom2. D12 and C01 also made an intense usage of appliances during the summer period, running the washing machine and the dishwasher every day (up to 3 times/day for C01).

Ventilation via window opening
A dramatic difference was found between different properties with regards to natural ventilation, as shown in Figure 3. In one-to-one interviews, residents were asked to further comment the data collected from window loggers helping to uncover scenarios where ventilation rates were significantly reduced, which were not captured by window loggers. This revealed how household C01 had often been using window restrictors during the day and always closed windows at night, mainly for fear of burglar and insects. Furthermore, all internal doors were kept closed, impeding cross-ventilation and as such greatly reducing the capacity to purge heat.

As for the flats, which were not surveyed using the questionnaires for budget limitations, a scarce reliance on natural ventilation (except for bedroom in A10, where nonetheless windows were left open with security restrictors) seemed not to affect thermal comfort as much as it did for the houses. This, combined with the information gathered during the interviews, confirming lower occupant densities and less time spent at home, suggested internal heat gains were the most impacting factor on overheating.

Ventilation via MVHR
While the primary function of an MVHR system is to provide fresh air, rather than purge heat (air extract/supply rates are not sufficient per se), the usage of MVHR in by-pass mode (i.e. excluding the heat exchange) was accounted for in the PHPP as a contribution to summer cooling. Furthermore, guides and user manuals distributed to residents seemed to be identifying mechanical ventilation as the main cooling strategy.

Following the summer study, an inspection was commissioned by the client, revealing how due to lack of maintenance and air filter replacement, the MVHR were providing insufficient low ventilation levels for block D and nearly no ventilation for the units in block C, requiring re-commissioning. This is believed to have exacerbated overheating, given the scarce reliance on window opening observed for some of the monitored households.

Conclusions

Overall, the monitored properties showed a poor thermal performance and a high occurrence of summer overheating, both above the PHPP predictions and the maximum allowed exceedance (10%) for the Passivhaus standard. However, this occurred with different degrees of severity and no factor alone was found to be responsible for it.

All properties were occupied by social housing tenants. The flats had smaller households and were not heavily occupied during the day. The houses, occupied by bigger families who stayed at home most of the time, showed more intense occupancy pattern and a more intense usage of appliances leading to high internal heat gains. This was true for all properties with the exception of D14, who showed the lowest occurrence of overheating.

Given the underperformance of the MVHR, cooling was entirely dependent on window opening. PHPP conservative assumptions only accounted for low air exchange rates through opening windows, and as such only the households who allowed abundant natural ventilation benefitted a lower occurrence of overheating compared to the PHPP predictions.

The PHPP, despite being a robust and extensively validated tool, may be inadequate to assess the full extent of the risk of overheating. While standardised assumptions are usually acceptable when seeking Passivhaus certification, a careful evaluation of critical factors such as occupancy patterns is crucial, if the PHPP overheating risk assessment is to be interpreted as an indication of present and future in-use performance.

Acknowledgments

The author is an Engineering Doctorate candidate, funded (grant ref. 1503407) by the Engineering and Physical Sciences Research Council (EPSRC) and Innovate at PRP. The author would like to thank Daniel Archard (Clarion Housing Group) for granting approval to the publication of the study, Marylis Ramos (PRP) for supporting the research and Marine Sanchez (Enhabit) for providing useful insights into the PHPP tool.

References

DECC, (2016). *Annual Fuel Poverty Statistics Report, 2016*, London.

Dengel, A. & Swainson, M., (2012). *Overheating in new homes: A review of the evidence*,

Grant, N. & Clarke, A., (2014). *Internal heat gain assumptions in PHPP*,

Jenkins, G. et al., (2009). *UK Climate Projections : Briefing report*, Exeter, UK: Met Office Hadley Centre.

Jones, R. V., Goodhew, S. & de Wilde, P., (2016). Measured Indoor Temperatures, Thermal Comfort and Overheating Risk: Post-occupancy Evaluation of Low Energy Houses in the UK. *Energy Procedia*, 88, pp.714–720.

Larsen, T.S. & Jensen, R.L., (2011). Comparison of measured and calculated values for the indoor environment in one of the first dasih passive houses. In *Proceedings of Building Simulation 2011: 12th Conference of International Building Performance Simulation Association*. Sydney, pp. 14–16.

McLeod, R., Mead, K. & Standen, M., (2011). *Passivhaus Primer – Designer ' s Guide : A guide for the design team and local authorities*,

McLeod, R.S., Hopfe, C.J. & Kwan, A., (2013). An investigation into future performance and overheating risks in Passivhaus dwellings. *Building and Environment*, 70, pp.189–209.

McManus, A., Gaterell, M.R. & Coates, L.E., (2010). The potential of the Code for Sustainable Homes to deliver genuine "sustainable energy" in the UK social housing sector. *Energy Policy*, 38(4), pp.2013–2019.

Met Office, (2012). Met Office Integrated Data Archive System (MIDAS) Land and Marine Surface Stations Data (1853-current). NCAS British Atmospheric Data Centre.

Passivhaus Institut, (2014). Summary and conclusions regarding indoor comfort in Passive Houses in summer. *Passipedia*.

Passivhaus Trust, (2016). Passivhaus Building Database.

Sameni, S. et al., (2015). Overheating investigation in UK social housing flats built to the Passivhaus standard. *Building and Environment*, 92, pp.222–235.

ZCH, (2015). *Assessing Overheating Risk: Evidence Review*, London.