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Evaluating the effect of occupant behaviour and expectations on actual energy use and environmental conditions in 'sustainable' social housing in South East England

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Abstract

This paper investigates the effect of occupant behaviour and expectations on energy use and indoor environmental conditions of six case study dwellings in three sustainable social housing developments in UK using building performance evaluation methods. The case study houses cover a variety of built forms and different types of construction systems but have similar occupancy profiles and tenures. The study captures quantitative data on fabric performance, commissioning and controls, energy consumption and environmental conditions, cross-related with qualitative data gathered through questionnaires and interviews with occupants.

Despite all the developments being designed to Code for Sustainable homes level 4 or 5, the actual energy use across the six case study houses varies by a factor of 3.3, with high occupant expectations increasing the gap between designed and actual performance. To ensure that low energy houses perform as intended, occupants need to be trained through graduated (and extended) handover, supplemented by visual home user guides. Controls need to be designed and installed in a more intuitive and user-friendly way that encourages occupants to interact with their environment in an adaptive manner. Otherwise there is a risk that UK Government's zero carbon housing policy may get undermined.

Keywords: building performance evaluation, low carbon houses, occupant behaviour, performance gap

1. Introduction

The UK Government has set ambitious targets for incremental changes to building regulatory standards, which are intended to achieve 'zero' carbon new housing from 2016 onwards (UKGBC, 2008) through the Code for Sustainable Homes (CSH[1]) which promotes sustainable design principles and micro-generation technologies. However there is a growing concern that many of these proposals and solutions are untried and untested within the context of the mainstream housing production in the UK, creating a gap between predicted and actual performance (Gupta et al, 2013). Moreover this performance gap may undermine zero carbon housing policy and carry considerable commercial risk for the wider industrial sector (Zero Carbon Hub, 2010).

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[1] CSH: Code for Sustainable Homes is a holistic standard for sustainable housing design and construction in the UK (Gaze et al., 2009)

The majority of the research on performance gap in the housing sector tends to focus on addressing differences between 'as designed' and 'as built' performance, highlighting the need for measuring actual fabric performance and commissioning reviews of services and systems (Windfield et al, 2011; Gupta and Dantsiou, 2012; Zero Carbon Hub, 2013). However, the energy performance gap tends to become wider at the in-use stage when occupants' comprehension, understanding and behaviour also influence the households energy consumption (Stevenson and Rijal, 2010; Stevenson and Leaman, 2010). Several studies have revealed the need to understand occupant behaviour along with other performance mandates (Sharpe and Shearer, 2013). Lomas et al. (2006) highlight that one of the main reasons for limited success in achieving energy targets is the lack of understanding of how people interact with domestic technology. Firth et al (2008) found significant variation in energy consumption in similar dwellings underlining the need for qualitative and quantitative studies to explore the technical, socio-demographic and behavioural factors. Steemers and Yun (2009) demonstrated that the physical building characteristics, local environment, systems servicing the building and occupant behaviour all play a significant role in determining consumption. The study of Gill et al (2010) demonstrates a method to account for the contribution of occupant behaviour to performance variation using the post-occupancy evaluation (POE) and reveals that resource-conscious behaviours account for 51% and 37% of the variance in heat and electricity consumption respectively between the same type of dwellings.

Within this context, this paper investigates the effect of occupant behaviour and expectations on energy use and indoor environmental conditions in six case study dwellings across three 'sustainable' social housing developments in UK, through building performance evaluation methods. The case study houses cover a variety of built forms and different types of construction systems but tend to have similar occupancy profiles and tenures. It is found that occupant behaviour, expectations, understanding and lack of user control over heating and ventilation systems play an important role in influencing housing performance and needs to be addressed through a deeper understanding of occupant expectations and interactions with the building and technologies.

2. Methodology - Building Performance Evaluation

The study adopts a mixed-methods building performance evaluation (BPE) approach, which is socio-technical in nature. BPE is the process of evaluating the performance of a building through a systematic collection and analysis of qualitative and quantitative information related to energy performance, environmental conditions and occupant feedback.

The study has been sponsored by the UK Government's Technology Strategy Board National Building Performance Evaluation (BPE) programme which is an £8m research programme, for both domestic and non-domestic buildings, to help the construction industry deliver more efficient, better performing buildings (TSB, 2012). The programme mandates a prescribed protocol for evaluation and reporting to maintain consistency and comparability in benchmarking and analysis.

This study involves capturing data on energy consumption, CO_2 emissions and environmental conditions including air quality and monitoring of opening and closing of doors and windows. This data is cross-related with qualitative data gathered through occupant satisfaction surveys and interviews, supplemented by occupant self-completion activity logging and thermal comfort diaries across different seasons. To understand the design intent, walkthrough interviews are conducted with the design team and clients, while the communication of design intent to users is evaluated through observations of handover process and assessment of home user guides. A detailed review of control interfaces exposes challenges faced by occupants in terms of accessibility, usability and clarity of purpose.

3. Overview of case studies

The six case study dwellings are part of three exemplar social housing developments (A, B and C) located in South East England. The six case studies (two per development – A1, A2, B1, B2, C1 and C2) were selected to represent a variety of built forms and construction systems, with similarities in occupancy profiles. The case study houses are two and three storey mid-terrace, end-terrace and detached houses of two, three and five bedrooms, located in residential areas. The size of the properties varies between a minimum of $94m^2$ to a maximum of $146m^2$. The layout of the houses is similar, with the living areas on the ground floor and sleeping areas on the upper floors. While Cases A1, A2, C1 and C2 are being monitored for a period of two years and Cases B1 and B2 were monitored for a period of one year. Table 1 presents the background characteristics about the case studies, while Table 2 presents an overview of their design specifications and construction details.

Development A was designed for Code for Sustainable Homes 5 and Developments B and C were designed for Code for Sustainable Homes 4. Different types of construction were used in the three developments ranging from hempcrete in Development A to light-weight steel frame construction with pre-insulated panels in Development B and more traditional timber frame with brick in Development C. Additionally, each of the developments features a different heating system; from Exhaust Air Heat Pumps (EAHP) in Development A to Air Source Heat Pumps (ASHP) in Development B and gas boilers in Development C.

All of the six case study houses are occupied by families with children. The number of occupants in the case studies ranges between four to six. Occupancy patterns are similar between the case studies. Cases A1, A2 and B2 are occupied 24 hours/7 days a week, and Cases B1, C1 and C2 are occupied 17-19 hours during weekdays and 24 hours during weekends. The occupancy time in the properties is highly correlated with heating and ventilation interactions and controls. In terms of occupancy and use of space, interviews with occupants have shown that the most occupied area in all properties is the living area whereas bedrooms are mostly used during sleeping hours only.

Table 1 Case studies information

	Development A		**Development B**		**Development C**	
No of case study houses	2		2		2	
Case study reference	Case A1	Case A2	Case B1	Case B2	Case C1	Case C2
Area (m^2)	94	94	88	123	128	146
Typology	Two bed, mid-terrace	Two bed, mid-terrace	Three bed, end-terrace	Four bed, mid-terrace	Four bed, mid-terrace	Five bed, detached
Floors	2	2	2	3	3	2
Occupancy patterns	Weekdays: 24h Weekend: 24h	Weekdays: 24h Weekend: 24h	Weekdays: 15:00-8:00 Weekend: 24h	Weekdays: 24h Weekend: 24h	Weekdays: 13:00-8:00 Weekend: 24h	Weekdays: 13:00-8:00 Weekend: 24h
Occupants	2 adults, 2 children	2 adults, 2 children	2 adults, 2 children	4 adults, 1 baby	2 adults, 3 children	1 adult, 5 children

Table 2 Design specifications and construction details

	Development A	**Development B**	**Development C**
Developer	Social housing / Local authority	Social housing / Local authority	Social housing / Local authority
Tenure	Mixed-private ownership, affordable housing rented	Mixed-private ownership, affordable housing rented	Mixed-private ownership, affordable housing rented
Construction type	Timber frame with cast hempcrete	Steel frame with pre-insulated panels	Timber frame and brick
Target design rating	CSH Level 5	CSH Level 4	CSH Level 4
Main construction elements (as designed) U-values W/m^{2}K	Walls: Rendered hempcrete cast into timber frame, U-value: 0.18 Roof: Tile on timber, U-value 0.15 Ground floor: Screed over insulation on beam and block, U-value 0.2 Windows: wood frame, double glazing, U-value 1.4	Walls: Light steel frame with pre-insulated panels, U-value: 0.15 Roof: Tile on timber, U-value: 0.15 Ground floor: Concrete over steel frame with Cube 6 EPS insulation block, U-value: 0.15 Windows: Timber frame, triple glazing, no trickle vents, U-value ≤1.2	Walls: Timber frame and brick, U-value 0.21 Roof: Slate roofing, U-value 0.13 Ground floor: Precast concrete with insulation, U-value 0.25 Windows: Aluminium frame, double glazing, U-value 1.3
Space heating and hot water system	Exhaust Air Heat Pump (EAHP), underfloor heating coils and4m^2 vaccum tube heat pipe solar collectors	Air Source Heat Pump (ASHP), underfloor heating coils, immersion heater back up	Gas condensing boiler with radiators
Target air tightness (m^3/hm^2 @50Pa)	2	3	3
Ventilation strategy	MEV through EAHP	MVHR	MVHR
Renewables	4kWpk Photovoltaics	1.5kWpk Photovoltaics	1.65kWp & 1.88kWp Photovoltaics

4. Actual energy performance

Monitoring data for energy consumption are provided for the period from January to December 2013 (Figure 1). Comparison of actual energy use with 'as designed' SAP predictions reveals discrepancies between them in all cases[2]. Actual energy use exceeds the SAP prediction by a factor of 4 in Case C1 and by a factor of 5 in Case C2. In Cases B1 and B2 actual energy use exceeds the SAP predicted value by a factor of two. Cases A1 and A2, which were designed for CSH Level 5, present the highest discrepancy from their SAP predicted performance, exceeding the SAP energy use prediction by a factor of six and five respectively.

These discrepancies are partly due to the fact that SAP does not cover all end uses of energy in dwellings. To overcome this the SAP predictions were extended using a TSB spreadsheet that extends SAP 9.81 to make a whole house energy model, including appliances and the ability to model substantial reductions in them and also reset the constant whole house temperature to 21°C.This way a more accurate

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[2] It should be noted that SAP calculations do not account for all end uses of energy such as appliances and lighting.

comparison can be made between the design predictions and the actual energy consumptions. Actual energy consumption exceeds the extended SAP prediction by a factor of 2 in Cases A2 and C1 and by a factor of 2.5 in Cases A1 and C2. Actual energy use in Cases B1 and B2 is a little higher than the SAP prediction. Actual CO_2 emissions[3], however, are much higher than the extended SAP prediction in all cases, with cases A1 and A2 presenting the highest discrepancies exceeding the values of the extended SAP model by a factor of 7 and 5 respectively .

Cases A1 and A2, although designed to CSH Level 5, consume much more electricity than Cases B1 and B2 that have been designed for CSH Level 4. In Cases B1 and B2 the design COP of the ASHPs is 3.13 whereas in Cases A1 and A2 the designed COP is 2.6. Furthermore, the actual COP for Cases A1 and A2 has been measured at 1.4 resulting in the lower actual performance of the heating system. As a result of that the council has decided to remove the EAHPs from all houses in Development A and replace them with gas boilers. Cases C1 and C2 have a similar performance to a typical UK house, despite being designed to CSH Level 4. Annual CO_2 emissions across the six cases differ by a factor of 3.3 despite all the developments being designed for CSH Levels 4 and 5.

There is also significant variation in the energy consumption of houses within the same development designed to the same standard and with similar occupancy patterns (Table 1). In Development A, occupants in Case A2 appear energy conscious and actively try to reduce their electricity bills by keeping the thermostats at 19^oC and heating the ground floor only. On the other hand, the qualitative data collected suggests the occupants in Case A1 cannot control the heating effectively due to lack of understanding of the underfloor heating system and control interfaces. To overcome this they closely follow the advice that they received by the housing officer during handover about ‘keeping the heating on at all times’, and never adjust the thermostats even during summer months and even when the temperatures in the house are above 25^oC. As a result, CO_2 emissions and energy use of Case A1 exceed those of Case A2 by a factor of 1.3, despite the fact that they have similar occupancies (patterns and family size).

Lack of control also led occupants in Case B1 to turn off their heating system during the day, only heating the house during the night in order to reduce their energy bills, thus reducing the efficiency of the heat pump. CO_2 emissions and energy use of Case B1 exceed those of Case B2 by a factor of 1.2, despite the fact that Case B2 is occupied continuously.

The highest CO_2 emissions are observed in Cases C1 and C2 which have gas boilers for space heating and hot water. Energy use of Case C2 exceeds that of Case C1 by a factor of 1.5. In both houses occupants set their thermostats as high as 30^oC throughout the day, but in Case C2 occupants tend to leave the windows open day and night even during winter thus increasing the heat loss and the heating demand.

These results imply the effect of occupant behaviour, understanding and control on energy consumption and the need to study these closely in relation to housing performance. To better understand the physical context and the cause for the

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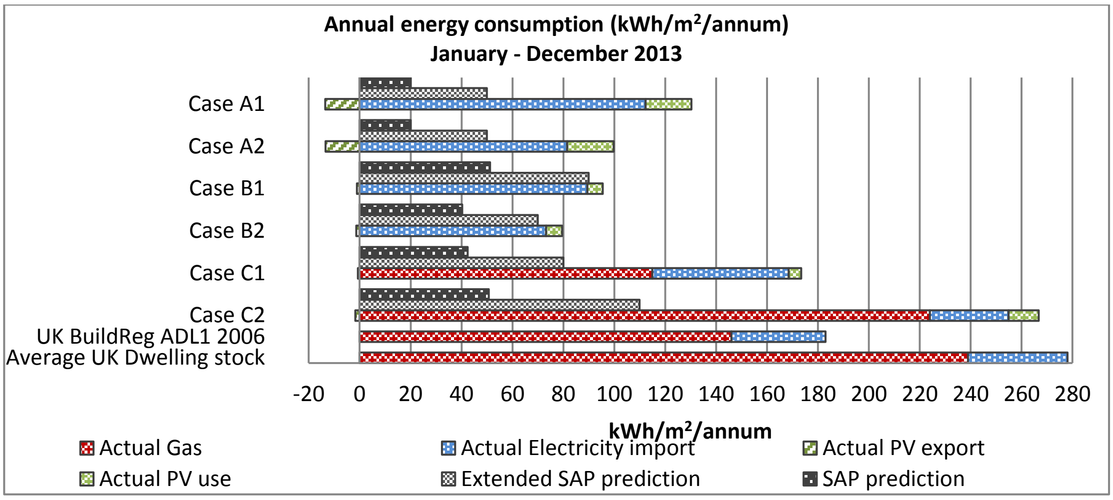
[3] CO_2 emissions were calculated by using with the energy conversion factors quoted as $kgCO_2e$ per unit of fuel. Grid electricity: 0.44548 $kgCO_2e/kWh$, Natural gas: 0.18404 $kgCO_2e/kWh$. The factors were taken from Carbon Trust 2013 update (Carbon Trust, 2013).

performance gap, it is vital to measure and compare the fabric and service performance of the houses.



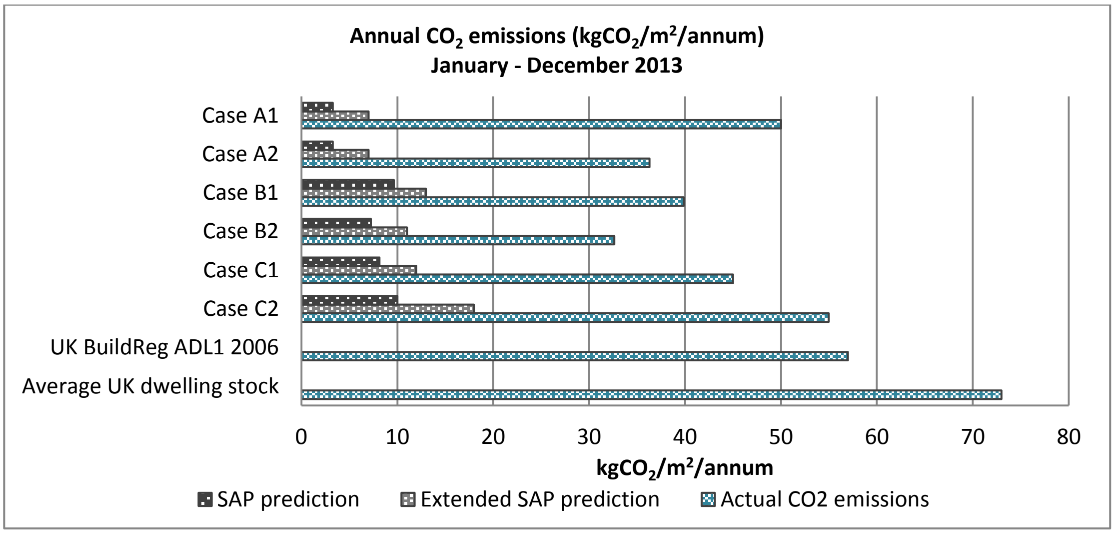


Figure 1 Comparison of actual annual energy consumption and CO_2 emissions with SAP predictions and Extended SAP model predictions across all cases (January – December 2013). Emission factors $kgCO_2e$ per kWh: Electricity 0.44548, Gas 0.18404 (Carbon Trust, 2013).

5. Evaluation of fabric performance and services

5.1 Measuring in-situ fabric performance

The fabric performance of the case studies was evaluated using diagnostic field tests which include: air permeability test[4], in situ U-value test and infrared thermography[5]. The common emerging issues across the three developments that were revealed from the assessment of the fabric performance are summarised in Table 3.

Wall insulation levels were found to be good in all cases. The findings from the in-situ U-value test showed that in Developments B and C actual wall U-values are similar or even better than those specified at the design stage. However, in all cases thermographic images revealed some heat loss through window and door frames, air

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[4] Air permeability tests or blower door tests help establish the air permeability and the heat loss due to air infiltration and exfiltration through the building fabric alone. Ventilation routes such as mechanical ventilation heat recovery (MVHR) units are sealed during the tests.

[5] Infrared thermography visually renders thermal radiation from building elements helping locate heat related construction faults and leakage.

leakage paths and thermal bridges across thresholds. In some cases thermal bridges through ceiling beams and heat loss through party walls were also identified.

Air permeability tests revealed a noteworthy gap between designed and actual air-tightness in all case studies. All homes missed their design target (2-3m3/m^2h) with air permeability in most cases being twice as high as designed (Figure 2). All houses failed to comply with the UK Building Regulation Best practice air permeability rate (5m3/m^2.h) and Case A2 did not even meet the UK Building Regulation Good practice (10m3/m^2.h). Better air tightness would have resulted from a higher quality of detailing at key junctions, skirtings and service penetrations, and detailed care around door and window thresholds and seals.

Heat loss through walls and frames and air leakage paths can affect actual performance by increasing energy use and undermining occupant comfort. However, it is noticeable that occupants in Case A2, despite high air permeability, consume 30kWh/m^2/annum less electricity than their neighbours in Case A1 (Figure 1). This comparison between similar houses within the same development that also have similar occupancies gives a strong indication of the effect of occupant behaviour and expectations on housing performance.

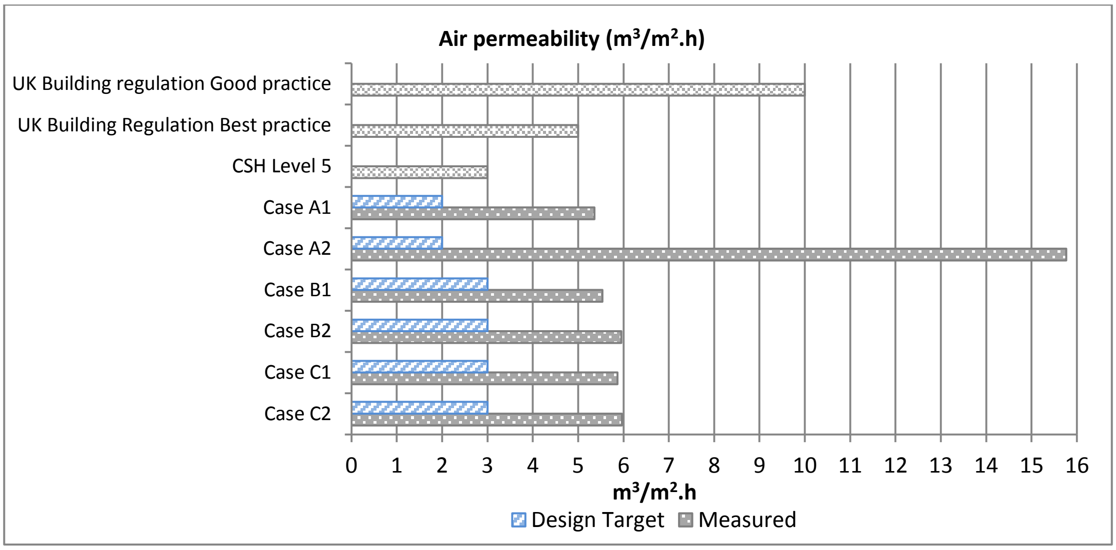

Figure 2 Comparison of measured and design air permeability.

Table 3 Common emerging issues highlighted by evaluation of fabric performance

	Development A	Development B	Development C
Heat loss through party walls	×	×	
Heat loss through external walls	×		
Heat loss through window and door frames	×	×	×
Thermal bridges in ceiling beams and/or thresholds	×	×	×
Actual U-values higher than design specifications	×		
Loft insulation not well distributed		×	×
Actual air-permeability much higher than design air permeability	×	×	×
Air-permeability rate did not meet UK Building Regulation Best practice (5 $m^3/h.m^2$)	×	×	×

5.2 Systems installation and commissioning review

A commissioning review was undertaken in all the cases to ensure that the commissioning of equipment and services is complete and the design and operational strategy was capable of creating the desired performance and comfort for occupants. Table 4 summarises the common emerging issues across the three developments. The MVHR system installation and commissioning was found to be one of the most problematic issues in all six houses, along with improper commissioning of heating controls and room thermostats.

MVHR systems in these developments were adopted in order to achieve code compliance. In all cases the developers had little, if any, knowledge and experience in MVHR systems. In all the houses, the MVHR systems proved to be problematic with issues including; improper commissioning and system imbalance (all Cases), breakdowns (Cases B1, B2), noise (Case C1) and cold draughts (Case B1). The MVHR supply and extract vents in all cases were not locked in fixed positions allowing the occupants to adjust them at will thus leading to severe system imbalance, which in turn can lead to increased heat loss and energy use, as well as increased system resistance and noise.

Improper commissioning of the MVHR system not only allows occupants to fiddle with the vents but often results in unpleasant draughts which in turn undermines occupant comfort and appears to have driven occupants to look for ways to override the system. This also appears to have had a severe impact on indoor air quality due to insufficient fresh air supply. Additionally, the location of the MVHR unit in the loft (Cases B1, B2, C1, C2) makes the unit inaccessible and along with the narrow space provided compromises proper installation and maintenance.

The commissioning of heating controls and room thermostats was also found to be problematic in most houses. In Development A, a commissioning check before the move-in revealed that the zone thermostats were not properly connected. In Development B the wireless thermostats in both the case study houses had not been connected to the heating system and the heating was subsequently always on. This was discovered by the BPE team several months after the move-in following occupants' complaints of not having good control over heating and of rooms being too hot. This commissioning problem made occupants in Cases B1 and B2 feel they lack control over heating and also made them sceptical towards the heat pump and the technologies used in the houses.

Installation and commissioning is clearly an area where increased training and awareness will have a large impact on improving the performance of houses.

Table 4 Common emerging issues highlighted by review of systems installation and commissioning

	Development A	**Development B**	**Development C**
MVHR imbalance between supply and extract air flow rates	×		×
MVHR unit located in loft inaccessible		×	×
MVHR vents not locked in fixed positions	×	×	×
MVHR vents shut by occupants		×	×
Several MVHR system breakdowns		×	
Occupants unaware of MVHR maintenance requirements	×	×	×
Poorly commissioned heating controls	×	×	

6. Environmental conditions and occupant interaction

Internal temperature data and occupant activities during the monitoring period (January – December 2013) reveal some insightful trends across all houses (Figures 3, 4). Overall temperatures are high with five out of six houses having mean living room and bedroom temperatures above 21°C and three out of six houses having a mean above 23°C. Peak temperatures above 27°C were also observed in the majority of the houses (five out of six). In Case A1, bedroom temperatures are 2°C lower than living room temperatures because occupants prefer to heat only the ground floor (living room and kitchen) and keep the first floor (bedrooms) unheated. Case B1 has the lowest minimum and average temperatures due to occupant's efforts to minimize their electricity bills by controlling the heating system and only heating their house during the night. Contrary to this, Cases A1 and C1 have the highest mean temperatures as the occupants use a lot of heating energy by keeping their thermostats around 25-27°C throughout the day. In Case C2 occupants also keep their thermostat very high throughout the day (30°C) but mean temperatures are around 21°C because occupants keep their windows open for many hours during the day (Figure 8), thus leading to the high gas consumption shown in Figure 1. In Case B2 bedroom temperatures are higher than living room temperatures because the heating in the first floor (bedrooms) was constantly on due to an error in the commissioning of the heating system. Figures for RH in the monitoring period suggest very low levels of relative humidity that are linked to the high indoor temperatures.

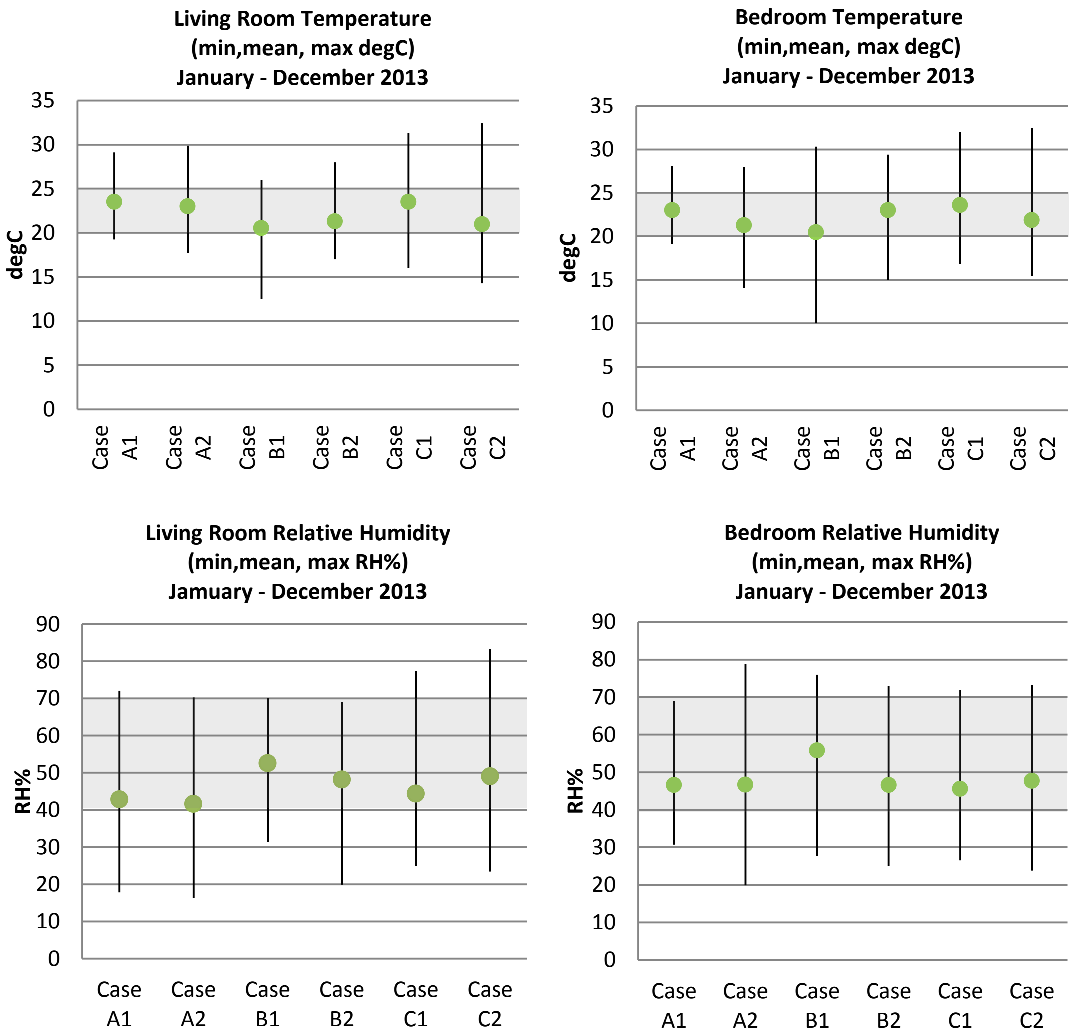

Figure 3 Mean, minimum and maximum temperatures and relative humidity levels in living rooms and bedrooms (January – December 2013).

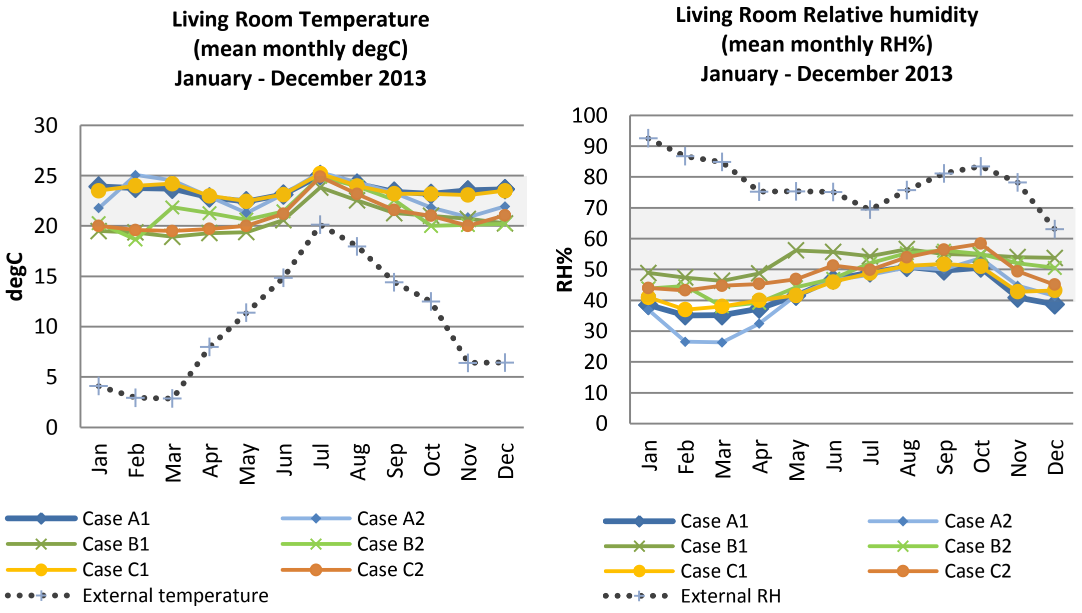

Figure 4 Mean monthly temperature and relative humidity in living rooms across all cases.

The temperature distribution throughout the year is shown in Figure 5. The majority of the houses (four out of six) show instances of overheating with temperatures remaining above 28°C for more than 1% of occupied hours (Case A1: 2%, Case B2: 1.1%, Case C1: 1.4%, Case C2: 2.3%). Interestingly, within the same development there are cases that show instances of overheating and others that do not. This indicates that overheating and summer performance is more related to internal heating gains and occupant activities such as window opening.

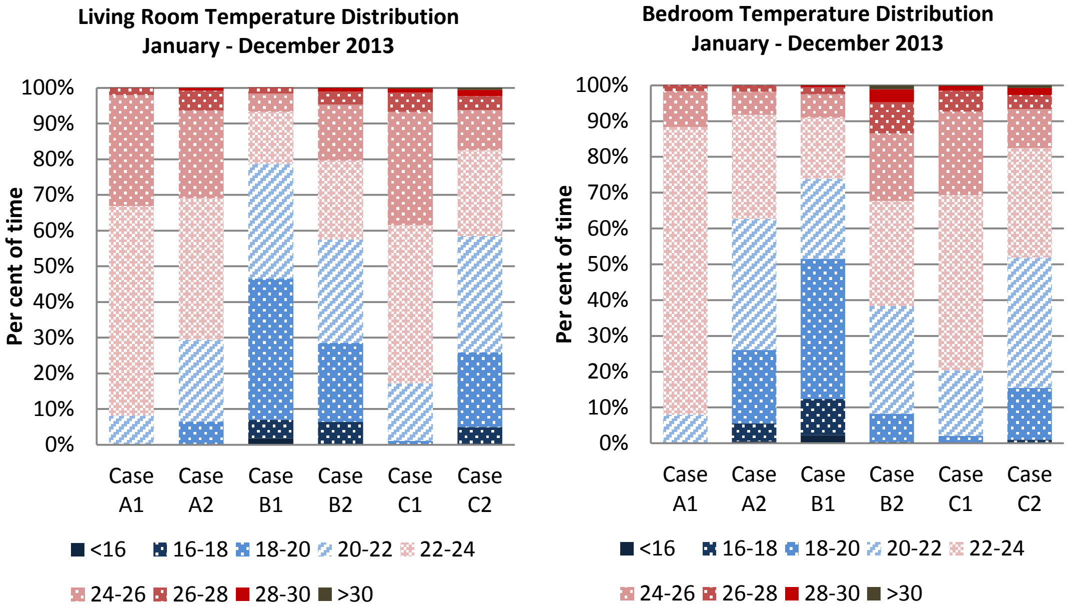

Figure 5 Temperature distribution in living rooms and bedrooms (January – December 2013).

CO_2 levels as an indicator of air quality is of particular interest in these dwellings, especially given the levels of airtightness. Mean, maximum and minimum CO_2 levels are shown in Figure 6. Mean CO_2 levels in Cases A1, A2, C1 and C2 range between 560-640ppm in the living rooms and between 650-730 in the bedrooms (CO_2 levels in Cases B1 and B2 were not monitored). Peak levels are well above 1000ppm in all cases, reaching 2270ppm in Case C2 living room and exceeding 2000ppm in Cases A2 and C1.

In order to evaluate the amount of time CO_2 levels are above the limit of 1000ppm during a year in each house Figure 7 was plotted. In Cases A1 and A2 CO_2 levels range between 500-750ppm for the majority of the time (50-60%). CO_2 levels are lower in Cases C1 and C2 living rooms with CO_2 levels remaining below 500ppm for 50% of the time. This is directly related to the window opening behaviour of occupants as analysis has shown that occupants in Cases C1 and C2 open their windows more frequently during winter than occupants in Cases A1 and A2 (Figure 8). In Cases A1, A2 and C1, CO_2 levels in the living rooms exceed 1000ppm for 3-4% of the time. CO_2 levels in the bedrooms are higher than those in the living rooms in all cases; exceeding 1000ppm for 4-6% of the time in Cases A1 and C2 and for 12-17% of the time in Cases A2 and C1. High bedroom CO_2 levels in Cases A2 and C1 are due to room occupancy levels (2 occupants per room during the night).

Overall, such high CO_2 levels indicate poor air quality, which appear related to insufficient supply of fresh air through the MVHR system. Given the fact that all of the houses exceeded their design air permeability target these findings suggest that CO_2 levels could have been even higher had the design target been achieved.

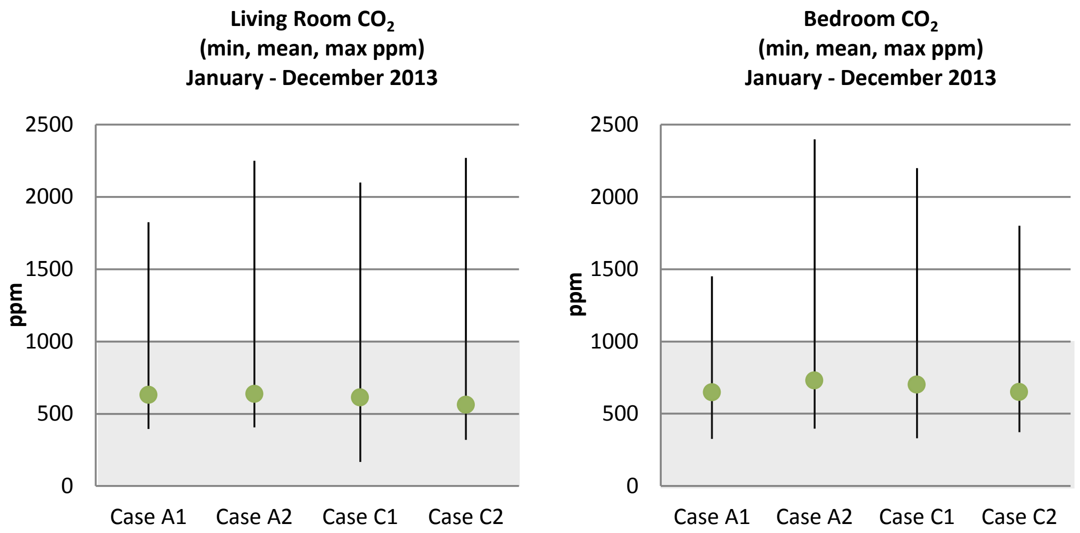

Figure 6 Mean, minimum and maximum CO_2 levels in living rooms and bedrooms (January – December 2013).

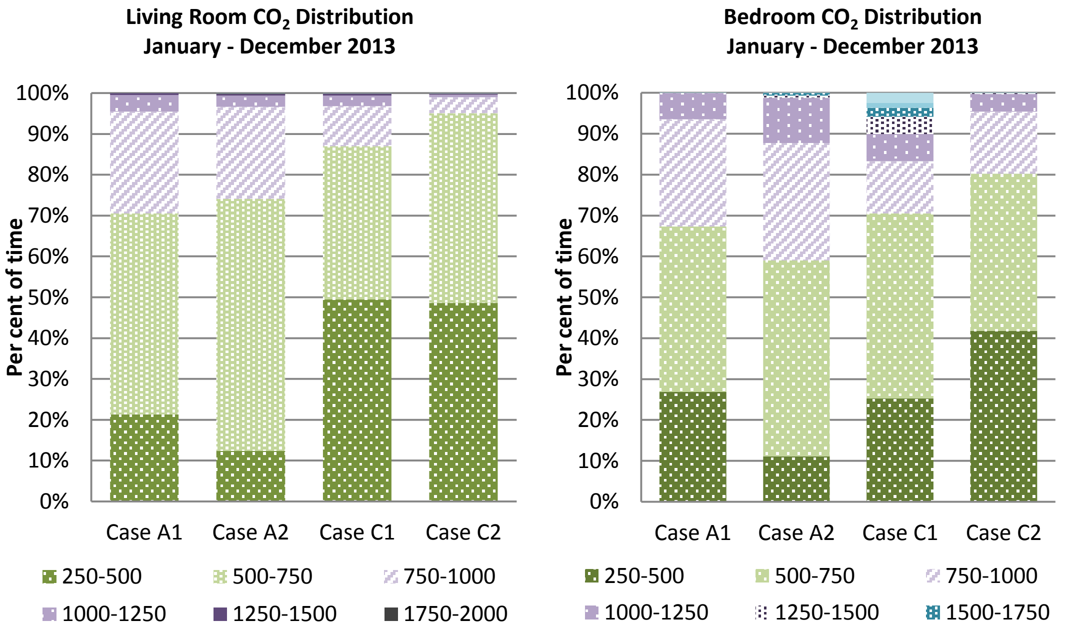

Figure 7 Distribution of CO_2 levels in living rooms and bedrooms (January – December 2013).

The hourly percentage of window opening in living rooms and bedrooms for winter and summer is plotted against hourly average internal temperatures in Figure 8. During winter, occupants in Cases A1 and A2 tend to mostly keep their windows closed and indoor hourly temperatures are kept steady throughout the day. In Case C1 occupants tend to open the living room window and back external door when indoor temperatures rise, whereas in Case C2 occupants leave the living room window open throughout the day. This behaviour explains the high energy use discussed in the previous sections.

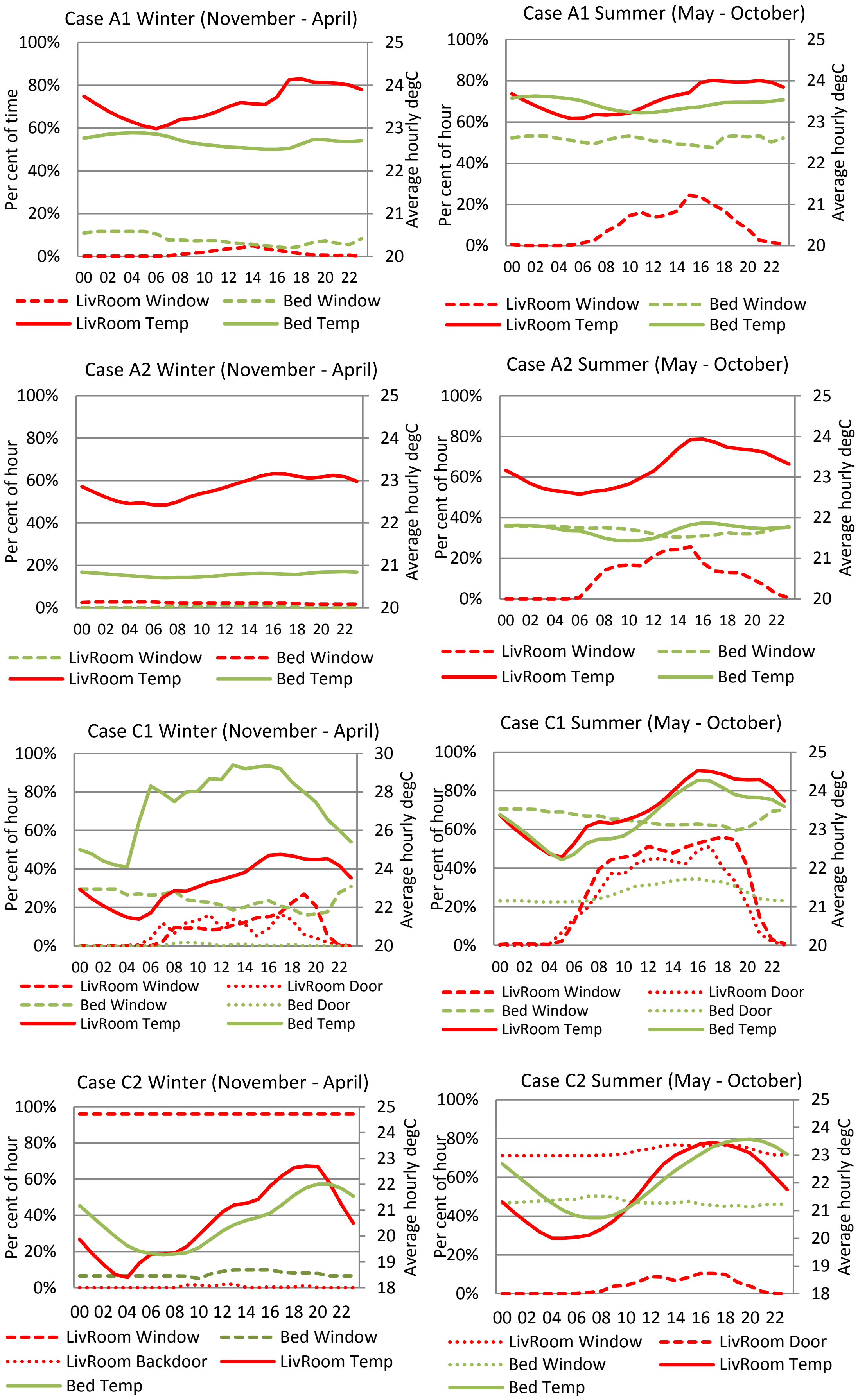

Figure 8 Hourly average temperatures and hourly percentage of window opening across a day.

As shown in the figures above, it is evident that demand temperatures in these houses are high and this is closely related to occupants' expectations of comfort. This level of demand is leading to a gap between design prediction and actual consumption in terms of both energy use and environmental conditions.

7. Occupant experience of operating systems and controls

7.1 User comprehension of systems through handover and user guidance

The handover process and documentation homeowners receive before and after moving into their new home was evaluated in order to gain better insight on the level of occupant understanding of the systems and to establish whether the information that the home owners received is sufficient in communicating the intent and operation of the new home without being overly technical or confusing. Table 5 lists the key findings from the evaluation of the handover and home user guide for all cases.

The study has shown that all local authorities, having experience of a large stock of homes and tenants, are more or less successful in organising and delivering comprehensive handovers and guidance. In Cases A and B the handover demonstrations were simple and clear but were missing some aspects like discussion on handover documentation and hands-on application by occupants. In Case C no phased approach was followed, undermining the occupants' potential of retaining information.

The review of Home User Guides showed that the guides generally contain extensive technical details but do not provide clear guidelines on how to make better use of systems on a daily and seasonal basis. This potentially has a negative impact on user understanding on how to control, operate and maintain the systems.

Follow-up conversations and interviews with occupants have revealed that, in all the three developments, some occupants have failed to understand the purpose and operation of the systems or have forgotten the information that was provided to them initially. Significant risk has been identified regarding the amount of information that the occupants can absorb on the day of the handover. Findings indicate the need for a graduated handover, as well as repetition, hands-on application and clear guidance but also suggest that attention to guidelines is a matter of personal interest.

Table 5 Common emerging issues highlighted by the review of handover and user guidance

	Development A	**Development B**	**Development C**
Handover			
Phased approach during handover	×	×	
Handover was clear and simple	×	×	
PV system was explained	×	×	×
Heating system and controls were explained	×	×	×
Handover would have benefited by follow-up sessions	×	×	×
Handover lacked hands-on application by occupants	×	×	×
Home User Guide			
Document was clear and visual			×
Guidelines on daily operation of systems and controls			
Information was missing	×	×	
Home user was long and confusing	×	×	
Contact information and troubleshooting guidance	×	×	×

7.2 Usability of control interfaces

Control interfaces are the meeting point between the users and the building technology. Investigations into the relationship between the design and usability of controls give an indication of their effect on occupant control and dwelling performance[6] (Topouzi, 2013). Table 6 summarises the key issues that emerge as a result of the review of control interfaces across the six case study houses.

Provision of usable and accessible controls for the MVHR system was an issue for all cases. In Cases A1 and A2 boost buttons are located in the unit cupboard on the first floor but occupants in both houses were not aware of it. The MVHR units in Developments B and C are located in the loft spaces which are very narrow and not easily accessible for maintenance. In Development B changes in the original ventilation and heating strategy late in the design stage led to complications and inadequate space provisions. Poor control over ventilation and poor maintenance has a negative impact on occupant satisfaction and indoor air quality.

Heating controls and thermostats were also found to be problematic in Developments A and B, but for different reasons. In Development B the designer's intention to provide occupants with good levels of control resulted in an excessive use of over-designed thermostats and zones that confuse the occupants and complicated commissioning. On the other hand, oversimplified control interfaces like the ones used in Development A led to similar results in terms of the occupant's understanding and use. Unclear, oversimplified or overcomplicated control strategies have a negative

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[6] The six-point criteria (clarity of purpose, intuitive switching, usefulness of labelling and annotation, ease of use, indication of system response, degree of fine control, accessibility) developed by Buildings Controls Industry Association (BCIA) is used to evaluate control interfaces (Bordass et al, 2007).

impact on the user's ability to understand and control the systems for optimal comfort and may increase energy use.

Table 6 Common emerging issues highlighted by review of control interfaces

	Development A	**Development B**	**Development C**
Conflicting control strategies (masterstat and room thermostats)	×	×	
Oversimplified control interfaces (no indication of system response, no labelling)	×		
Overcomplicated heating controls and zoning		×	
No indication of MVHR failure or maintenance	×	×	×
MVHR unit inaccessible, located in loft		×	×
Windows and doors intuitive and with good fine control		×	×

8. Assessing occupant expectations and satisfaction

8.1 Occupant satisfaction survey

Occupant surveys were carried out in all three developments using BUS questionnaires to assess occupant expectations and satisfaction. Questionnaires were collected from eight houses in Development A, sixteen houses in Development B, and eight houses in Development C. Table 7 lists the positive and negative feedback from the BUS analysis of the three developments (n=32).

Findings give an overall positive opinion of the developments with most elements scoring similar or above the current BUS domestic benchmark (Figure 9). In all developments space, design, layout and appearance were rated favourably. However, control over ventilation and heating was found to be an issue in all developments.

Despite being designed as 'sustainable' housing developments, occupants in all developments consider energy bills to be high. Interestingly, control over heating was rated poorly in Developments A and B that feature heat pumps and underfloor heating. Control over ventilation is rated low in Development B as occupants are confused with the purpose and operation of the MVHR system and underfloor heating.

Dedicated storage space is one of the aspects that was not rated very favourably in Developments A and B as much of the cupboard space is taken up by systems especially since no extra storage provisions were made by the designers.

Overall, the occupant survey indicated that occupants are not very familiar with new technologies such as heat pumps, underfloor heating and MVHR systems and are confused with their operation. This lack of understanding rends occupants sceptical towards these technologies and undermines occupant comfort.

Table 7 Common emerging issues highlighted by occupant satisfaction survey.

	Development A	**Development B**	**Development C**
Positive feedback			
Good overall comfort	×	×	×
Satisfaction with space and layout	×	×	×
Satisfaction with design and appearance	×	×	×
Satisfaction with location		×	×
Satisfaction with light levels (natural, artificial)	×		×
Good storage space			×
Temperatures good overall	×	×	×
Air quality good overall	×	×	×
Negative feedback			
Poor control over heating	×	×	
Poor control over ventilation		×	
Hot during summer		×	
Low daylight levels		×	
Lack of dedicated storage space	×	×	
Noise between houses	×	×	
High energy bills	×	×	×

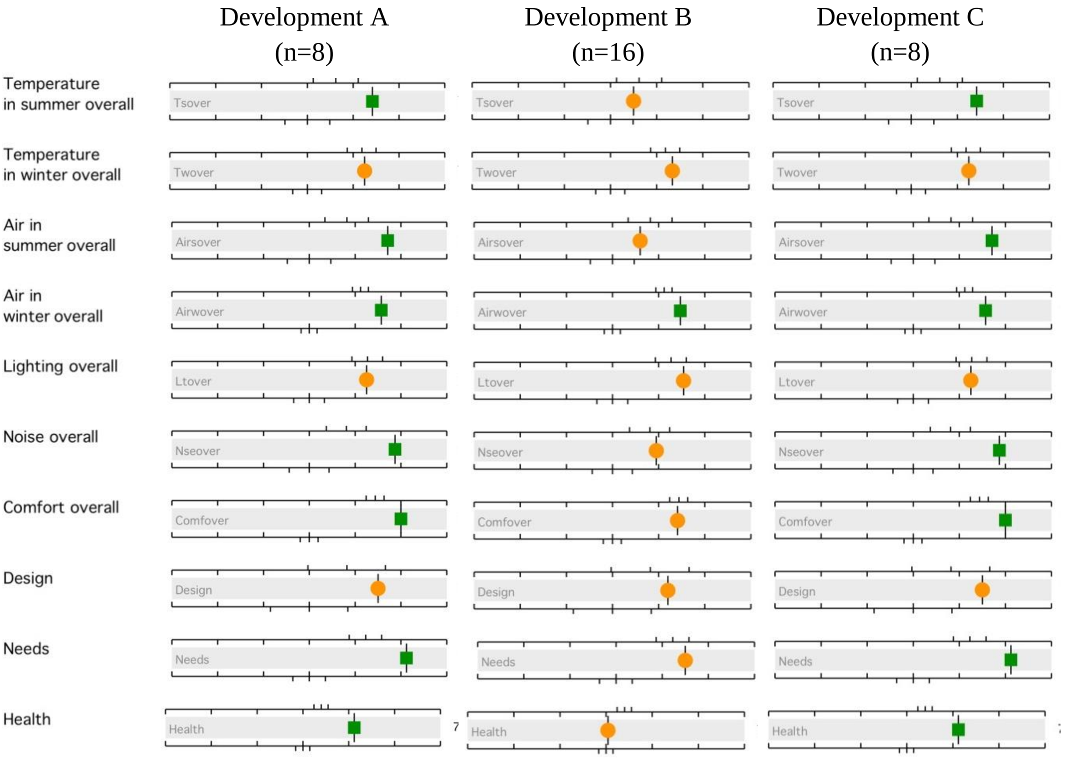

Figure 9 Overall findings from BUS survey in all cases (green=higher than benchmark, amber=similar to benchmark)

8.2 Insights from interviews and walkthroughs

Following the occupant surveys, more detailed information on occupant views, satisfaction and concerns was gathered through semi-structured interviews and walkthroughs with the occupants of the six case study houses. Table 8 summarizes the positive and negative feedback given by the occupants of the six houses during the interviews.

Similar to the results of the occupant survey, occupants in all three developments are fairly satisfied with the appearance, design and space of the houses. Most negative feedback involves the operation and control of the heating and MVHR system. Occupants in Developments A and B feel they do not have enough guidance on how to operate the heat pumps on a daily and seasonal basis and find the Home User Guide confusing. Occupants in Cases A1, A2 and B1 also reported that the guidance they receive is often contradictory and that technicians sent out by the council are not always familiar with the technologies installed in the houses. In addition to this, most occupants are unsatisfied with their electricity bills and occupants in Cases A1, A2 and B1 are dissatisfied with the performance of their heating system.

In Case C2, although the occupants appear to be satisfied with the induction process home user guide, when asked about the purpose and operation of the MVHR and the performance of the PV panels, they were found to be completely unfamiliar with these technologies. This indicates that the information given during the induction process failed to be absorbed by the occupants and also indicates that occupants may have been reluctant to read the home user guide. Despite the fact that occupants within the same development have received the same training and guidance documents, big discrepancies were observed in the level of understanding between different houses, suggesting that attention to guidelines is a matter of personal commitment and motivation; and not just a matter of knowledge and access to information.

Control over ventilation and heating is one of the primary issues affecting occupant comfort. Occupants in Case A1 are confused with how to control the heating and are more dissatisfied with comfort and temperatures than their neighbours in Case A2. Alternatively, faults with commissioning in Development B have left occupants feeling less in control of their thermal environment and have had negative impacts on comfort levels. In some cases MVHR was perceived to be the cause of high electricity bills as it is ‘always on’. Lack of understanding of the purpose, consumption and operation of the MVHR system, resulting from inadequate handover and guidance, in combination with poor commissioning that created noise and unpleasant draughts, made most occupants sceptical towards the system, with some occupants actively closing the supply vents or looking for ways to de-activate the system, thus leading to a potential negative impact on indoor air quality and energy use.

Findings from the interviews indicate that it is challenging to engage occupants in social housing developments and improve their motivation in relation to operating and maintaining the houses. Moreover the combination of many new technologies, unfamiliar to both the occupants and the developers, leads to lack of comprehension.

Table 8 Common emerging issues highlighted by occupant interviews and walkthroughs.

	Case A1	Case A2	Case B1	Case B2	Case C1	Case C2
Positive feedback						
Satisfaction with space	×	×	×	×	×	×
Satisfaction with design and layout		×		×	×	
Satisfaction with daylight	×	×	×		×	
Satisfaction with location		×	×	×	×	
Satisfaction with appearance		×	×	×	×	×
Negative feedback						
Home User Guide considered complicated.	×	×	×			×
Occupants feel lack of control over heating	×	×	×	×		
Dissatisfaction with heating system performance	×	×	×			
Lack of understanding of heating system	×	×	×	×		
Lack of knowledge about MVHR	×	×	×	×	×	×
Draughts and/or noise from MVHR			×		×	
Lack of knowledge about PV panels	×			×	×	
Lack of dedicated storage space	×		×	×		
Noise problems between houses	×			×		×
Occupants think their energy bills are high	×	×	×		×	×

9. Discussion on findings

The key findings from the study of the six case study houses are listed in Table 9. It is clear that energy use in houses depends heavily on the occupants' expectation of comfort and their attempts to attain comfortable conditions. Satisfaction with thermal comfort appears to be closely linked to the level of understanding and control over the heating and ventilation systems in terms of accessibility, clarity of purpose, intuitive switching, usefulness of labelling and annotation, ease of use, indication of system response and degree of fine control.

High indoor temperatures that exceed design assumptions indicate high occupant expectations. Poor air quality, due to inefficient fresh air supply from the MVHR system, along with high occupant expectations, leads to activities such as opening windows when the heating is on during winter. Such behaviours help explain the discrepancies between the designed and actual performance of houses and also between houses of similar occupancies within the same development.

Occupants in most of the case study houses lack understanding of the systems installed, their purpose, operation and energy consumption. Lack of knowledge, on the daily and seasonal operation of systems and maintenance requirements, due to poor or confusing guidance, leads to poor use of systems and subsequently increased energy use. Poor commissioning of heating and ventilation leads to system inefficiency. In particular inadequate commissioning of MVHR system appears to have led to a system imbalance creating an insufficient fresh air supply and as a result, poor indoor air quality and high energy consumption. Additionally, it may lead to draughts and noise that increase occupant discomfort and leads occupants to shut the supply vents or de-activating the units.

Conflicting, confusing and unintuitive heating controls has led to poor occupant control over heating which in turn has a negative effect on comfort and impacts on increased energy use and indoor temperatures. The same applies for inaccessible MVHR controls that have a negative impact on indoor air quality and user satisfaction. Overall findings indicate that lack of control and understanding, resulting from poor commissioning and non-intuitive control interfaces, undermines occupant comfort and has a negative impact on energy consumption.

Table 9 Key findings from the BPE study elements and their effect occupant behavior and energy use

	Findings	**Effect on occupant behaviour and energy use**	**Recommendations**
Fabric performance	• Good wall insulation. Fabric first approach works well. • Thermal bridging across thresholds and beams. Heat loss through party walls. Heat loss through window and door frames. • Air permeability rates much higher than design specifications. Many air leakage paths.	• Positive impact on indoor temperatures. Increased occupant comfort and expectations. • Undermine envelope performance. Negative impact on occupant comfort and energy use.	• Detailing and construction needs more focus to avoid thermal bridges and air leakage paths and ensure airtightness. • Better communication of expectations from design to construction. Improve onsite communication, training and support.
Review of systems installation and commissioning	• Heating system and control not properly commissioned. • MVHR not properly commissioned, vents not locked. System imbalance. Units in lofts inaccessible. Ducts not insulated. • Undersized services and appliance cupboards.	• System inefficiency. Poor occupant control over heating and undermines occupant comfort • System imbalance. Negative impact on energy use and indoor air quality due to insufficient fresh air supply. Draughts and noise increase occupant discomfort undermines IAQ. • Lack of dedicated storage space and occupant dissatisfaction. Occupants use the loft space for storage.	• Installation and commissioning procedures to be more robust, training of engineers and technicians. • • Stronger coordination for services, space needs and design.
Energy & Environmental monitoring	• High temperatures in spaces in winter. Overheating during summer. High thermostat settings. • High CO_2 levels in spaces. • Big discrepancy between designed and actual performance. CO_2 emissions across the six cases differ by 10-23kgCO_2/m^2.	• High occupant expectations. • Not sufficient fresh air supply from MVHR. Window opening when the heating is on during winter. • Gap between designed and actual performance.	• Occupant training and awareness. • On-going energy monitoring and feedback.

Review of handover process and user guidance	• Handover phased approach needed. Handover without follow-up and hands-on experimentation. • Home User Guide long and uninviting. Not clear instructions on daily system management. Unnecessary specification details. • Lack of information on daily and seasonal operation of systems.	• Little information is being retained. • Occupants reluctant to read through guide. • Poor use of systems and increased energy use.	• Well timed, phased training, hands on demonstration. System operation should be explained in a very simple and easy-to-follow way, without technical information, and should only focus on daily and seasonal routines for optimum use. • Visual, simple but comprehensive guides with information on daily and seasonal operation. Avoid technical specification details.
Review of control interfaces	• Conflicting and confusing, unintuitive heating controls. Oversimplified or overdesigned. • MVHR controls without indication of system response. MVHR unit inaccessible. No indication of maintenance or failure. Occupants unaware of boost button.	• Poor occupant control over heating. Negative effect on comfort. Increased energy use and indoor temperatures. • Poor understanding and control over ventilation. Negative impact on indoor air quality and user satisfaction.	• Design controls at initial stages to be accessible, intuitive and with indication of system response, faults and maintenance.
Occupant satisfaction survey & Interviews with occupants	• Occupants are satisfied with space, design, appearance and layout. • Occupants are very appreciative of good daylight levels. • Poor control over heating and ventilation. • High energy bills	• Occupant needs and comfort improved. High expectations. • Undermines occupant comfort and has negative impact on energy consumption and IAQ.	• Empowerment through sense of control. • Occupants need to gain good understanding or the relationship between their daily practices and energy bills. • Occupants need to fully understand how to operate systems and services.

10. Conclusions and recommendations

The overall objective of this research was to evaluate the effect of occupant behaviour, understanding and control on housing performance using a case study based approach. Case study results showed that occupant expectations and perception of comfort has a significant impact on energy consumption and environmental performance of houses with similar family size and occupancy; actual energy use varies by a factor up to 1.5 between houses of similar occupancy within the same development. Actual energy use between houses of different developments varies by a factor of 3.3. Occupants have been recognized as one of the best instruments for measuring housing performance, even if they are hard to calibrate (Cole et al., 2008), and their feedback can quickly demonstrate why a technology does or does not work, as demonstrated in this study. A mixed-methods BPE approach is a robust way to assess the contribution of occupant behaviours to actual energy use and environmental conditions and to reveal the reasons behind the performance gap.

This kind of feedback, provided by the occupants as they inhabit their homes, cross-related with physical monitoring can be fed back into improving the modelling and design of housing as well its management and maintenance in order to reduce carbon emissions.

In order to ensure that low-energy dwellings perform as intended, occupants need to be trained through graduated and extended handover that involves hands-on demonstration, supplemented by visual home user guides offering clear guidance on the daily and seasonal operation of systems and controls. System operation should be explained in a very simple and easy-to-follow way, without unnecessary technical information. Furthermore, occupants need to gain a clear understanding of the effect of their daily activities on energy consumption and controls through energy monitoring and feedback. Informing occupants of the relationship between daily activities, habits and energy bills and showing them ways to actively reduce their fuel bills could attract their interest.

Findings highlight the need for integrating a controls and systems strategy early in the design process. An easy-to-understand but detailed and coordinated services layout plan showing location of systems and controls will provide the basis for a clear and straightforward strategy that occupants need to follow. Controls need to be designed and installed in a more intuitive and user-friendly way that encourages occupants to interact with their environment in an adaptive and positive manner. Strong coordination is required between services and space provisions to avoid any unintended consequences related to access to controls especially for mechanical ventilation.

It has been shown that the installation and commissioning of services and systems influences occupant comfort which is why seasonal commissioning (by certified and experienced engineers) needs to be encouraged for houses with technologies such as heat pumps and MVHR systems. Finally learning from real-world case studies (physical data and stories) is an insightful way for understanding the reasons behind the performance gap between design and actual performance, in order to achieve low carbon housing in practice. This requires a formalized briefing, commissioning and feedback protocol, such as ‘Soft Landings’, that has started to be used in some domestic projects. This will help to ensure that these lessons are captured and fed back to the developers, constructors and the designers. Otherwise there is a risk that UK Government’s zero carbon housing policy may get undermined.

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