MONITORED ENVIRONMENTAL CONDITIONS IN NEW ENERGY EFFICIENT HOUSING IN SCOTLAND – EFFECTS BY AND ON OCCUPANTS

Prof. T. R. Sharpe[1] J. A. Foster[1] A. Poston[1,2]
1. Mackintosh Environmental Architecture Research Unit, Glasgow School of Art, Glasgow, UK.
2. School of Engineering and Built Environment, Glasgow Caledonian University, Glasgow, UK.

ABSTRACT

The need to improve building performance to meet the challenges of climate change has led to increasing numbers of low energy houses being constructed and occupied. Given the drivers for rapid change and use of new materials and technologies, it is vitally important that we understand how these building are working to ensure that they meet expectations, both in terms of energy use but also liveability, comfort and health from the occupants perspective. However, unlike other disciplines, construction rarely evaluates the performance of completed buildings. It is crucial that industry adopts these processes. These buildings are in effect a series of experiments, and the occupants are the subjects of these. There is therefore both a practical and ethical need to review the results and to apply this knowledge in future design.

This paper presents findings emerging from a two-year Building Performance Evaluation (BPE) study, funded by Innovate UK, of 26 new build low energy houses in Scotland, UK. The programme aimed to develop capacity for undertaking BPE and this research undertook detailed monitoring of energy consumption and internal environmental conditions, as well has gathering information from users about how they use their houses. Although it is clear that housing standards are improving, the study has found evidence of performance gaps between design expectations and actual performance, both in terms of energy and also the quality of the internal environment. This paper presents data from four case study houses, which illustrates both the effects of occupancy on performance, but also how the building performance can affect the occupants' experience.

INTRODUCTION

The European Performance of Buildings Directive [1] indicates that 40% of carbon dioxide emissions are attributed to buildings and sets out the legislative framework for EU member states to meet energy and carbon dioxide reductions in buildings in line with Kyoto protocol commitments. In the built environment in Scotland, the carbon emission reduction commitment is legislated through the Building Regulations (Scotland), which has increasing requirements to reduce energy use through fabric and technical measures [2]. This has resulted in a number of low-energy buildings being designed, constructed and occupied. However, as a sector, building performance is not routinely monitored to establish whether the actual performance meets the design intent, despite this being a direct recommendation of an expert panel that authored the Sullivan Report [3].

MEARU have been engaged in a two-year programme funded by Innovate UK for the building performance evaluation (BPE) of 26 new build low-energy homes on six sites across Scotland, part of a wider UK study. The research included the monitoring of internal environmental conditions, energy consumption and the engagement with inhabitants to understand how their homes are used. The results uncovered evidence of design and construction errors that have resulted in the behavior of occupants being adapted to suit their new home environments. Poor usability and a lack of understanding in operation of systems have led to increases in energy consumption and poor environmental performance.

This paper provides four case study examples that illustrate the effect that occupant behavior has on building performance, but also how buildings performance affected the occupants living experience.

METHDOLOGY

The study buildings are located in six separate developments in Scotland, UK. All of the dwellings were constructed post 2009 and designed to be energy efficient to reduce space heating demand and costs. The homes are occupied by social housing tenants (n=20) and owner occupiers (n=6) who purchased through a Shared Equity Scheme operated by the Scottish Government.

Variables monitored in the BPE project included: remote monitoring and data logging of gas and electrical consumption; external and indoor air temperature (°C); relative humidity (%RH); carbon dioxide concentrations (CO_2); and window opening occurrences. These parameters were simultaneously recorded at 5 minute intervals in at least three rooms in each dwelling throughout the monitoring period. The Post Occupancy Evaluation (POE) with householders consisted of: walkthroughs; interviews; surveys; diaries and occupant feedback sessions. This aimed to understand how occupants interact with their homes and to establish aspects of operation of their homes which occupants were concerned about.

The case studies discussed in this paper draw on the variables discussed above, framed by the initial interview with occupants, which aimed to determine dwelling use, understand occupant comfort levels and establish satisfaction of dwelling operation.

RESULTS AND DISCUSSIONS

Across all the dwellings the monitoring showed a clear pattern for high internal space temperatures throughout the year; in some cases the temperatures recorded would be considered to be overheating [4] when compared with the CIBSE guidelines [5] used at the time of their design. Operational misunderstandings were common for both heating and ventilation systems. This included unnecessarily high thermostat settings and the use of electric immersions in domestic hot water systems instead of gas or wood-fuel. There was little use of background ventilation, but more reliance on windows for purge ventilation. Although overall fabric performance was good, there were some exceptions and there was a common lack of thermal continuity in the building fabric particularly at junctions and openings which caused heat loss. Although airtightness on the whole was good - in some cases higher than intended - there were dwellings where construction errors had impacted on the overall airtightness and performance of the building fabric, this in turn affected occupants' thermal comfort and energy consumption.

The lack of occupant knowledge and awareness was addressed by the research team who produced dwelling specific 'quick start user guides' for their homes, which aimed to simplify the operational intent. The guides included boiler details, optimal settings for thermostatic radiator values, how to ventilate etc. In some of the dwellings these were effective. However it was apparent that behaviour developed through occupants previous housing experience, and in early occupancy were difficult to change. The following four case studies indicate the effects experienced by the occupants and their impacts on building performance.

CASE STUDY 1- Central Glasgow, Scotland, UK.

This property is a masonry construction, shared equity, owner-occupied, 2-bedroom ground floor flat located adjacent to a busy main road in central Glasgow. The property is occupied by a single male first-time buyer. The initial interview revealed that overall satisfaction with the dwelling was high except for the occupant indicating that he found the property cold and experienced difficulty heating the living room to a comfortable temperature using the heat emitter (radiator) installed in the room, especially when there were northerly winds. Due to the window openings being floor to ceiling, the radiator was located on an internal wall in the property which could not reduce cold downdraughts from the cooler internal surface temperature of the double glazed windows.

A review of the design intent illustrated that the development was designed and constructed using construction details from the then current, Accredited Construction Details (Scotland) [6] which if used during the design process leads to an assumed airtightness of $10m^3/(h.m^2)$@50Pa by Building Standards and negating the requirement for post construction air permeability testing. At the outset of the BPE project an air permeability test was commissioned by the research team to determine the infiltration rate. Smoke testing was used to identify significant areas of air leakage; these were detected at floor to skirting junctions; wall to ceiling junctions; window to wall/floor junctions; settlement cracks; heating pipework penetrations; electrical socket outlets; services penetrations in the kitchen, bathroom and electrical services entry point. The mean air permeability result was $10.39m^3/(h.m^2)$@50Pa. Additionally, thermographic images revealed cool air paths behind the plasterboard wall linings, reducing interior wall surface temperatures in all rooms within the dwelling. However the occupant only reported thermal discomfort in the living room. This correlates well with the north-east orientation (lack of solar gains) and sedentary activities such as watching television, listening to music and socialising with friends that normally takes place in the living room. The master bedroom and kitchen are orientated south-west and are subject to solar gains. The kitchen also benefits from heat gains from the fridge/freezer and cooking activities.

Reviewing data for the living room over the winter period of 2013-14 illustrated a distinct diurnal heating pattern. Temperatures during unoccupied periods were between 14-19°C depending on corresponding external temperatures, gradually increasing once the property was occupied to peak between 20-24°C during the evenings. Despite this the occupant reported the need to vacate the living room and occupy the two south-westerly rooms (kitchen and master bedroom) during cold, windy periods, on some occasions for days at a time. Although in theory the internal temperature indicates thermal comfort in the living room is reached, the high infiltration rate indicates the cold draughts are of a temperature and airspeed sufficient to affect the occupant's thermal sensation.

The occupant placed bath towels on the floor beneath the full height glazed doors in the living room to help reduce cold draughts from glazing and poor sealing and settlement cracks at the window sill. The occupant also purchased an electrical radiator to improve heat distribution from the radiator, mounted on an internal wall, into the living room. These interventions helped the occupant to feel slightly more comfortable however he still rarely socialises in his home when outdoor temperatures are low. Additionally, the occupant maintains trickle vents in closed positions throughout the property and is not a habitual window opener due to his perception of cold draughts, the need to maintain heat, security fears from being a ground floor property and noise issues from the adjacent main road to the north-east and the dwelling above. The data gathered for window opening occurrences reinforces the lack of window opening in the property, during winter 2013-14 the living room windows were permanently closed with average CO_2 concentrations of 815ppm, indicating during winter the ventilation in the property was met entirely through infiltration. During the winter, the kitchen was seen to have the highest (3000ppm) and most frequent peaks in CO_2 concentration production averaging 1145ppm through the winter.

In this instance the fabric performance, its ground floor position and the wider environment is affecting the lifestyle of the occupant in a quest to achieve thermal comfort. This adaption to living in a modern well-insulated building combined with the noise issues affecting sleep patterns has the potential to cause health implications and increased energy costs.

CASE STUDY 2- Inverness, Scotland, UK.

Monitoring was undertaken in two identical two-bedroom properties located on the ground floor of a block of six flats. The design provides open plan living with sunspaces, off the principal living areas, facing west. Both properties are the homes of first time buyers who are young married couples with no children. The original design concept of the flats included one bedroom and large open-plan living areas with sunspaces with high levels of thermal mass to buffer internal temperatures. However, during the later design stages the housing association requested the accommodation be altered to permit a second bedroom to meet the housing association space standards for affordable homes. This resulted in a smaller living area.

The study found that the sunspace design was compromised due to the omission of high level openings. The internal bi-fold door sets, designed to form the thermal envelope, were downgraded from double to single glazed units and the outer glazing became double glazed to form the thermal envelope. This change undermined the ability of the sunspace to perform as the design intention and combined with the much reduced living area meant the occupants expanded into the sunspace area by permanently leaving the bi-fold doors open. The initial interviews with both sets of occupants revealed they liked their homes and particularly enjoyed the social benefits of the open-plan layout. However there were shortcomings with the properties which included; summer overheating, draughts, impact noise issues from properties above and heating control and hot water generation issues. The monitoring of internal temperatures, airtightness testing and thermography of the building envelope were revealing and supported the claims of the occupants.

Figure 1: Open-plan living area, Case Study 2.

The residual sunspace was found to have negatively impacted thermal comfort in both the summer and winter months. In summer the internal temperature are high, partly due to reduced ventilation opportunities and solar gains through the large west facing glazed façade. The design phase compliance software warned of the 'HIGH' likelihood of high internal temperatures, yet the glazed façade was not optimised. Summer temperature peaks in the now occupied sunspace reached 36°C and the open-plan living room simultaneously reached 31°C. CIBSE guidance [5] suggests temperatures greater than 28°C for more than 1% of the year in a living room is termed overheating. The occupants found difficulty in cooling the space and used electric fans to create air movement. On cloudy days and at night in the winter, the surface temperatures of the double glazing provided a cooling effect through downdraughts which affected occupant thermal comfort, particularly for one household where their sofa is positioned in the sunspace. The sunspace operation was also compromised by advice from the police to use internal curtains or blinds on the external glazing to improve security during the day (although this is a low-crime area). This resulted fewer winter solar gains. To compensate for this the occupants increase the thermostat setting to 23°C on one dwelling and in the neighbouring property the occupants have placed their sofa against the only radiator in the open-plan space and consider their heating to be ineffective. The dwellings are served by a communal biomass system which also had technical difficulties and the occupants reported an inability of the heating system to simultaneously provide heat in the open-plan living room and the two bedrooms. To overcome this, bedroom radiators had been turned off. However, the (small) master bedroom maintained a comfortable temperature despite its north facing aspect and lack of solar gain. Thermography revealed the fridge/freezer and radiator in the adjacent open-plan living space was heating the separating wall and acting as a large low surface temperature radiator in the master bedroom. Hot water outlets in the bathrooms are fitted with thermostatic controls to limit water temperature; however the occupants found the water temperature too low for taking baths and they subsequently topped up the bath water using boiling water from the kitchen kettle.

Other building defects were identified using thermography and thermal bridges in large areas of external wall were identified, in particular surface temperatures in the sunspace were considerably cooler than the adjacent living room. There appeared to be insulation missing in the separating ceiling between vertical neighbours, which could be the route for the impact noise from the property above. It was noted occupants of both households did not frequently open bedroom windows to conserve heat, and condensation on windows and frames was observed. During feedback sessions the research team reported the recording of high CO_2 levels in bedrooms that during January 2014 peaked over 4550ppm correlating to an air flow rate of 1.42l/s (average 1595ppm (4.86l/s)) and advised that windows could be opened during the night to improve internal air quality. Following the feedback the occupants began opening their bedroom window during the night and during February 2014 the peaks were around 2525ppm (2.75l/s) with a February average of 1085ppm (8.37l/s). Although the peaks were above the recommended 1000ppm the occupants reported they had noticed an improvement in the quality of their sleep and the room was not as stuffy as before; they now routinely sleep with the window open.

As described there are a number of defects that could have been avoided through attention to detailing during the design and construction process. Each of these has an energy and environment implication for the occupants living experience as well as potential to affect the health of the occupants. Thermal discomfort during winter and summer was observed by unacceptably high temperatures and cooling downdraughts which caused the occupants to compensate for their discomfort by increasing energy use for heating and cooling. As the heating is not adequately functioning in one of the properties and spaces are unheated, there is an increased risk of microbial growth on cooler wall surfaces in the sunspace and at locations where thermal bridges are present as well as windows. The communal biomass heating and hot water system is operated by a Factor (building management company) who took over the system when the building was completed. This was the first communal heating system they had operated and they had no operational training or advice on how to initiate a charging structure for the delivered heat. This initially caused confusion among the occupants who believed there to be a one-off annual payment. The system has no system for remote monitoring by the off-site factor and they are unaware of system breakdowns as the back-up gas boiler is automatically activated when the biomass boiler fails. The claims of poor heat distribution within the properties has not been checked as the factor considers any faults on the tenant side of the heat exchanger is for the homeowner to investigate.

CASE STUDY 3 - Central Glasgow, Scotland, UK.

This property is located in Central Glasgow in an award winning sheltered housing development which was highly commended for environmental excellence. The property is a rented, one bedroom ground floor flatted dwelling of 49.3m², occupied by a single female retiree. The occupant likes to cook and bake and is very engaged with the communal and social aspect of the sheltered housing complex, providing meals for communal events on a regular basis. She smokes 3-5 cigarettes per day in the kitchen, never anywhere else in the flat.

In her initial interview the occupant stated that she likes her property but highlighted issues with the kitchen lighting and poor ventilation in the kitchen and bathroom. She became very involved in catering for social events, but did not like to cook in the communal kitchen; consequently she did most of the cooking at home using her own cooker.

The design intent of the flats was to provide energy efficient flats which would cut fuel costs for residents, reduce fuel poverty and reduce overall CO_2 emissions from the development. A 'buffer' corridor space was placed between the flats and busy main road to the north-east to improve thermal and sound insulation. The monitored flat kitchen is adjacent to this corridor. To maximise natural light, a large, openable window was proposed, however due to fire regulations (Building Regulations Scotland) the aperture size was reduced and the glazing was required to be non-opening. A pendant light fitting with an energy efficient luminaire was installed to the centre of the kitchen ceiling. The kitchen is located off the living room, separated by a timber door with a large glazed panel to allow borrowed light to the kitchen. Despite this, the occupant found the kitchen to be very dark, which necessitated artificial lighting to be switched on when the kitchen was occupied. The position of the lighting in the centre of the room resulted in shadows being cast over the work surfaces and cooker when the occupant was cooking. To overcome this the occupant fitted plug-in under-counter task lighting and replaced the existing ceiling pendant with a fitting containing four halogen luminaires for better output. This provided more light that allowed her to see when performing cooking tasks, but due to the lack of daylighting the occupant still requires the light to be on when the kitchen is occupied. The luminaire choices have resulted in noticeably higher electricity consumption. The light fitting was changed on 24th June 2013 the electrical consumption for lighting was 24kWh May, 30kWh June and 54kWh during July 2013.

Figure 2: Living room with glazed partitions to kitchen for borrowed light, Case Study 3.

The kitchen is ventilated using a central mechanical extract unit which also serves the bathroom. This is light switch controlled and consequently activated when the bathroom and kitchen lights are on. The occupant had complained that the extract fan was not sufficient at removing smells from the property. The study identified poor quality of installation leading to the exhaust duct separating from the extract unit (located in the hall cupboard) which resulted in moisture, cooking smells and cigarette smoke extracted from the kitchen being dumped in to the hall cupboard and then distributed around the flat. This had implications on indoor air quality; stuffiness; smells and increased potential for microbial activity, which would have health implications for the occupant. Inadequacies in the extract system and increased use due to the lighting problem impacted on energy consumption, both through the ventilation system and the increased energy consumption from the kitchen lighting.

The development consisted of both rented sheltered flats and mainstream flats, some of which were sold under a shared equity scheme. Those purchasing were provided with choices of 'A' rated (for energy) kitchen appliances, whilst rented properties were required to purchase their own kitchen appliances. The occupant of the monitored flat considered an 'A' rated cooker too expensive and purchased a second-hand 'B' rated cooker with electric 4-ring solid plate hob. The impact of this choice is greater in this household because the occupant cooks frequently for the community in the sheltered housing complex (around twice per week for circa 30 people), resulting in higher fuel bills. Based on two years data, the annual electrical cooker consumption for this dwelling was 385kWh, compared with standard benchmark data documented in DomEARM (electrical audit) of 183kWh, over 53% higher. If she cooked in the kitchen located in the communal area designed specifically for communal event catering the fuel costs would be borne by the landlord. However she is reluctant to use this facility as she is unfamiliar with the landlord supplied cooker and is afraid of burning the food. She also worries that she might need to travel between her home and the kitchen for forgotten, utensils and ingredients; which would be difficult for her to do. Consideration needs to be paid to the accessibility and usability of communal spaces, where occupants are nervous or lacking confidence in operation of unfamiliar equipment.

CASE STUDY 4 – Barrhead, Scotland, UK.

This property is a rented, two bedroom end of terrace, single storey cottage located in a housing association development for older people in the town of Barrhead, West Scotland. The property is occupied by a retired couple, who spend most of their time at home. Both of them have health issues and one of the occupants favours a warmer living environment. The design intent of the development was to provide a safe, energy efficient residential development for elderly people. This included installation of a solar thermal system (STS) for domestic hot water and for occupants to save on fuel bills; this was a prerequisite of all developments from this housing association. The property achieved an airtightness of $4.63m^3/(h.m^2)$@50Pa in July 2014 which was below the $5m^3/(h.m^2)$@50Pa threshold at which it is recommended an alternative ventilation method be adopted. Buildings Regulations (Scotland) at the time were $10m^3/(h.m^2)$@50Pa).

In the initial interview the occupants termed the property the "Friday House" they explained that "it's as if the builders were busy to get away on the Friday afternoon and rushed their work". They have had a number of problems, including flooding in the loft space from valves serving the STS and domestic hot water cylinder, leaks from pipes embedded in the bathroom walls to serve the shower, poor drainage issues from the shower and boiler operation problems. Despite these they felt that it was a nice house and much better previous accomodation.

Data from February 2013 indicates the occupants heated their living room to an average of 23°C and the bedrooms 22°C. The maximum temperature in the living room during this month was 27°C and 26°C in the bedroom with internal temperatures frequently exceeding CIBSE comfort guidance [5] for living rooms (22-23°C) and for bedrooms (17-19°C). Despite the occupants preference for warm temperatures they noticed issues relating to overheating particularly in relation to the television and when socialising with a number of people in the living room. The latter has caused the occupants to hire a nearby hall for group gatherings, impacting how they use their home. The male occupant has a condition which requires medical equipment to be operated through the night; the occupants had noted this equipment contributes to heat gains in the bedroom.

In this dwelling, heating control via the hall thermostat is routinely set to 30°C and thermostatic radiator valves (TRV) in each room are set to maximum. There is a digital programmer but it is quite complex and the occupants reported that it took two years to learn how to programme the heating system; however despite the high settings they felt that they used their home efficiently. Lack of control leads them to open their windows when high temperatures had been reached, resulting in energy loss and cost implications.

The occupants felt the STS supply was not adequate and often boosted their domestic hot water. This was reflected through the monitoring period as this dwelling of three monitored had the highest gas consumption and greatest issues with the STS. The monitoring also identified the thermostat in the domestic hot water cylinder had not been properly connected; the repair of this caused a leak. The positioning of the cylinder, STS controls and valves in the loft meant the elderly occupant had to climb a ladder to access the loft to turn off the unit to prevent further damage and subsequently water stains formed on their living room ceiling. The contractor who came to repair the unit did not have access to a drain down point for a container or hose connection and this increased the water damage. The escaped water was left to dry out naturally, the occupants became worried about developing a mould problem and the health effect from associated mould spores. They were also embarrassed by the stain to their living room ceiling and later became distressed and anxious about the length of time it took for the housing association to repair the ceiling.

Whilst the use of the STS system was with the best of intentions, the study found that this user group had relatively low hot water use. As a result the output from the STS system frequently exceeds demand and not fully utilized. Consequently the financial value of this is quite small (circa £45 pa). This may be compared with electrical savings (and incidental heat reductions) of £113 pa when comparing the difference between fridge-freezers in different properties. Given the relatively high capital cost and maintenance burden of the STS this may not be a cost-effective or useful strategy.

CONCLUSIONS

The project revealed a clear link between increase in energy consumption due to fabric defects and higher infiltration rates, but in particular occupant interaction with systems. However in the case of the monitored dwellings, some occupants were on low incomes and the increase in energy consumption could impact on the affordability of heating. This is a particular problem in Scotland, where fuel poverty affects 1 in 3 Scottish households [7], and could have wider consequences on the health and wellbeing of the occupants. An issue with controls was apparent where many of the occupiers were experiencing new technology and they had developed a fear factor of adjusting the technology, in case they broke it. Adaptation and acceptance of problems became the norm rather than engagement and subsequent enhancement of their day to day lives.

The case studies reveal real world impacts of design decisions on occupants' lives, health and well-being. Whilst improvements in building standards aimed at reducing energy consumption are important and necessary, they tend to be predicated on technical measures, with little thought given to usability, comfort and performance. Getting occupants to change behaviors, but crucially giving them the knowledge and tools to achieve this, is crucial and in the long run more effective than technical measures alone. The most energy efficient device is ineffective if it is turned off because the occupant does not know how to use it.

The development of the 'Quick Start Guides' helped to better engage occupants with their homes and the systems. However further work needs to be undertaken to ensure that these are developed by developers and housing associations to be available at the occupants' point of entry into the property.

However it is equally important that designers consider usability and performance requirements at early stages, and ensure that these strategies are robust and buildable. Of greatest importance however is that the construction industry beginning to develop building performance evaluation as a matter of course to improve knowledge, understanding and innovation.

ACKNOWLEDGMENTS

Innovate UK (formerly the Technology Strategy Board, TSB); Glasgow School of Art research funding; participating architects, housing associations and occupants.

REFERENCES

[1] The European Parliament, Council of the European Union: Performance of buildings directive. Journal of the European Union, (2010).
[2] Scottish Government: Technical Handbook – Domestic: Section 6: Energy. Building Standards (Scotland), pp8-14 (2015).
[3] Scottish Government: A Low Carbon Building Standards Strategy for Scotland (The Sullivan Report). Scottish Building Standards Agency, (2007).
[4] Morgan, C; Foster, J.A; Sharpe, T; Poston, A: Overheating in Scotland: Lessons from 26 Monitored Low Energy Homes. CISBAT Conference proceedings, (2015).
[5] CISBE: Guide A: Environmental Design (7th Edition). CISBE, London, (2006).
[6] Scottish Government: Accredited Construction Details (Scotland). Scottish Building Standards Agency, Edinburgh, (2009).
[7] National Energy Action and Energy Action Scotland: UK Fuel Poverty Monitor 2014-2015. NEA. (2014).