Do passive houses need passive people? Evaluating the active occupancy of Passivhaus homes in the United Kingdom

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Abstract: The Passivhaus model emphasises a high standard of building fabric insulation and controlled ventilation with heat recovery in order to achieve comfort and reduce energy use. The implication is that environmental control is achieved by the building fabric and ventilation system with little need for significant occupant interaction or behaviour change in order to achieve comfort and energy efficiency. This paper challenges such views with new research that draws upon empirical data from case studies of houses in the UK built to the Passivhaus standard. It uses inductive analysis of interview data, documenting user-interactions with the houses, and opinions and attitudes of the occupants towards living in a Passivhaus. The research includes both social rented housing and private ownership tenures. The results of this study show both comfort-driven and energy saving-driven behavioural adaptations among the occupants and that the Passivhaus system demands a high level of occupant interaction in order to achieve both comfort and energy efficiency. 'Designing out' occupant's behaviour and reinforcing the image of automated comfort without facilitating occupant behavioural adaptations, could lead to user dissatisfaction in Passivhaus buildings.

Keywords: Passivhaus, behavioral adaptation, comfort, energy efficiency

1. Introduction

The principle of Passivhaus[1] implies that a house designed to Passivhaus standards will achieve good environmental control through its high standards of building fabric and controlled ventilation. Using high levels of insulation, airtight fabric, passive solar gain and mechanical ventilation with heat recovery (MVHR), comfort should be achieved without significant occupant interaction. This study shows almost the opposite: to maintain comfort a significant level of occupant interaction is required. It also finds that the majority of occupants are able and willing to make behavioural adaptations to achieve comfort and improve energy efficiency, in spite of their differing demographics, attitudes and tenures.

The Passivhaus standard has been gaining popularity in the UK over the past decade. Data [1] shows a figure of 270 completed projects and a further 145 under development. While the majority of the projects are privately developed, social housing with Passivhaus standards is also growing, though with a slower rate. To date, more than 50 social housing Passivhaus projects have been recorded. The largest development, which won the 2019 Stirling Prize, contains 93 new built Passivhaus homes [1]. As a direct result of the growth in social housing built to Passivhaus standard, there is a big increase in the number of social tenants living in Passivhaus.

[1] For this research, the term 'Passivhaus' specifically refers to buildings that are modelled in PHPP software, designed to and meeting the Passivhaus standard, both certified, and non-certified.

Despite the potential effectiveness of energy saving that a Passivhaus can bring, the role of the occupants has remained a relatively unexplored topic. A study that gathered opinions from housing professionals shows an assumption that the general public is lacking in knowledge to understand technology in their homes and is unable or unwilling to change their lifestyles [2]. This assumption as criticised by Cherry *et al.* [2], reinforces the view that the occupant interaction should be ‘designed out’ of the Passivhaus model [2]. Similarly, research by Sherriff *et al.* [3] argues that buildings that are designed to engage occupants’ interaction ‘*may result in greater comfort and satisfaction*’. As Janda [4] suggested, ‘Buildings don’t use energy: people do’. Research found that the variance in occupants’ technical knowledge, lifestyle and attitudes affected the performance of Passivhaus homes to a great extent [5] [6] [7].
These studies have shown that tenants of Passivhaus who engage less with the operation of the building can experience a larger performance gap in energy use. Private owners of Passivhaus have also shown dissatisfaction in relation to a lack of knowledge or familiarity of the control system [8]. It is recommended that educational assistance [9] provided by housing associations or design professionals should be readily available after handover stage.

2. Research context

Contrary to the perspective in which comfort is viewed merely as an attribute provided by the built environment and passively received by human beings, researchers have argued that an active process of ‘achieving comfort’ requires people to move into a participative role in buildings. Ever since the 1970s, the comfort model in built environment research has been undergoing a major paradigm shift from the PMV/PPD [10] to the ‘adaptive comfort’ model [11], [12]. The adaptive model integrates humans’ perceptions and activities with their environments, suggesting the concept of comfort is not a static measurement but rather is dynamic and closely related to regional climatic conditions and local cultural and social norms. The three adaptive processes include behavioural adaptation (e.g. personal adjustment of clothing, turning on an air conditioner, or having a siesta), physiological adaptation (acclimatisation) and psychological adaptation (change of expectations or habituation) [13]. The adaptive model indicated the importance of the role of the occupants in household energy use, suggesting the need for a deeper understanding in how occupants perceive indoor comfort as well as their adaptive behaviours in relation to it. With the improvement of building envelope and efficient mechanical systems in the development of low-energy houses, comfort, once again, is in danger of being perceived as an ‘attribute’ [3]. This could lead to the risk of ‘unlearning’ comfort practices and introducing vulnerability towards weather extremes.

A large body of research explores the factors influencing occupant behaviour in residential housing. The major influencing factors can be organised into three categories. The first category is the occupants’ social and economic demographics - including household size, income, ownership, age as well as habitual behaviour [14] [15] [16] [17] [18] [19]. The second category concerns the occupants’ perception of sustainability - including attitudes, lifestyle and awareness of environmental issues [20] [21] [22]. The third category is the occupants’ technical control and received support [23] [11] [24] [25] [26] [27].

Another topic that relates occupant behaviour to particularly low energy buildings is ‘the rebound effect’. It is defined as an economic mechanism that drives an increase in energy consumption following a ‘below-cost improvement’ in energy efficiency [44]. In other words, the energy-saving house also acts as a potential incubator of non-sustainable behaviour. As some previous research reported an increase in pro-environmental behaviour in the users of low energy buildings [3] [22], a number of studies show evidences of 'rebound effect' following increased energy efficiency [28] [29] [30]. The conflicting evidence demands a closer investigation into the occupant behaviour in low energy dwellings.

Developed in and primarily for a continental climate, the Passivhaus standard provides better comfort in extreme cold than in extreme heat conditions. For a mild temperate climate such as in the UK, where prediction of the future climate shows a continuous increase in summertime temperature [31], the summertime comfort and energy related adaptive behaviours in Passivhaus is in particular need of a thorough investigation. A case study by Sassi [32] compared the energy use of two very similar flats built to the *Passivhaus* standard in Cardiff, UK, and questioned the suitability of the standard Passivhaus model for the UK climate. The research surveyed two Passivhaus flats with the main difference being that one flat was operated using an MVHR system for the winter and most of the summer while the other was naturally ventilated (the resident never switched on the MVHR system), with non-uniform temperatures recorded throughout the house (15.5 ˚C–21 ˚C between rooms). Both occupants regarded their home environment to be comfortable, with the naturally ventilated *Passivhaus* achieving lower energy consumption. A recent increase in research of overheating issues in Passivhaus projects has brought occupant interaction into the spotlight [33] [34] [35] [36] [37] [38] [39]. This makes the process of adaptive comfort and the need to investigate occupant behaviour ever more important.

Research on Passivhaus occupants explored their behavioural variations in relation to category 3) technical control and support. It has been suggested that usability of control interface [7] and educational assistance (or soft landing) [9] in controlling Passivhaus systems are important factors in occupant behaviour variance. Furthermore, it has been suggested that preference of temperature settings [32] [37], the control of MVHR as well as preventing overheating [8] can alter occupants' behaviour and activities. Though the first two categories 1) social and economic demographics or 2) perception of sustainability of Passivhaus occupants has not been well explored in Passivhaus research.

3. Methodology and data collection

3.1 Grounded theory methodology in case studies

As a primarily exploratory research study, qualitative methodologies were considered suitable for 'accessing more in-depth information' [40]. Guided by a constructivist epistemology the research explores the 'lived experience' of Passivhaus occupants. The research adopts a case study framework, using Grounded Theory Methodology (GTM) to analyse data from semi-structured interviews conducted with occupants of households living in Passivhaus homes. GTM is a well-established methodology in the field of social research [41] [42] and has been widely adopted in social and behavioural research. Grounded theory is considered to have the potential to contribute to a relatively new field or bring a fresh perspective to areas in which extensive research has already been conducted. Applying grounded theory to the analysis of occupants' behaviours and experiences in a social context allows relevant themes to emerge not only from the built environment field but also from a holistic range of domains. It is, therefore, highly appropriate for adoption in this study in order to construct the complex picture of interactions between the Passivhaus system and its occupants.

GTM focuses on theory development and is unique in the way that it takes a concurrent approach to both the collection and analysis of data. It provides an inductive research procedure and a robust method for analysing qualitative interview data. The systematic framework for sampling, data analysis and theory generation greatly simplifies the research process. Data collection and analysis in this research is carried out simultaneously, thus enabling precision in the sampling of appropriate cases for theory building and a gradual increase in the theoretical sensitivity of the researcher.

The framework of the GTM approach follows a three-step data collection and analysis process, using a progressive coding framework to group and categorise the themes emerging from the interviews. Each interview transcript has gone through open coding, axial coding and theoretical coding before a cross case analysis is carried out to further refine the resulted categories. Complementary to GTM, the case study framework is used to evaluate the architectural and technical characteristics that exist in the studied projects.

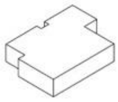
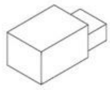
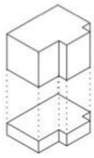
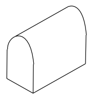
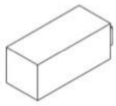
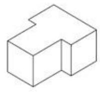
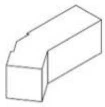
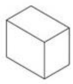
3.2 Sampling and data collection

The data collection in this research uses a progressive sampling method, where the sampling of the subject is not completed in one single, fixed period. This sampling method was used due to the requirement of the methodology as well as the extent of the sampling pool of Passivhaus projects analysed in this research. During the progressive sampling procedure, three groups of Passivhaus projects were investigated between November 2013 and May 2016.The qualitative data collection and analyses were carried out in two phases during this period. Sixteen households living in eleven Passivhaus projects built after 2011 in the UK took part in this research. Ten of these are private households and six are in social rent. The first set of interviews took place between November 2013 and October 2015. The second set of interviews was carried out during 2016 to obtain more information and to have a longitudinal survey. Table 1 provides demographic data on the interviewees. PR1 – 8 are single family private Passivhaus homes. PR9 is a cohousing project in which two households (PR9a and PR9b) took part in the research. SO1 is a social Passivhaus project where four households (SO1a – d) were interviewed. SO2 is another social Passivhaus project with two households participating (SO2a and SO2b). The occupants' ages vary. Most of the two-person households are couples aged between 50-69. SO1c household is occupied by one adult and her grandson. The oldest occupants are in their 80s (SO2a). Houses with more than two occupants usually involve a younger couple or one adult with children of various age.

Household Code	Date of occupancy	Occupancy length on 1st interview date (months)	Occupancy length on 2nd interview date (months)	Gender of interviewee(s)	Ownership	Household size
PR1	2011 - 11	24	N/A	M+F	Private owners	2
PR2	2013 - 01	22	40	M	Private owners	2
PR3	2013 - 02	21	39	M+F	Private owners	2
PR4	2011 - 08	42	N/A	M	Private owners	2
PR5	2013 - 01	24	N/A	M	Private owners	2
PR6	2013 - 03	24	N/A	F	Private owners	4
PR7	2014 - 04	10	N/A	M	Private owners	3
PR8	2014 - 10	6	19	M+F	Private owners	2
PR9a	2012 - 10	32	42	F	Private owners	3
PR9b	2014 - 09	7	N/A	F	cohousing	3
SO1a	2011 - 07	34	N/A	F		3
SO1b	2011 - 07	34	N/A	F		5
SO1c	2011 - 07	34	N/A	F		2
SO1d	2011 - 07	34	N/A	F	Social tenants	2
SO2a	2015 - 06	4	11	M+F		2
SO2b	2015 - 06	4	N/A	M	Social tenants	2

Table 1: Demographic data on interviewees

A majority of the projects are oriented due south or within 30 degrees south and have a Heat Loss Form Factor[2] of 3 or lower. The U-values of the external walls, ground and roofs of all ten projects achieve the recommended U-value (*0.15* W/m^2K), with the lowest U-value of 0.077 $W/(m^2K)$ in PR4. The U-values of the windows in all projects are less than 1 $W/(m^2K)$. All projects had MVHR systems installed, but heating and water strategies vary among the projects. The detailed project data and representative geometries of each project are presented in Table 2.

Code	**TFA** (m^2)	**Building type**	**Bioclimatic region**[3]	**Ventilation strategy**	**Heating strategy**	**Water strategy**	**Typology of project**
PR1	297	Detached	Scotland S	Paul Novus 300 MVHR, open windows	Wood-burning stove	Solar thermal panels backed up by immersion heater	
PR2	184	Detached	Scotland N	Paul Novus 300 MVHR, openable windows	Underfloor heating by combi boiler	Solar thermal panel backed up by combi boiler	
PR3	151	Detached	England E & NE	Paul Novus MVHR, openable windows	Condensing LPG boiler, radiators, in every room	Solar thermal system backed up by boiler, foul water treated by Reed bed system	
PR4	160	Detached	Midlands	Paul Thermos 200 MVHR, openable windows	A one-bar electric fire	PV panel backed up by a 1kw immersion heater	
PR5	163	Detached	Scotland W	Paul Novus 300 MVHR, openable windows	wood stove and 2x electric radiators and 2x heated towel rails	Air source heat pump (connected to MVHR)	
PR6	211	Detached	England SE & S	Paul Novus 300 MVHR, openable windows	Post heater on MVHR, wood burner	Solar thermal and PV panel connected to immersion heater	
PR7	193	Detached	Scotland E	Paul Novus 300 MVHR, Openable windows	wood stove and gas underfloor heating, two towel rails in the bathroom	Solar thermal panels and wood burning stove, backed up by boiler	
PR8	219	Detached	England E & NE	Paul Novus 300 MVHR, openable windows	Post heater and 4 gas powered wall panel heaters	PV, Solar thermal panels and wood burning stove, backed up by combi gas boiler	
PR9a	85						
PR9b	65	Mid-terrace	England W & Wales N	Paul focus 200 MVHR / ComfoAir 200, openable windows	Living room and bathroom radiators, centra l biomass boiler + solar district heating	Central biomass boiler + solar thermal district heating	
SO1a SO1b	102						
SO1c SO1d	88	Semi-detached	Scotland W	Paul Novus 300/200 MVHR, openable windows	Wood burning stove	Solar thermal panels backed up by wood burner and immersion heater	
SO2a	74		Scotland E				

[2] Heat Loss Form Factor = Heat Loss Area / Treated Floor Area (Lewis, 2014)
[3] The summertime temperature average differences among regions fall within 5°C, wintertime temperature 2°C.

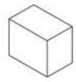
SO2b	80	Semi-detached flat		Genvex MVHR, openable windows	Post heater on MVHR, 3kw electric fire in living room	PV Panel backed up by immersion heater	

Table 2: Project data

According to the Köppen climate classification, the ten projects fall into the category of Cfb (M. C. Peel, 2007), which denotes warm summers ($T_{hot}>10$) and cool winters ($0<T_{cold}<18$). There is a relatively narrow annual temperature range with few extremes of temperature and typical lack of a dry season (M. C. Peel, 2007). However, there are still climatic variations among the projects' locations. According to the UK Met Office, the eleven projects are located in seven different climatic zones. As can be observed from the following table, PR6 is located in the southernmost England SE & S region, with a maximum average daily summer temperature of 21 °C and a minimum average daily winter temperature of 1.8 °C over the past five years (2011–2015). House PR2 is located in the northernmost Scotland N region where there is a maximum daily summer temperature of 15.6 °C and a minimum daily winter temperature of 0.2 °C as an average from the past five years (2011–2015). It appears that the difference in average temperatures between the south and the north during the summer (5.4 °C) is greater than that between the south and the north in the winter (1.6 °C).

In addition to the mechanical devices required to achieve Passivhaus standard, the majority of the household have also installed extra measures to either save energy consumption or/and to improve comfort of the house:

Case code	**Measures and devices installed post-occupancy**
PR1	None
PR2	External automatic blinds on the south-facing bedroom windows Weather station to measure the outside temperature Thermostat control on heated tower rail in the main bathroom
PR3	None
PR4	None (the house is built with other energy saving features such as rainwater collection, composting toilet, etc.)
PR5	(Planned) to install more shading devices (Planned) to move the stove downstairs
PR6	Weather station outside as the occupants had inaccurate expectations of the outdoor temperature Thermometer on the thermal tank to improve accuracy for controlling hot water supply
PR7	Electric heater installed to heat the hot water
PR8	Canopies over south-facing windows Post heater on MVHR system (to be turned into a cooling aid)
PR9a, b	Extra insulation on thermal tank to prevent heat loss from within the tank
SO1a, b, c, d	Fitting in a lighting system as an indicator to control the stove more efficiently
SO2a,b	None

Table 3: Measures and devices installed post-occupancy

4. Data analysis and result

4.1 Two levels of behavioural adaptations

The interview data has been analysed using NVivo computer-aided qualitative data analysis software (CAQDAS). The occupant interaction can be categorised into two levels: the first level of occupant interaction is a result of occupants actively pursuing comfort, termed 'comfort-driven behavioural adaptations'. The second level of occupant interaction is termed 'energy saving-driven behavioural adaptations' where the goal is to achieve further energy savings. Both levels of behavioural adaptations focus on a general and habitual behaviour rather than a detailed daily operational schedule. However, the two levels are not mutually exclusive. Some comfort-driven behaviours could eventually lead to energy saving, though the energy-saving behaviours are exclusively learned behaviours with energy saving as the main aim. The behaviours are categorised based on the main aim of the occupants.

The full list of behavioural adaptations adopted by different are reported in Table 4.

	Behavioural adaptations	**Households**	**Notes**
Comfort – driven behavioural change	Change of attire, bedding	ALL	Cooler clothes, thinner beddings
	Learned behaviour to operate openable windows	ALL but SO2a-b	To intelligently open windows to prevent overheating
	Extra canopies, blinds fitted to prevent overheating	ALL	Mostly post-construction, canopies and blinds have been fitted
	Learned behaviour to operate MVHR	ALL but SO2a-b	Mostly the different fan speed and boost function
	Learned behaviour to operate other basic service system	ALL but SO2a-b	Wood burner, thermal hot water system
	Change of sleeping habit or social habit	SO1a-d, PR4, 5, 6, 7, 8, 9b	Change of focal point in living rooms, Sleep in north-facing bedroom
	Individual room temperature control	PR2, 8	Separated zoning in back-up heating system
	Extra technology installed that increases energy use	PR7, 8	Extra heating/cooling device, automatic heater
Energy saving -driven behavioural change	Being patient on a slow-response system using internal gains	SO1a-d	Wait for internal gain to heat up the house
	Developing habit of checking the weather frequently	SO1a-d, PR2, 4, 6	Use different mechanical systems to the appropriate weather
	Being mindful of additional energy use	SO1a-d, PR4, 5, 6	Be careful not to or set schedule to use immersion heater/heated towel rail
	Learned behaviour to use electric appliances more efficiently	PR4, 5, 6, 8, SO2b	Occupants use PV powered appliances during sunny daytimes
	Extra technical fitting for a more energy efficient control	SO1a-d, PR2, 4, 6	Weather station, thermometer, signal lighting installed
	Keeping an energy data log	PR4	Keep track of energy use
	Community-based learning on energy efficiency	SO1a-d, PR9a-b	Learning from neighbours, energy hearing in community

Table 4: Behavioural adaptations in occupants

As demonstrated in the table above, 'Comfort-driven behavioural adaptation' includes a change of indoor attire into mostly cooler clothes, moving into a north-facing bedroom for a cooler temperature, a shift of focal point in the living room away from the fireplace, a series of learned behaviours to operate windows, blinds to prevent overheating (Table 4).

On the second level of behavioural adaptation, the behavioural change is not essential to achieve desirable thermal comfort but to further achieve energy savings. Not every household has gone the extra mile to ensure the optimum use of Passivhaus system. A few occupants have developed the habit of checking weather more frequently and operate the mechanical systems in relation to the weather for a better efficiency. For example, a weather station, extra thermometer within the house, thermometer on the water tank have been installed for a more precise control (Table 3,4).

The documented behavioural adaptations indicated a certain level of activeness in post occupancy of Passivhaus living for the occupants. Most of the households engaged in comfort-driven or/and energy saving-driven behavioural adaptations. However, a few occupants (PR1, 3, 7, 8) are lacking in energy saving-driven behavioural adaptations. A lack of any behavioural adaptations at all are found in SO2a and b occupants (Table 4).

The interview data also suggests that the occupants have a wide range of indoor comfort preference and temperature uniformity preference. In this research, the set point temperature deviates between 17 – 23^{o}C from one household to another. The interview revealed that the potential reason for setting a high temperature and the motivation to set a low temperature are to a great extent depending on the social implications of comfort. For instance, PR7 occupants suggested that they set the temperature quite high in order not to 'live a life in a jumper'. On the other hand, PR9a household considered the jumper to be an appropriate and comfortable household attire so that the heating didn't have to be always on.

What is also interesting from the interviews is the polar preferences of the temperature deviations throughout a Passivhaus. Most of the occupants appreciated the even temperature throughout the rooms whereas PR3 occupants complained that the temperature was 'too even'.

> […] if you just sit here in the evenings, we want be just a little bit warmer to sit comfortably, so you want to be at 21, but then you go to bed, 21 is too hot, we missed individual temperature control, I think it would be good to have this room at 21 and not have the bedroom the same. (PR3 occupant)

The following table summarises the thermal preference among the households.

Set point temperature	Even temperature across rooms	Slightly varied temperature across rooms
17 - 19^{o}C	PR1, PR9a, PR6, SO1a, c, d	PR3, PR8
20+^{o}C	PR9b, SO1a,b, PR4,	PR7, PR2, PR5,

Table 5: Thermal preference of the studied households

The behavioural adaptations made by each household can be seen as an effort to achieve this variance of indoor comfort within a building system that is designed to have thermal consistency and uniformity. In further investigation into the reasons behind the variety of behavioural adaptations, or a lack of, the research has confirmed the importance of the three categories of factors that affect the occupants behaviours as summarised in previous literature.

4.2 Explaining the behavioural adaptations

In examining the behavioural adaptations with further interview data, it has been revealed that the two levels of behavioural adaptations, i.e. comfort-driven behavioural adaptation and energy saving-driven behavioural adaptation, can be explained by the three categories established in the literature. Technical control and support; perception of sustainability and social and economic demographics. A detailed analysis is as follows:

a. Technical control and support

The first factor that influences the occupant's behaviour is technical control and support. This factor contributes to both comfort-driven and energy saving-driven behavioural changes. The majority of the interviewees reported an increase of confidence and knowledge in post occupancy stage. This set of knowledge includes the basic understanding of Passivhaus principle, passive gain, internal gain, function of MVHR and PV panels.

The following table summarises the means by which the occupants increased their knowledge and confidence:

Increase in knowledge and confidence to control Passivhaus	Households
by trial and error	SO1a, b, c, d, PR2, 4, 5, 6, 7, 8
by reading manuals and books/other built projects/self-learned	PR4, PR7, PR8
by support of professionals/housing association	SO1a, b, c, d, PR1, PR2, PR5, PR6, PR9a
by support of community/neighbours	SO1a, b, c, d, PR9a, b
increased but need more support	PR3, PR1
Not increased	SO2a, b

Table 6: Means to increase the knowledge and confidence in controlling Passivhaus

It can be observed from the table that the majority of the occupants experimented in a trial and error period where knowledge and confidence both grew during their occupancy. Most of the occupants increased their knowledge in control through a combination of self-learning and the support of professionals. Community support and learning also appeared in private owners PR9a and PR9b in a co-housing community of 35 households, as well as in social housing SO1a, b, c, d in a community of 8 household. However, the occupants of PR1, PR3 and SO2a, b reported technical problems that they could not resolve or get any support for. PR1 and PR3 occupants expressed confusion about controlling MVHR or individual room temperature control. Social tenants SO2a and b expressed extreme confusion and dissatisfaction on the ineffective communication of information and support from their housing association. They suggested that the housing association has asked them not to open windows or change MVHR controls.

b. Perception of sustainability

The second category of factors, which has not been well explored in previous literature, includes the occupants' view of climate change, their lifestyle and environment consciousness. During the interview, the occupants were asked questions like 'why choose Passivhaus?', or 'what features of Passivhaus attracted you?', the answers of the occupants can be grouped into three groups using terms borrowed from Verhaller & Van Raaij (1981) based on their attitude towards sustainability. The three groups are comfort-conscious, cost-conscious and environment-conscious. The groups do not exclusively divide the occupants. However, the occupants that belong to each group prioritise either comfort, cost or the environment respectively (Table 7).

Perception of sustainability	Households
Comfort-conscious	PR1, PR7, PR8, SO2a
Cost-conscious	PR3, PR5, PR6, SO1a, c, d
Environment-conscious	PR2, PR4, PR9a, b, SO1b, SO2b

Table 7: Three groups of perception of sustainability

For occupants in comfort-conscious group, the attractiveness of a Passivhaus system is quite exclusively the comfort it provides. As suggested by PR1 occupant, 'comfortable, but not TOO eco-friendly'. The occupants holding such viewpoints often considered comfort and established lifestyle as more important than further energy saving strategies. Hence fewer energy saving behavioural adaptations were made. On the contrary, retaining a passive control has led to adoption of automated mechanical system and subsequently an increase in energy consumption in two households in this research. Interview data revealed that PR8 occupant installed a cooling device in the MVHR to provide cooling in the summer rather than using passive means. In project PR7, the occupant installed an automatic electric heater so hot water supply does not rely on a regular behaviour to control the wood burner.

> In terms of the heating, we got the tank which you can heat water, you have to make sure the tank has heat in it, so it will be able to heat the house any given time. […] Previously, you got to make sure you light the fire

> reasonably regularly, hm... so initially I thought that was a bit of negative change, tight to having to do that. Now we have a little electric heater, so if we are lazy or ill, or having difficulties, that just kicks in and that's... removed a little bit of stress, so it's much better, we only just started last week. It increases our energy bill slightly yes, but it's mainly comforts and easy use… (PR7 occupant)

The 'cost-conscious' group is more conscious of energy use in relation to its cost. For social tenants especially. According to the interview with SO1a, SO1c, SO1d occupants, even without any preconceived ideas of Passivhaus, those occupants appreciated the physical comfort and low energy use, which in turn motivated them to reduce energy use even more. The occupants suggested that the motivation of saving money has become the drive for them to be active in operating the house to its best performance.

The occupants that belong to 'environment-conscious' group are more radical on the topic of sustainable living and consider the Passivhaus system only one part of their sustainable lifestyle. In their own words, they are 'doing my bit for the environment'. The PR4 occupants, for example, lives off-grid from the mains water and gas supply and employs their own waste management system with composting toilet, something considered by the PR1 occupants as 'over the top', and 'too eco-friendly'. PR2 occupant who, after completing his Passivhaus project, continues to tour around the country in construction events to promote Passivhaus system because of his core belief of climate change. Similarly, in the PR9 co-housing project, the two interviewed residents held a deeper green view of the environment. This group also included two social tenants SO1b and SO2b.

c. Social and economic demographics

As can be seen in Table 1, the occupants in this study are a mixture of differing age groups, household size and ownerships. No direct correlations has been found between the variance in social and economic demographics and the behavioural variations. However, the research revealed certain relationships between the ownership and the occupants' behaviour. The majority of the private owners in this research have a higher knowledge level and better access to professional support, whereas the support for social tenants vary between the two projects. For private owners, the professional support comes from a continued communication with the architect and specialist in the post occupancy stage. The support for PR1 and PR3 occupants who showed a lack of confidence in control is insufficient however available. The four social tenants in SO1 project also benefited from an active on-site professional support from the housing association. As a result, all four occupants of SO1, despite their various age and interest in technology, understood the principles of Passivhaus and showed confidence in explaining the system. The knowledge they have about Passivhaus systems is 'basic' but quite adequate for controlling their home environment, and they are quite clear about the principle behind Passivhaus. On the contrary, the two occupants in SO2 were given ineffective information and little support by the housing association and discouraged to experiment with the controls or even open a window. This has led to a lack of any behavioural adaptation of the occupants and frustration and dissatisfaction of the Passivhaus system.

Furthermore, the majority of social tenants adopts a 'cost-conscious' or 'environment-conscious' view on sustainability (Table 6) and are more motivated to save energy than 'comfort-conscious' occupants. In comparison, a higher proportion of private owners of Passivhaus prioritises comfort over cost and the environment than social tenants. Despite of a higher knowledge level and control ability, those occupants retain a passive control and engage in a more energy intensive practice as observed in PR7 and PR8 households.

4.3 Summary of the result

The results have been summarised in Table 8. The activeness of the occupants in comfort-driven behavioural adaptation (CDBA) and energy saving-driven behavioural adaptation (ESDBA) have been graded low, medium and high based on the interview data analysis summarised in table 4, and cross-referenced to their thermal preference, perception of sustainability, social and economic demographics, knowledge and support level for each household.

Code	Social and economic demographics	Technical control and support	Perception of sustainability	Activeness in CDBA	Activeness in ESDBA
PR1	Private owner	Medium knowledge, insufficient professional support	Comfort - conscious	High	Medium
PR2	Private owner	High knowledge, professional support available	Environment - conscious	High	High
PR3	Private owner	Medium knowledge, insufficient professional support	Cost - conscious	Medium	Medium
PR4	Private owner	High knowledge, professional support available	Environment - conscious	High	High
PR5	Private owner	High knowledge, professional support available	Cost - conscious	High	High
PR6	Private owner	High knowledge, professional support available	Cost - conscious	High	High
PR7	Private owner	High knowledge, professional support available	Comfort - conscious	High	Low
PR8	Private owner	High knowledge, professional support available	Comfort - conscious	High	Low
PR9a	Private owner (cohousing)	High knowledge, high community support	Environment - conscious	High	High
PR9b	Private owner (cohousing)	High knowledge, high community support	Environment - conscious	High	High
SO1a	Social tenant	High knowledge, high professional and community support	Cost - conscious	High	High
SO1b	Social tenant	High knowledge, high professional and community support	Environment - conscious	High	High
SO1c	Social tenant	High knowledge, high professional and community support	Cost - conscious	High	High
SO1d	Social tenant	High knowledge, high professional and community support	Comfort Cost - conscious	High	High
SO2a	Social tenant	Low knowledge, ineffective professional or community support	Comfort - conscious	Medium	Low
SO2b	Social tenant	Low knowledge, ineffective professional or community support	Environment - conscious	Medium	Low

Table 8: Rated activeness in behavioural adaptations in relation to sustainability and perceived knowledge

It can be observed that the majority of the occupants show a high level of behavioural adaptation in both comfort-driven and energy saving-driven levels. The relatively less-active households either have a low level of knowledge and support, or/and prioritise comfort over cost and environment. The analyses suggest that even with a cost-conscious or environment-conscious mind, the occupants' behaviours do not necessarily lead to a change of energy saving behaviour if not facilitated with relevant information and support as seen in PR3 and SO2b occupants. It can also be argued that a higher level of technical knowledge and effective professional and community support could increase energy saving-driven behaviours amongst comfort-conscious occupants such as PR1 and SO2a.

The behavioural differences and the level of engagement revealed in various tenure groups further suggested that the technical control and support is more important to social tenants than to private owners. As demonstrated in SO1 and SO2 cases, a higher degree of knowledge and support can directly lead to higher behavioural adaptations and vice versa. Such relationship implies that an effective soft-landing strategy, and a continuous professional and community support throughout post occupancy are critical.

The findings of this research show similar results of behavioural variations as reported in studies on Passivhaus occupants [5]. The comfort-driven and energy saving-driven behaviour changes reflect findings from Brunsgaard et al [8] and Zalejska-Jonsson [22]. The relatively lower behavioural adaptations occurred in PR1, PR3 and SO2 occupants confirms the importance of technical control [7] [27] and professional support [9] as reported in previous research on Passivhaus. Two private owners PR7 and PR8 occupants show a slightly different pattern in their behavioural adaptation by adding more energy-intensive devices is due to a comfort-conscious attitude that confirms the findings regarding comfort and energy saving by [43]. These two households also echo the rebound effect discussed in a number of previous studies [44]. In this research, evidence of a low motivation to reduce energy use can be found in the interview with the PR7 and PR8 occupants. In the PR7 case study, the occupant devised a hot water system with an extra electric heater for convenience, justifying this by suggesting that it did not compromise the Passivhaus concept financially since it only 'increased the bill slightly'. Similarly, the PR8 occupant pondered 'whether putting the MVHR on unoccupied mode when going on holiday' was dwelling on 'such a small amount of cost'. Paradoxically, in the above cases, the energy efficiency provided by the Passivhaus model to some extent prevented the occupants from achieving further energy savings.

The motivations for adopting energy efficient-driven behavioural adaptations concerning three main issues that of comfort, cost and environment echoes the research by Kapedani [20] on Passive homes in Belgium, where the lack of support from architects to implement energy efficiency measures has also been reported. More importantly, the research confirms the argument put forward by Cherry et al. [2] that occupants' behaviour influence need to be 'designed for', rather than 'designed out', by housing professionals to achieve the full designed potential of low energy housing.

5. Concluding remarks, limitation and future research

Although the Passivhaus system is designed and promoted as a building standard that provides comfort and energy reduction with minimum occupant involvement, this research demonstrates that Passivhaus homes demand active users making behavioural adaptations to achieve desired comfort levels without compromising energy savings. To assume that 'Passivhaus supports passive occupants' can misinform prospective residents when making their decisions to choose a Passivhaus. It also reinforces the image of comfort supported by passive control and an automated mechanical system that has been and will continue leading to energy-intensive practice as seen in PR7 and PR8 households. It is especially dangerous where the social tenants of Passivhaus are concerned. On one hand, failing to recognise the behaviour variance of the tenants could lead to unexpected energy spikes as reported in previous research; on the other hand, recognising the issue could also lead to the housing associations preventing the tenants from interacting with the houses, in order to achieve predicted energy performance, which in turn, will result in a negative users' experience, mal-behaviour and increased energy consumption as seen in the case of SO2 occupants. Those assumptions, together with a lack of support for the occupants prevented the Passivhaus model from a wider application in the UK.

As shown in this research, the majority of the occupants are both able and willing to adapt their behaviour if facilitated with sufficient support. Rather than designing out the role of occupants, strategies should be explored to embrace and facilitate the behavioural adaptations of the occupants. The SO1 project has demonstrated that an active support team that provides information and technical support to the social Passivhaus community could improve the users' experience. Moreover, in order to provide the occupants with opportunities to adapt their behaviour and to experiment with the mechanical systems, the design of the Passivhaus needs to be able to provide sufficient adaptive opportunities such as providing adaptive layout and furnishings.

It is important to acknowledge that the existence of a number of limitations during the research design process may have limited the findings. Firstly, the results may have benefitted from further comparison and analysis if environmental measures had been taken at the time of the interview. It may have been possible to achieve more compelling evidence within this experiential data with the inclusion of reference to relevant environmental measures and monitoring of actual energy consumption. Secondly, while emphasising the rigorous methodological approach of this research, it is also important to acknowledge that the conclusions drawn from cross-case analysis with the interview data and a comparison of the cases remain context based. The established categories are true to the collected data, though they could benefit from further research in exploration of their properties with a larger sample size. Further research is needed in the design of Passivhaus dwellings, not with the aim to design out the occupant interaction, but with open arms to embrace and facilitate occupant behavioural adaptations.

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References

[1] Trust, P. (2015) Low Energy Buildings Projects, 2015. Available online: http://www.passivhaustrust.org.uk/projects/

[2] Cherry, C. et al., 2017, Homes as machines: Exploring expert and public imaginaries of low carbon housing futures in the United Kingdom, Energy Research & Social Science, p. 36. doi: 10.1016/j.erss.2016.10.011.

[3] Sherriff, G. et al., 2019, Coping with extremes, creating comfort: User experiences of "low-energy" homes in Australia, Energy Research & Social Science, 51, pp. 44–54. doi: 10.1016/j.erss.2018.12.008.

[4] Janda, K., 2011, Buildings don't use energy: people do, Architectural Science Review, 54:1, 15-22, DOI: 10.3763/asre.2009.0050

[5] Hastoe Housing Association, 2014, Building Performance Evaluation Hastoe HA - 14 Passivhaus at Wimbish. The Technology Strategy Board. [online] Swindon: Building Data Exchange. Available at: https://buildingdataexchange.org.uk/wp-content/uploads/2016/06/450038-Hastoe-HA-14-Passivhaus-at-Wimbish.pdf [Accessed 3 May 2019].

[6] Carruthers, J. and Foster, J., 2018, Occupant Experience and Monitoring Results. Passivhaus Social: Glasgow. 05, 2018.

[7] Stevenson, F., Carmona-Andreu, I. & Hancock, M., 2013, The usability of control interfaces in low-carbon housing. Architectural Science Review, 56(1), 70-82.

[8] Brunsgaard, C., Knudstrup, M.-A. & Heiselberg, P., 2012, Occupant Experience of Everyday Life in Some of the First Passive Houses in Denmark. Housing, Theory and Society, 29(3), 223-254.

[9] Schoenefeldt, H. N., Adam ; Ringrose, Jessica ; Seaman, Rosie ; Willett, Sebastian ; Ashdown, Sam ; Bowers, Karl ; Gandhi, Natasha ; Waterson, Tim ; Hayward, Thomas ; Peluffo - Navarro, Miguel ; Hill, Cordelia ; Fleming, Sam, 2014, Interrogating the technical, economic and cultural challenges of delivering the PassivHaus standard in the UK. Kent school of architecture, the Centre for Architecture and Sustainable Environment.

[10] P.O. Fanger, 1970, Thermal comfort: Analysis and applications in environmental engineering, Danish Technical Press.

[11] de Dear, R. J., Akimoto, T., Arens, E. A., Brager, G., Candido, C., Cheong, K. W. D., Li, B., Nishihara, N., Sekhar, S. C., Tanabe, S., Toftum, J., Zhang, H. & Zhu, Y., 2013, Progress in thermal comfort research over the last twenty years. Indoor Air. Dec.

[12] Humphreys, M. A. & Nicol, J. F., 1998, Outdoor Temperature and Indoor Thermal Comfort: Raising the Precision of the Relationship for the 1998 ASHRAE Database of Field Studies, Transactions- American Society of Heating Refrigerating and Air Conditioning Engineers.

[13] de Dear, R., & Brager, G., 1998, Developing an adaptive model of thermal comfort and preference. UC Berkeley: Center for the Built Environment. Retrieved from https://escholarship.org/uc/item/4qq2p9c6.

[14] Groot, E. d., Spiekman, M. & Opstelten, I., 2008, Dutch Research into User Behavior in Relation to Energy, 25th Conference on Passive and Low Energy Architecture. Dublin.

[15] Guerra Santin, O., Itard, L. & Visscher, H., 2009, The effect of occupancy and building characteristics on energy use for space and water heating in Dutch residential stock. Energy and Buildings, 41(11), 1223-1232.

[16] Kane, T., Firth, S. K. & Lomas, K. J., 2015, How are UK homes heated? A city-wide, socio-technical survey and implications for energy modelling. Energy and Buildings, 86, 817-832.

[17] Liao, H.-C. & Chang, T.-F., 2002, Space-heating and water-heating energy demands of the aged in the US. Energy Economics, 24(3), 267-284.

[18] Sardianou, E., 2008, Estimating space heating determinants: An analysis of Greek households. Energy and Buildings, 40(6), 1084-1093.

[19] Sodagar, B. and Starkey, D., 2016, The monitored performance of four social houses certified to the Code for Sustainable Homes Level 5, Energy & Buildings, 110, pp. 245–256. doi: 10.1016/j.enbuild.2015.11.016.

[20] Kapedani, E., Herssens, J. and Verbeeck, G., 2019, Designing for the future? Integrating energy efficiency and universal design in Belgian passive houses, Energy Research and Social Science. doi: 10.1016/j.erss.2019.01.011.

[21] Verhaller, T. M. M. & Van Raaij, W. F., 1981, Household Behavior and the Use of Natural Gas for Home Heating. Journal of Consumer Research. Dec 1981.

[22] Zalejska-Jonsson, A., 2012, Evaluation of low-energy and conventional residential buildings from occupants' perspective. Building & Environment. Dec2012, 58, 135

[23] Guerra Santin, O., 2011, Behavioral Patterns and User Profiles related to energy consumption for heating. Energy and Buildings, 43(10), 2662-2672.

[24] Darby, S., 2010, Smart metering: what potential for householder engagement? Building Research & Information, 38(5), 442-457.

[25] Van Dam, S. S., Bakker, C. A. & van Hal, J. D. M., 2010, Home energy monitors: impact over the medium-term. Building Research & Information, 38(5), 458-469.

[26] Peffer, T., Pritoni, M., Meier, A., Aragon, C. & Perry, D., 2011, How people use thermostats in homes: A review. BUILDING AND ENVIRONMENT, 2529.

[27] Isaksson, C., 2014, Learning for lower energy consumption. International Journal of Consumer Studies, 38(1), 12-17.

[28] Haas, R. and P. Biermayr., 2000, The rebound effect for space heating—Empirical evidence from Austria. Energy Policy 28(6–7): 403–410.

[29] Bentzen, J., 2004, Estimating the rebound effect in US manufacturing energy consumption. Energy Economics 26(1): 123–134.

[30] Sorrell, S., Dimitropoulos, J., & Sommerville, M., 2009, Empirical estimates of the direct rebound effect: A review. Energy Policy, 37(4), 1356–1371. https://doi-org.proxy.library.lincoln.ac.uk/10.1016/j.enpol.2008.11.026

[31] UKCP09 (2009) UK Climat Projections, 2009, Available online: http://ukclimateprojections.metoffice.gov.uk/21678 [Accessed.

[32] Paola Sassi., 2013, A Natural Ventilation Alternative to the Passivhaus Standard for a Mild Maritime Climate. Buildings, (1), 61. https://doi.org/10.3390/buildings3010061

[33] Lavafpour, Y. & Sharples, S.,2015, Summer Thermal Comfort and Self-Shading Geometries in Passivhaus Dwellings: A Pilot Study Using Future UK Climates. Buildings, 5(3), 964.

[34] McLeod, R. S., Hopfe, C. J. & Kwan, A., 2013, An investigation into future performance and overheating risks in Passivhaus dwellings. Building and Environment, 70, 189-209.

[35] Sehizadeh, A. & Ge, H., 2016, Impact of future climates on the durability of typical residential wall assemblies retrofitted to the PassiveHaus for the Eastern Canada region. Building and Environment, 97, 111-125.

[36] Tabatabaei Sameni, S. M., Gaterell, M., Montazami, A. & Ahmed, A., 2015, Overheating investigation in UK social housing flats built to the Passivhaus standard. Building and Environment, 92, 222-235.

[37] Rojas, G., Wagner, W., Suschek-Berger, J., Pfluger, R. & Feist, W., 2015, Applying the passive house concept to a social housing project in Austria – evaluation of the indoor environment based on long-term measurements and user surveys. http://dx.doi.org/10.1080/17512549.2015.1040072.

[38] Fletcher, M. J. et al., 2017, An empirical evaluation of temporal overheating in an assisted living Passivhaus dwelling in the UK, Building and Environment, 121, pp. 106–118. doi: 10.1016/j.buildenv.2017.05.024.

[39] Costanzo, V., Fabbri, K. and Piraccini, S., 2018, Stressing the passive behavior of a Passivhaus: An evidence-based scenario analysis for a Mediterranean case study, Building & Environment, 142, pp. 265–277. doi: 10.1016/j.buildenv.2018.06.035.

[40] B.K. Sovacool, J. Axsen, S. Sorrell, 2018, Promoting novelty, rigor, and style in energy social science: towards codes of practice for appropriate methods and research design, Energy Res. Soc. Sci., 45 (2018), pp. 12-42, 10.1016/j.erss.2018.07.007

[41] Glaser, B. G. & Strauss, A. L., 1967, The discovery of grounded theory: strategies for qualitative research. Aldine Pub. Co, Chicago, New York.

[42] Strauss, A. L. & Corbin, J. M., 1990, Basics of qualitative research: grounded theory procedures and techniques. Newbury Park, Calif.; London: Sage Publications.

[43] Xu, X. et al., 201, Investigating willingness to save energy and communication about energy use in the American workplace with the attitude-behavior-context model, Energy Research & Social Science, 32, pp. 13–22. doi: 10.1016/j.erss.2017.02.011.

[44] Bourrelle, J. S., 2014, Zero energy buildings and the rebound effect: A solution to the paradox of energy efficiency? Energy & Buildings. https://doi -org.proxy.library.lincoln.ac.uk/10.1016/j.enbuild.2014.09.012