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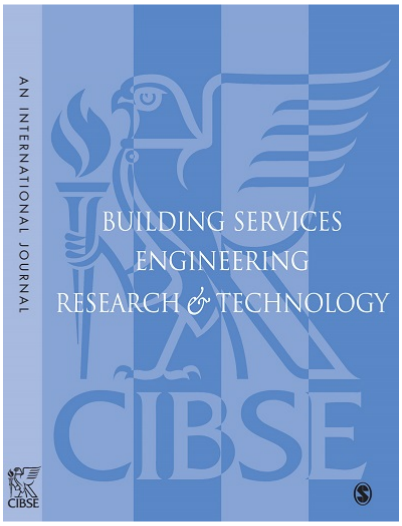

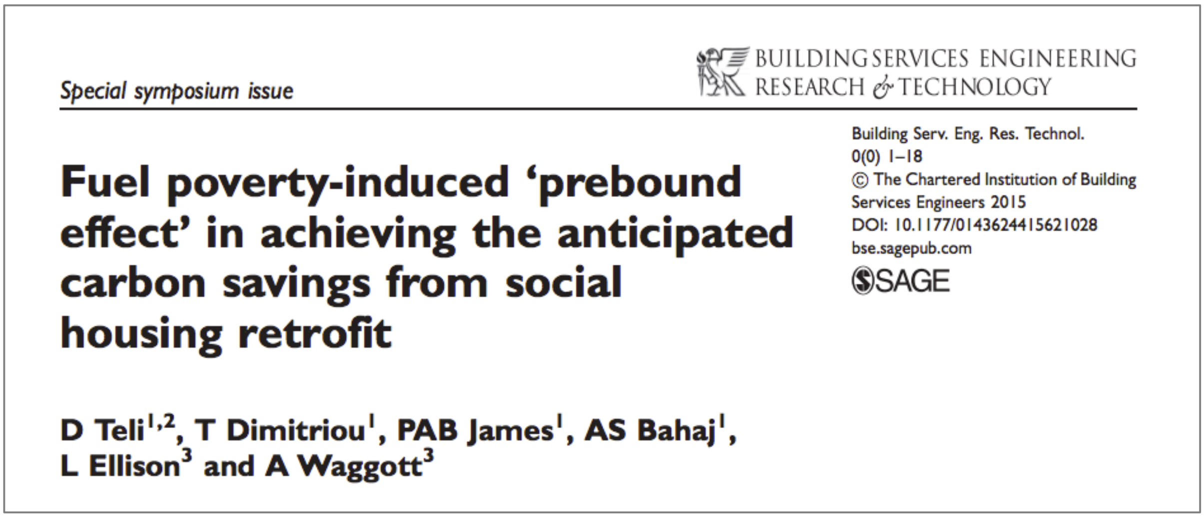

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Fuel poverty-induced 'prebound effect' in achieving the anticipated carbon savings from social housing retrofit

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Fuel poverty-induced ‘prebound effect’ in achieving the anticipated carbon savings from social housing retrofit

Abstract

Social housing retrofit is often seen as a way to contribute to carbon reductions as it typically encompasses large-scale interventions managed by one landlord. This work investigates the carbon savings potential of a deep retrofit in a local authority owned 107-flat tower block, taking into account the tenants’ pre-retrofit heating strategies. Prior to the retrofit, temperature and relative humidity monitoring was undertaken in 18 flats for 35 days. The measurements were then used to develop occupant heating profiles in the 18 homes. Dynamic thermal simulation of the flats pre- and post-retrofit using the identified user heating profiles highlights that for these fuel poverty constrained flats the estimated carbon savings of retrofit will be typically half those predicted using standard rules for temperatures in living spaces.

Keywords

Prebound effect, rebound effect, MVHR, occupant behaviour, retrofit, fuel poverty

Practical application

The findings presented in this paper demonstrate the impact of fuel poverty on the expected benefits from social housing retrofit schemes, providing information relevant to multiple stakeholders: 1. Building industry: The study highlights the need to use empirical data in building energy modelling, as typical conditions could be far from representative in social homes 2. Policy makers and social landlords: Targets for CO_2 reduction may not be achieved through retrofitting, but the social impact could be much greater and more critical than assumed. The findings under this work help to direct incentives for retrofit schemed towards the social and health benefits achieved.

Introduction

The UK government’s Climate Change Act has set a target of an 80% reduction in carbon emissions by 2050 from the 1990 baseline, with an interim target of a 34% by 2020.[1] The domestic sector currently accounts for approximately 29% of UK’s carbon emissions,[2] making this an area of interest for potential carbon savings. However, the replacement rate of

UK housing stock is currently low, being less than 1% per annum.[3] A large proportion of dwellings that will exist in 2050 are already built and therefore house retrofit has been recognised as an essential area for carbon reductions.[4, 5]

Retrofitting has become the focus of several UK Government financial schemes, such as the recently closed Green Deal[6] and ECO (Energy Company Obligation)[7] - which replaced schemes such as CERT (Carbon Emission Reduction Target)[8] and CESP (Community Energy Saving Program).[9] Retrofitting involves interventions to the building with the aim of improving energy performance,[10] such as changes to the building fabric, replacement of fixed appliances, provision of controls and monitoring systems. Despite government support and recognition of the savings potential of such measures, uptake has not been as rapid as had been hoped.[11] Retrofitting of existing buildings is a complex process which needs to consider numerous parameters such as building size, age, social value, function, occupants' needs, behaviour and financial state.[12, 13] This process becomes even more challenging in social housing buildings, where social and economic vulnerabilities are high.

Social housing and fuel poverty

The UK social housing sector represents 18% of the UK building stock (4.7 million homes)[3] and provides affordable housing for households with an average income equal or less than £11,000 a year.[14] 'Fuel poverty' describes a combination of interacting factors, i.e. low income, inefficient building fabric, inefficient heating systems and poor access to fuel services.[15]

In 2012 the Fuel Poverty Review by John Hills was released.[16] This has led to a change in the definition of fuel poverty from the simple '10% of household income on energy' to a twin low income-high cost threshold.[17] The report's recommendation is that a household is considered fuel poor if:

'They have required fuel costs that are above the median level' and 'were they to spend that amount they would be left with a residual income below the official poverty line'.[16, 17]

Fuel poverty is measured using a methodology, which calculates the cost of heating a home by taking into account the current price of heating fuels, the household income and the energy efficiency of the building.[18] The household energy consumption is modelled using BREDEM, the BRE domestic energy model.[19] The adequate warmth for comfort, defining the 'poverty line' used in fuel poverty assessments, is 21°C for the living room and 18°C for all other rooms, as defined by the World Health Organization.[20]

According to the annual report on fuel poverty statistics 2015, the total number of fuel poor households in the UK in 2013 was estimated at around 4.5 million, accounting for around 17% of the UK households.[17] The efforts to improve the energy performance of buildings, and especially retrofit projects in low-income houses, resulted in a decrease in fuel poverty figures in 2010, the first decrease since 2003. Since that drop and until 2013, figures show a slight but increasing trend of fuel poverty.[17]

Minimum recommended indoor temperatures

One of the main roles of a building is to ensure comfortable conditions for its occupants, with temperature being considered as the most important factor for comfort.[21] Cold temperatures in the home can have direct effects on health, e.g. increased morbidity and mortality and indirect effects, such as mental health illness.[22] The ‘Cold Weather Plan’ of 2013 provided recommended minimum temperatures of 21°C and 18°C, for the rooms occupied during the day and during night-time respectively,[23] based on recommendations from the World Health Organisation.[20, 22] A review published in 2014 revisited the temperature thresholds, looking at evidence to support the recommended values.[24] Following this review, the Cold Weather Plan was updated in 2014, recommending a single temperature threshold of 18°C for a sedentary person, wearing suitable clothing,[25] as no sufficient evidence was found to fully support the 21°C limit. However, based on the 2014 review,[24] temperatures up to 21°C may be beneficial for health. Considering that social housing is intended for vulnerable groups and often accommodates elderly people, higher temperatures than 18°C may be required. In this study, the WHO recommended thresholds of 18°C and 21°C are used, as these are considered to be the “adequate level of warmth” in fuel poverty assessments.[17]

It should be highlighted that, besides air temperature, thermal comfort is also influenced by radiant temperature, air velocity, relative humidity, occupants’ clothing insulation and metabolic rate. [26] Furthermore, comfort is affected by the outdoor climate and the way building occupants adapt to it.[21] This paper focuses on the recommended indoor temperature thresholds for winter; therefore a detailed thermal comfort study is not included. However, further research needs to address this aspect, since thermal comfort is one of the goals of energy efficiency improvement projects and a driver of occupant behaviour.

Energy efficiency improvement of social housing buildings

Social housing has been identified as a leading sector for retrofitting[27] as it can support large-scale development since it is not restricted by personal financial circumstances. This is very important with the implementation of the Green Deal, which was designed to support the development of sustainable retrofit for both the private and social stock.[10] According to the Communities and Local Government plan, a 29% reduction in the emissions from 2008 in the social housing sector is expected by 2020.[14] However, the social housing stock appears to have better energy performance than the housing stock as a whole and therefore other sectors, such as older privately owned houses, might present better opportunities for deep carbon reductions.[28] On the other hand, fuel poverty is a common problem in social homes, driven by their low incomes,[29] which further justifies the need for retrofitting of social housing buildings. This is in line with the new fuel poverty target for England, which focuses on improving the energy efficiency of fuel poor homes.[30]

In the case of implemented retrofitting projects, there is often a gap between the theoretical designed and actual performance of retrofit measures,[31, 32] which can reach up to 50%.[14] The main sources of discrepancy between predicted and actual performance that have been reported [33] include: a) design assumptions which can lead to oversimplifications regarding building construction, management and user behaviour, b) oversimplified energy modelling tools, c) management strategies that can lead to waste of energy, d) occupant behaviour and e) quality of construction. In social housing retrofits, the inability to achieve significant carbon reductions has been attributed to a lack of extensive technological solutions[11] or to funding constraints and lack of acceptance of refurbishment measures by the residents.[34] This paper investigates the impact of occupants' present and pre-retrofit heating regimes on the expected carbon savings in a council owned tower block undergoing retrofit.

Case study characteristics

The study presented here was undertaken in 2013 on a social housing tower block. The building is located in the central Portsea Island area of Portsmouth, UK and is owned and managed by the local authority Portsmouth City Council (PCC).

Tower block

The tower block was constructed in 1968 using prefabricated concrete sandwich panels with a thin 25mm layer of insulation (overall U-value = 1 W/m^{2}K). This leads to significant heat losses through the building’s fabric, as determined by our thermal survey conducted on the building (Figure 1). The property is an 11-storey development of three linked blocks. It contains 107 properties and the dwelling format is that of stacked maisonettes accessed on alternate floors via a communal deck. A typical maisonette includes three bedrooms: two on the entrance level along with a kitchen-dining room and a third on the upper level coupled with a living room and a bathroom. The living rooms incorporate a ‘sunspace’ on a section above the access deck. The maisonettes are heated with electric storage heaters, contributing to the challenge of providing adequate economic heating in the properties. Therefore, the case study building considered is poorly insulated and electrically heated, with potentially high fuel costs, and houses low or very low income tenants. Almost all these tenants would meet the definition of fuel poverty if they chose to heat their home.

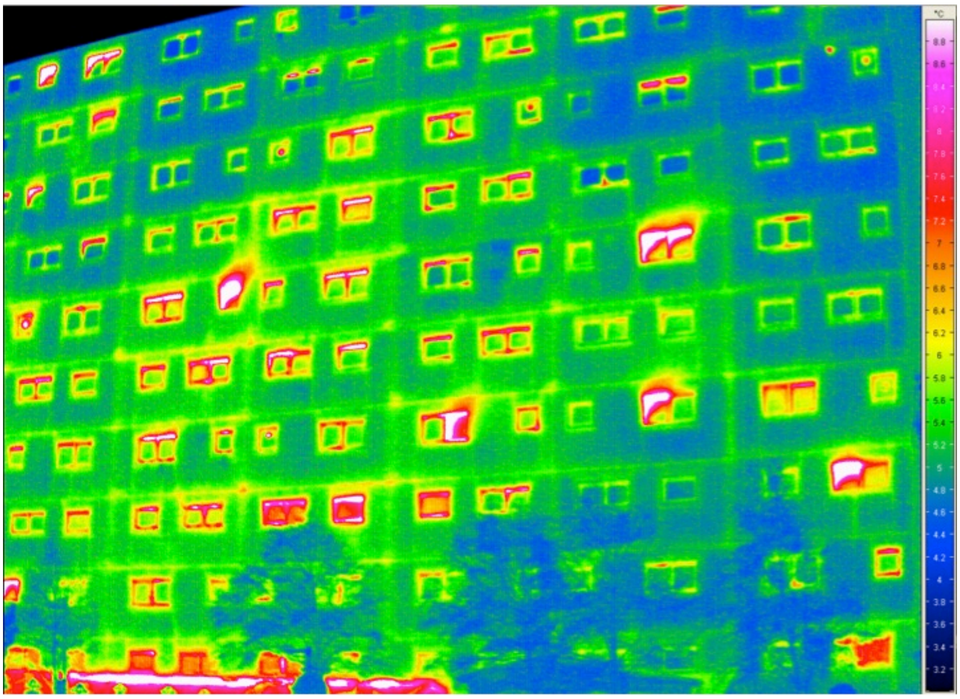

Figure 1. Thermal survey showing results of infra-red image of the North façade of the tower block prior to retrofit. Heat loss through the fabric and thermal bridging are evident.

Retrofit scheme

A number of major elements of the building have reached the end of their serviceable life, which has led to a major refurbishment scheme being established. A pre-refurbishment evaluation assessed 21 out of 107 properties calculating an average SAP rating of 54.[35] The measures proposed by the design team ECD Architects Ltd aim to meet the stringent EnerPHit criteria,[36] the Passivhaus certificate for retrofits.

The Passivhaus certificate is recognised internationally and aims to achieve low building energy consumption (15 kWh/m^2/annum space heating) and airtightness. Its criteria are often difficult to meet in refurbishment projects due to the existing building infrastructure, technical challenges such as thermal bridging and cost. Therefore, the criteria have been adjusted for retrofits, developing the EnerPHit standard,[36] which limits the annual space heating to 25 kWh/m^2/annum.

In order to achieve the EnerPHit standards in the case study tower block, the following strategies were set:

- External wall insulation render for the North/West elevation, with building fabric upgrade to at least 0.15 W/m^{2}K, and roof upgrade to 0.10 W/m^{2}K.
- South/West surface over-cladding, enclosing the living room sunspaces and the access decks.
- At the roof level, high performance insulation with waterproof membrane solution.
- Triple-glazing fenestration with a maximum U-value of 0.8 W/m^{2}K.
- Improvement of air tightness of the fabric to 1.0 m^3/hr/m^2 @ 50Pa.
- Installation of mechanical ventilation with heat recovery system (MVHR).

Methodology

The study includes prior to retrofit environmental monitoring during the heating season and thermal simulations using TRNSYS, as described below. Data from a questionnaire survey conducted by Portsmouth City Council (PCC) are also used for comparison.

Environmental monitoring

Eighteen flats were monitored for 34 days from 18 March 2013 to 22 April 2013. Due to different installation and collection dates of the data loggers between flats, the monitoring period with simultaneous measurements in all 18 flats is from 23/03/13-20/04/13 inclusive. Figure 2 shows the daily average ambient temperature and relative humidity during the entire monitoring period, using data provided by Gosport Weather station,[37] which is located 2km West of the case study building. As can be seen, the ambient temperature profile presents two distinctive periods: (a) a very cold week between 25 March and 31 March and (b) a warmer week from 13 to 19 of April. This enables an investigation into tenants' response to very cold conditions and to the transition to higher temperatures within this study.

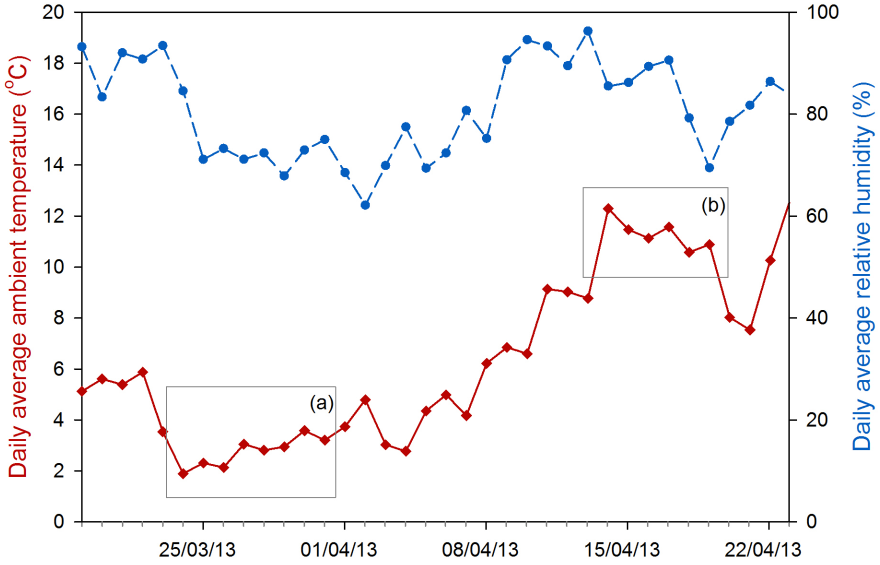

Figure 2. Daily average ambient temperature (bottom line) and relative humidity (top line) during the monitoring period (data from: Gosport weather station), (a) Prolonged cold period, (b) warmest days of study.

The monitoring in the flats was undertaken using MadgeTech 2.04 matchbox size data loggers which record snapshot readings of air temperature and relative humidity. The accuracy of the reading for the temperature is ± 0.5 °C and the relative humidity calibrated accuracy is ± 3%. The sensor output integrity of the loggers was validated prior to installation by comparing readings in a controlled environment.

Two loggers were placed in each of the flats under study, one in the lounge and the other in the bedroom. The loggers were configured to take snapshot (single-value) readings every three minutes. The positions of the data loggers in the rooms were chosen so as to minimise direct exposure to the heating system or any source of abnormal humidity and to avoid any disturbance to the residents.

Such high frequency of measurements helps to identify the occupants' heating patterns during the monitoring period. These were then crosschecked with a questionnaire survey conducted in 76 properties in 2014, before the refurbishment, by Portsmouth City Council. In total 72 responses were used in this analysis, after excluding those that had recently moved in and therefore had not experienced a heating season in the property.

TRNSYS thermal modelling

In order to assess the potential impact of user behaviour to projected performance of the refurbishment scheme, a representative maisonette of the tower block, shown in Figure 3, was simulated using the thermal simulation software TRNSYS.[38] The flat (total area 89 m^2) was modelled as two zones; namely the lounge and bedroom, with areas of 22 m^2 and 11.1 m^2 respectively. The results of the bedroom zone were then used for the calculation of the heating demand of the remainder of the flat, since the same criterion of 18°C applies and the space characteristics of the remainder of the flat are similar. On average, the internal gains of the rest of the flat were assessed to be similar to the bedroom. To account for vulnerable groups typically found in social housing, the recommended WHO temperature threshold of 21°C was used for the lounge, instead of the general threshold of 18°C set by the Cold Weather Plan for England 2014.[25]

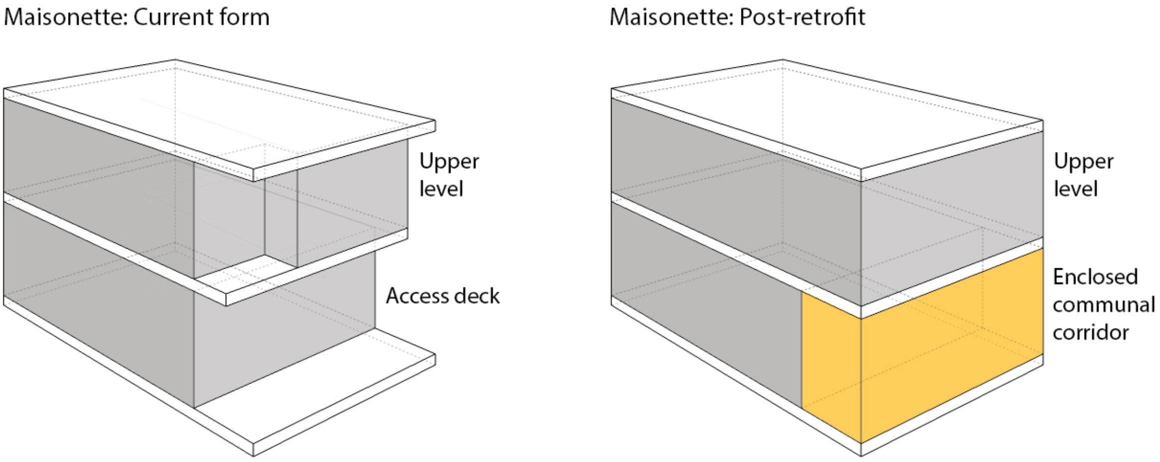

Figure 3. Schematic of the maisonette form pre- and post-retrofit (Access deck on the ‘South’ elevation) used in the thermal modelling.

In the pre-retrofit thermal simulations, an overhang shading parameter was included, which is created by a recess walkway of the flat on the South façade (Figure 3). After refurbishment, this recess will be incorporated within the building fabric to create a thermal buffer zone. The high thermal mass of the building (concrete structure) was also taken into consideration. The pre-retrofit infiltration rate was determined through air leakage testing[35] and was on average 3 ACH (air changes per hour) @ 50 Pa, which is equivalent to an annual average of 0.3 ACH in normal use, as defined by CIBSE Guide A.[39] The pre-retrofit maisonette was therefore modelled with an air change rate of 1 ACH, combining the infiltration and ventilation rates.

The post-retrofit ventilation, infiltration and net heat recovery efficiency were determined at design stage by the architects using the Passivhaus Institute, Passive House Planning tool (vn 7.1 2012). These values were used in the TRNSYS modelling. It should be noted that the overall MVHR efficiency used (which includes all system losses) is low as a generic MVHR unit was selected at design stage. The effective air exchange was modelled at 0.349 ACH, accounting for MVHR average ventilation air change rate of 0.44, infiltration air change rate of 0.1 ACH (information provided by the design team) and the effective heat recovery efficiency of 43%. All simulations used London weather centre 37790 TMY2 weather file. The thermal modelling was undertaken in 3 stages, as illustrated in Figure 4. The first model (Baseline) simulates the baseline thermal performance of the flats using the standard rules for temperature in living spaces; 21°C for the lounge and 18°C for the other rooms. [20] In the second model (Baseline with occupant profiles) the same thermal parameters were used but with the unique flat specific identified occupant behaviour profiles, determined by the environmental monitoring, as the key parameter. This model represents the actual pre-retrofit indoor conditions of the monitored flats.

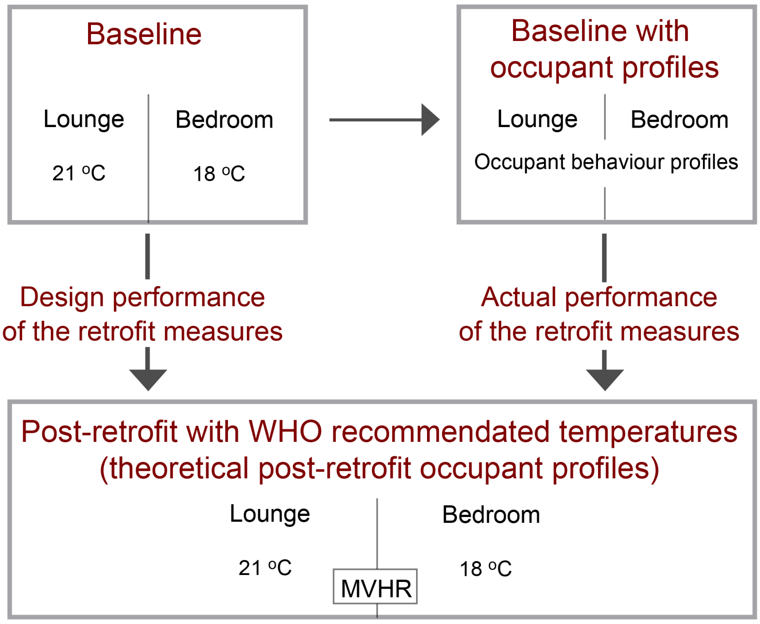

Figure 4. Thermal modelling process to predict heating loads with theoretical (18, 21 temp zones) and observed zone temperatures.

The representative flat was then simulated in a third model (Post-retrofit) with the post retrofit thermal performance, including the installation of the MVHR system, using the standard rules of 21°C for the lounge and 18°C for the bedroom. This is also assumed to be the actual post-retrofit scenario, as the improved thermal performance of the building will help to achieve the WHO recommended temperatures with minimal energy use. It is assumed that the MVHR is run to provide ventilation in all cases.

The designed performance and energy / carbon savings of the proposed retrofit measures are identified by comparing the baseline and post-retrofit models, using the standard rules for temperatures in living spaces. The estimated 'delivered' performance of the proposed measures with the use of mechanical ventilation with heat recovery system is determined by comparing the 'baseline with occupant behaviour profiles' and 'post-retrofit' models. Therefore, in this case, flats are assessed based on their unique pre-retrofit occupant behaviour profile. Table 1 summarises the input parameters for each of the models produced. It should be noted that the input values for the current and post-retrofit models were based on design values rather than field measurements. Construction related discrepancies between the 'designed' and 'as built' performance are not examined in this study, but could also contribute to the performance gap.

Table 1 Input parameters for the TRNSYS thermal simulations pre and post retrofit of a representative flat.

Input Parameter	Baseline	Baseline/ occupant profiles	Post-retrofit
Air change (ACH) [2]	1.0	1.0	0.349
Walls U-value (W/m^2K)	1.0	1.0	0.15
Windows U-value (W/m^2K)	2.8	2.8	0.8
Shading	Overhang	Overhang	-
Ventilation	Naturally ventilated	Naturally ventilated	MVHR system[3]
Set temperature	L: 21°C B:18°C	Occupant behaviour profiles	L: 21°C B: 18°C

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[1] In all models typical values of internal gains were used

[2] ACH: Air changes per hour

[3] MVHR operation: 4200h running at $0.4W/m^3h = 4\ kWh/m^2$ (flat: $214\ m^3$)

Results

Thermal performance evaluation

The measured temperature and relative humidity (RH) data from the eighteen flats provided an insight into occupant's behaviour with respect to residents' use of the heating systems. The 3-minute measurements were compared to the outdoor climatic conditions during the monitoring period (Figure 2) to better understand occupants' behavioural response to these conditions.

Analysis of the detailed monitoring data in relation to response to the ambient conditions led to classification into four categories for each room type. Example hourly air temperature profiles in the bedroom during the coldest week in March [week (a) in Figure 2] for the 4 categories (listed in Table 2), in relation to the hourly ambient temperature, can be seen in Figure 5.

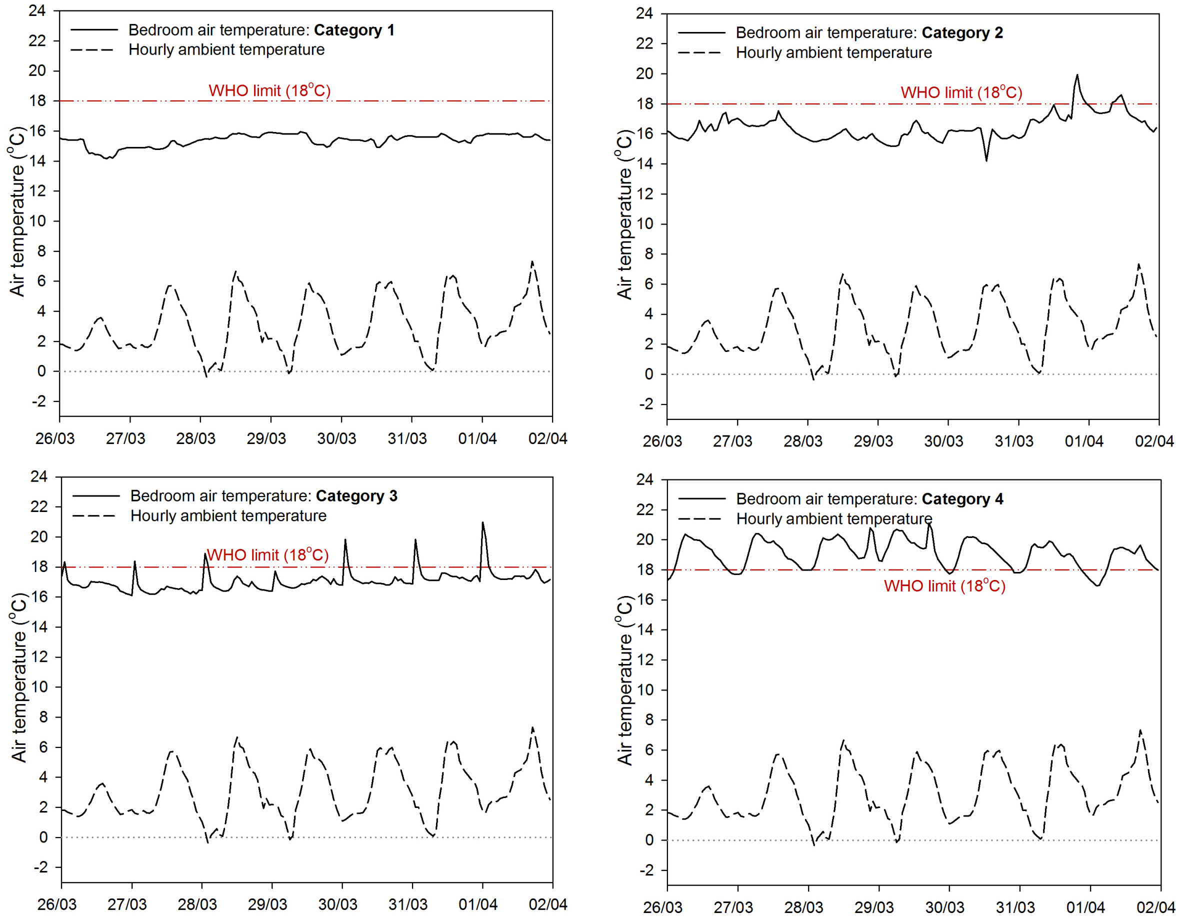

Figure 5. Examples of the hourly air temperature profiles in the bedroom during the coldest week in March per heating strategy category: *'1-free running', '2-limited individual heating', '3-scheduled heating using a timer', '4-scheduled heating using the Economy 7 Tariff'*. (Ambient temperature data from: Gosport weather station).

The ‘1-free-running’ category corresponds to unheated rooms throughout the monitoring period and was observed only in bedrooms. Small temperature increases of less than 1^{o}C occurred mainly during the night and can be attributed to internal and occupancy gains. The ‘2-limited individual heating’ category describes a strategy where the heating was on for just a few hours during the coldest days in March. The ‘3-scheduled heating using a timer’ represents a constant pattern of everyday use of heating for certain hours during the day, ranging from 1 to 8 hours. Finally, some tenants tried to benefit from the Economy 7 Tariff system, which offers lower electricity price for the night time period (midnight - 7 am). Table 2 provides the distribution of the monitored flats in the four categories for the bedroom and the lounge separately. The results indicate that 6 out of the 18 monitored flats chose not to heat their bedrooms at all (category ‘free running’), a result most probably related to fuel poverty as this happened even during the cold week in March [week (a) in Figure 2]. In addition to this, 56% and 39% of the flats turned the heating on for two or four hours during the coldest days, in the lounge and the bedroom respectively. This resulted in low indoor temperatures, lower than the 21^{o}C for the living room and 18^{o}C for other rooms, recommended by the World Health Organisation.[20] The classification of the data also reveals that some residents chose different heating strategies for the bedroom and lounge, which results in discrepancies between room temperatures.

Table 2 Distribution of the flats across the four identified heating strategy categories, based on observed bedroom and lounge heating strategies.

Category	Bedroom	Lounge
1: ‘free running’	33% (6 flats)	0%
2: ‘limited individual heating’	39% (7 flats)	56% (10 flats)
3: ‘scheduled heating using a timer’	17% (3 flats)	22% (4 flats)
4: ‘scheduled heating using the Economy 7 Tariff’	11% (2 flats)	22% (4 flats)

Table 3 summarises the average temperature, relative humidity ratio and heating strategy of the eighteen monitored flats for the period 23/03/13-20/04/13, which corresponds to the period when monitoring was undertaken in all flats simultaneously. It can be seen that, on average, more than half of the monitored flats failed to achieve the suggested indoor temperature of 18^{o}C in the bedrooms. Tenants chose to heat their bedrooms for a limited time during cold days or decided not to heat their bedrooms at all, most likely due to their financial constraints. In some cases, the use of limited individual heating every day for more than two hours achieved the proposed temperature. In contrast, all the residents that chose the scheduled heating strategy using either a timer or the Economy 7 tariff achieved the suggested temperature of 18 degrees for their bedrooms and lounges.

Table 3 Summary of the temperature range, average temperature and relative humidity and heating strategy of the 18 monitored flats during the period 23/03/13-20/04/13.

Flat No (encoded)	Bedroom				Lounge				Heating strategy
	T_{min} (^{o}C)	T_{mean}	T_{max}	RH_{mean} %	T_{min} (^{o}C)	T_{mean}	T_{max}	RH_{mean} %	
1	16.8	19.7	23.8	41%	16.1	18.6	22.6	44%	B4-L4
2	16.0	17.3	20.7	67%	16.6	19.6	24.1	42%	B2-L4
3	14.9	17.2	19.2	69%	13.6	17.3	20.7	67%	B1-L2
4	16.0	17.9	20.9	66%	14.4	18.6	22.9	52%	B1-L3
5	12.5	19.6	23.2	69%	20.4	22.7	25.1	54%	B3-L4
6	14.8	17.2	19.5	69%	14.3	17.6	23.8	65%	B2-L2
7	14.0	16.3	19.8	56%	14.9	20.0	25.8	44%	B2-L2
8	12.0	14.8	17.3	50%	13.6	17.3	22.6	46%	B1-L3
9	18.8	21.5	23.9	68%	17.7	20.6	24.4	63%	B2-L3
10	16.1	18.1	24.6	72%	15.0	18.6	23.5	63%	B3-L2
11	14.1	16.5	18.9	65%	12.8	15.9	20.4	58%	B1-L2
12	14.2	16.8	22.1	73%	15.0	17.8	22.6	60%	B2-L2
13	16.2	20.7	28.7	55%	15.6	20.6	26.2	50%	B3-L3
14	16.7	20.0	24.4	54%	15.5	19.6	25.4	61%	B4-L2
15	13.8	16.3	25.9	59%	9.0	13.0	18.7	71%	B2-L2
16	16.0	18.4	21.8	66%	18.9	21.5	24.5	54%	B1-L4
17	13.0	17.5	22.0	57%	13.6	18.5	29.7	54%	B2-L2
18	14.1	17.3	20.7	62%	8.2	15.6	24.5	67%	B1-L2

Notes:

B: Bedroom, L: Lounge

RH: Relative Humidity

1: ‘free running’

2: ‘limited individual heating’

3: ‘scheduled heating using a timer’

4: ‘scheduled heating using the Economy 7 Tariff’

The results show that the WHO standard rules for temperatures in living spaces (21^{o}C for the lounge and 18^{o}C for the other rooms) are not representative of the actual indoor temperatures in our case study sample. In Figure 6, which shows box plots of the measured air temperature in each lounge, it can be seen that over 80% of the monitored lounges failed to achieve the suggested temperature of 21°C. This is further supported by the infra-red image of Figure 7, where most of the sunspaces appear to be 'cold'.

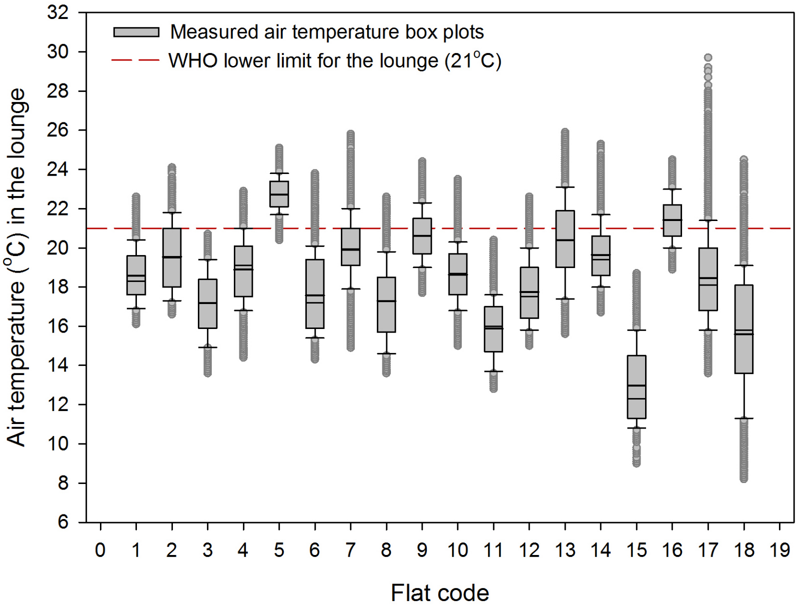

Figure 6. Box plots of the air temperature in the lounge in each flat with the median (thick black lines), 25th and 75th percentiles (box edges), 10th and 90th percentiles (whiskers), mean values (thin black lines) and extreme values (dots) (flat numbers are encoded).

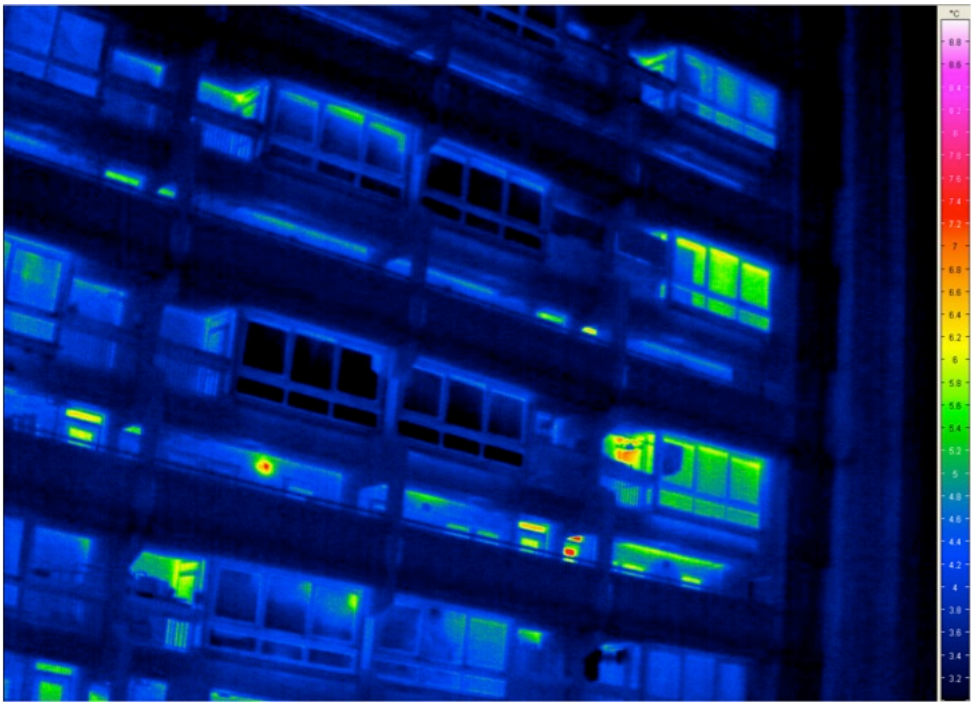

Figure 7. Thermal survey showing infra-red image of the South-East façade of the tower block prior to retrofit. Cold sunspaces can be seen (dark blue glazing areas).

Furthermore, despite the fact that some of the residents chose a scheduled heating strategy using a timer or a tariff system, the overall thermal performance of the flats is clearly insufficient and failed to achieve the World Health Organisation’s recommendations. Figure 8 shows the air temperature in four of the warmest lounges of the dataset during a cold day in March. It can be seen that in these flats tenants made use of the off-peak night-time tariffs. This led to the increase of air temperature during the night, reaching the WHO recommended temperature early in the morning. However, during the day, which is the time that these spaces are typically occupied, the temperature remained at lower levels.

In addition, the data indicates that in some cases there might have been ineffective use of the storage heaters. For example, the air temperature in lounge B of Figure 8 appears to have had an increase of almost 6°C during the night, reaching 22°C in the morning, when it started to decrease. This indicates that the output on the storage heater was set to maximum during the night releasing more heat than it should, which reduced its capacity to provide balanced heat during the day. It is likely that residents do not understand how the storage heaters work and how they should be operated. This is only a hypothesis that needs further investigation, as lack of knowledge of appropriate use of controls might be exacerbating fuel poverty.

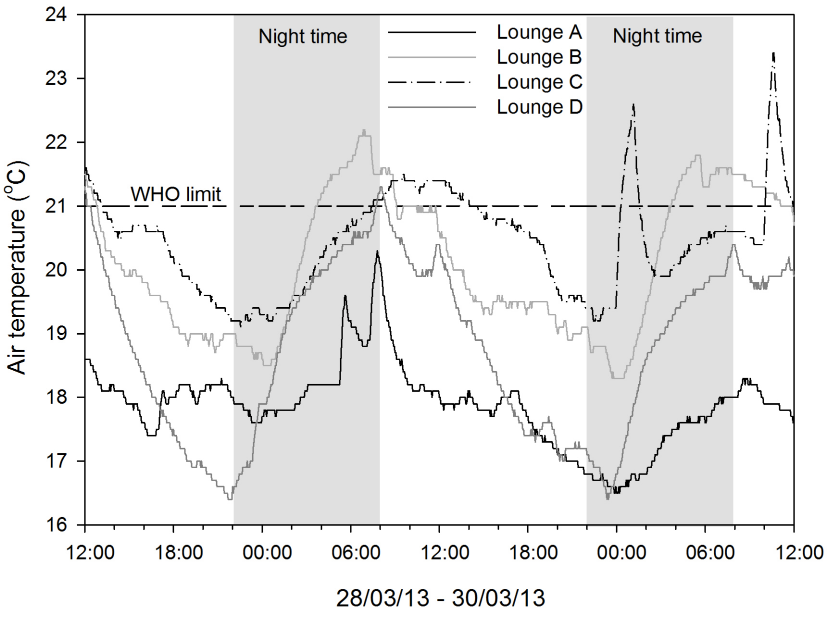

Figure 8. Air temperature measurements in four of the warmest lounges, from 28/03, 12:00 to 30/03, 12:00 based on 3 minutes sampling of each point.

The overall low indoor temperatures observed highlight that the retrofit measures, including the MVHR installation which was specified based on the WHO recommended temperatures, is unlikely to deliver the anticipated 80% carbon reduction target. However, the proposed interventions will deliver improved levels of thermal comfort, which is welcome, but may, in some cases, deliver little or no reduction in carbon. This is even more evident when looking at the observed wide temperature ranges: lounge temperatures spanned 8.2 - 29.7 ^{o}C and bedroom temperatures 12 - 28.7 ^{o}C (Table 3).

Occupant survey

The occupant survey was carried out in September 2014 by PCC with the aim of establishing how the households used electricity. The 76 properties included in the survey accommodate 304 residents, 47% of whom are under 18 and 13% under 5 years old. Apart from the high percentage of young residents, 57% of the respondents stated that there is at least one person with health problems in their household, with asthma and diabetes the problems most frequently mentioned.

When asked in an open question about the heating pattern in their households, 21 of the respondents (28%) reported that they never use the night storage heaters (NSH). The most frequently reported reason is the cost, with most stating that NSHs are too expensive to run and they do not provide enough heat. One of the comments made by a respondent was that "it comes on in the middle of the night", which might indicate inappropriate setting of the output control, as mentioned earlier (set to 'high').

When asked about secondary heating, 67% of the respondents replied that they use mobile (portable plugin) electric heaters. In half of these households the mobile heaters are used as the main heating source, whilst 21% reported using them for short periods during the day and 13% only when it is very cold. Overall, the results from the occupant survey appear to agree with the monitoring data, highlighting the pattern of under-heating in a thermally poor building, which accommodates a highly vulnerable population.

TRNSYS Modelling results

Model 1 provides the baseline heating demand of a representative flat using the WHO temperatures for acceptable thermal environment in the lounge and bedroom. These resulted in an estimated 7,928 kWh annual space heating demand. For the 'baseline with occupant profiles' model, the 'scheduled heating using a timer' and the 'limited individual heating' profile categories were extended into new subcategories to provide more accurate simulations for flats slightly departing from the main category profile. This resulted in 10 flat subcategories, A-J, as can be seen in Figure 9.

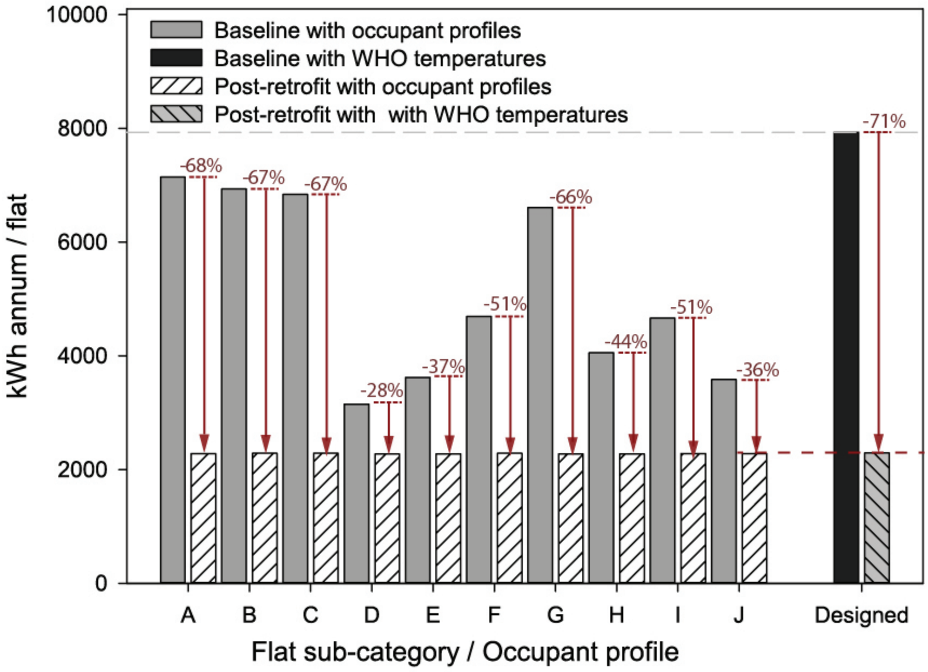

Figure 9. Thermal simulation results of the representative flat, prior and post-retrofit, using WHO temperature recommendations and occupant profiles.

Figure 9 summarises the results of the TRNSYS thermal simulations. It can be seen that using the WHO temperatures instead of occupant based temperature profiles leads to an overestimation of the amount of heat (kWh annum) delivered in the rooms. This overestimation ranges from 10% (flat subcategory A) to +150% (flat subcategory D). In the case of flat type D, the WHO annual demand would be 7,928 kWh compared to 3,150 kWh for the actual occupant profile. The difference between the WHO demand and the occupant profile value corresponds to 4,778 kWh, i.e. 150% of the occupant profile value. On average, the overestimation for all flat subcategories is 70%. This means that the actual energy / carbon savings from retrofit measures can be expected to be less than half that estimated for a WHO compliant flat.

Thermal simulation of the post retrofit performance using the WHO temperatures verifies that the proposed retrofit strategy meets the stringent EnerPHit standard. The standard defines that the specific heat demand must be equal or less than 25 kWh/m^2/annum. The modelled demand in TRNSYS is 25.8 kWh/m^2 per annum (including MVHR power), therefore the 25 kWh/m^2 annum limit is essentially achieved (also including the 4 kWh/m^2 of the MVHR system). The simulation indicates a 71% energy reduction, if the recommended temperature values were to be achieved in the flats (Figure 9). The annual demand would decrease from 7,928 kWh to 2,293 kWh (including MVHR load).

Table 4 shows the estimated 'delivered' savings in each flat sub-category in comparison to the designed savings (5,635 kWh annum). It can be seen that, depending on the sub-category, savings can be expected to be from 14% to 84% less than expected, with an average of 49%.

Table 4 Designed and estimated 'delivered' savings of the proposed retrofit measures for each flat sub-category and the performance gap in savings.

Flat sub-category	Occupant behaviour profile	Designed savings based on WHO temps (kWh/annum/flat)	Estimated 'delivered' savings (kWh/annum/flat)	Performance gap (%)
A	B2-L2	5,635	4,860	14
B	B3-L3		4,647	18
C	B2-L2		4,553	19
D	B1-L1		878	84
E	B1-L1		1,346	76
F	B1-L3		2,405	57
G	B3-L1		4,334	23
H	B2-L1		1,778	68
I	B1-L2		2,883	58
J	B0-L2		1,302	77

Conclusions

The work presented here covers environmental monitoring and thermal modelling of a council owned tower block, which is undergoing refurbishment. Results from an occupant survey conducted by Portsmouth City Council were also analysed and found to agree with the monitoring outcomes. It should be noted that the use of only 18 flats in this analysis does not provide a complete assessment of the conditions encountered in social housing tower blocks. Furthermore, the monitoring data was gathered during March and April which means that extremes of weather have not been captured during this period. Such issues will be addressed in the monitoring which is planned to start after the retrofit's completion. The post-retrofit investigation will include as many of the previously monitored properties as possible for direct comparison. New participants will also be approached in order to further extend the analysis. Overall, monitoring over extended periods and field data collection combined with thermal comfort studies in social housing buildings are needed in order to gain a better understanding of the interaction between the buildings and their occupants.

The data analysis of the eighteen monitored flats revealed that more than half of the flats failed to achieve the recommended indoor temperatures for an acceptable level of thermal environment. This resulted in under-heated flats with lower heating demand compared to that predicted using standard rules for indoor temperatures. The most likely reason for this is fuel poverty, highlighting a contradiction in the perceived high potential of social housing for carbon reductions. Clearly, meeting the carbon reduction targets requires good understanding of occupant usage, as the current approach leads to an overestimation of the carbon reduction potential of houses in fuel poverty.

Thermal modelling of the post-retrofit conditions showed that the proposed measures meet the strict EnerPHit standard and will overall improve the indoor environmental conditions. However, using the observed occupant behaviour profiles, the results highlight that the actual energy / carbon savings will be less, typically around half, than those predicted using the standard building physics – temperature guidelines.

The performance gap presented here is related to occupant behaviour, bearing similarities to a well-documented occupant-related reason for not achieving the expected energy use reduction in building refurbishment projects, the "temperature take-back" rebound effect.[40] This refers to the increase in energy consumption after energy efficiency improvement in buildings due to behaviour change of occupants who increase their temperature settings.[41] The temperature take-back factor has been estimated to reduce the expected CO_2 reductions by approximately 6%.[42] A slight increase of comfort temperatures after building refurbishment has been also found in low-income dwellings.[43] In this study however, the performance gap is due to the lower pre-retrofit energy consumption as a response to financial constraints, which determined a low baseline heating demand and subsequently low carbon reduction potential. This type of performance gap has been recently described as the 'prebound effect'.[44] The term was used in order to describe the situation where the pre-retrofit energy use is lower than estimated, leading to overestimation of the expected carbon savings from the retrofit.[45] The 'prebound effect' here is induced by fuel poverty and was estimated at an average of 40%, a much higher effect compared to the 6% caused by temperature take-back. A combination of 'prebound' and 'rebound' effects would further widen the performance gap here. Post-retrofit monitoring will help to investigate this possibility.

This paper notes differences in occupant behaviour and variations in temperature which should be investigated further in order to inform future reports and policies. The study also highlights the social dimension of refurbishment projects, which are often initiated by carbon savings incentives. Based on this study, occupant thermal comfort, well-being and health appear to be critical factors. Addressing these factors could also lead to indirect savings associated with health care of fuel poor tenants and changes to demand for health services.[29] Overall, it appears necessary to value occupant comfort as well as carbon reduction in under-heated houses, and this makes the challenge of building retrofit even greater. Placing a monetary health value against winter warmth has been a focus of a number of studies in the UK. It is estimated that the NHS saves between 23 and 42p (higher figure usually quoted) for every £1 invested in housing efficiency.[46-48] The 40% prebound effect observed here means a Green Deal type mechanism, which relies on financial savings from energy use reductions to repay the capital cost of retrofit, would not work. Interestingly, this 40% prebound effect is balanced by the long term NHS savings – the challenge is to create the policies which reflect this fiscal balance to enable councils and social housing providers to fund these retrofits.

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