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A method for estimating scheduled and manual override heating behaviour and settings from measurements in low energy UK homes

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Abstract

Purpose – The purpose of this paper is to present a methodology for estimating scheduled and manual override heating events and heating settings from indoor air temperature and gas use measurements in UK homes.

Design/methodology/approach – Living room air temperature and gas use data were measured in ten UK homes built to low energy standards. The temperature measurements are used to establish whether the central heating system is turned on or off and to estimate the heating setpoint used. The estimated heating periods are verified using the homes' average daily gas consumption profiles.

Findings – Using this method, the average number of heating periods per day was 2.2 (SD = 0.8) on weekdays and 2.7 (SD = 0.5) on weekends. The weekday mean heating duration was 8.8 h and for weekends, it was 9.8 h. Manual overrides of the settings occurred in all the dwellings and added an average of 2.4 h and 1.5 h to the heating duration on weekdays and weekends respectively. The mean estimated setpoint temperatures were 21.2°C and 21.4°C on weekdays and weekends respectively.

Originality/value – Manual overrides of heating behaviours have only previously been assessed by questionnaire survey. This paper demonstrates an alternative method to identifying these manual override events and responds to a key gap in the current body of research that little is currently reported on the frequency and duration of manual heating overrides in UK homes.

Practical implications - The results could be used to better inform the assumptions of space heating behaviour used in energy models in order to more accurately predict the space heating energy demands of dwellings.

Keywords: Domestic space heating, Scheduled heating periods, Manual overrides, Setpoint temperatures, Residential buildings.

Paper type – Research paper

1. Introduction

In the UK, nearly 90% of homes are heated with a gas-fired central heating system comprised of an individual boiler, pump and radiators (Department for Communities and Local Government (DCLG), 2015). Space heating accounts for over two thirds of a typical household's total energy consumption (BEIS, 2017), resulting in 11% of the nation's greenhouse gas (GHG) emissions (DECC, 2012). These figures highlight the importance of reducing domestic energy use associated with space heating, if the UK is to achieve its new target of bringing all GHG emissions to net zero by 2050 (HM Government, 2019). Consequently, in recent times, understanding occupant space heating behaviours has become a focus of attention for the UK research community and a detailed review of these previous studies has been presented by Wei *et al.* (2014). A major concern of the built environment is the performance gap between design and operation of buildings. A case study of an apartment block(containing 98 apartments) is presented in CIBSE TM61, which focuses on a holistic evaluation of operational building performance (CIBSE, 2020a). A review of the annual heating demand of the apartments that had reliable energy data showed that actual heating demand was up to three times more than the design performance in the worst cases. In this Technical Memorandum, it is suggested that the variation and increase in heating demand is predominantly driven by occupant behaviour (e.g. heating set points and schedules). To address the performance gap, operational performance can be collected and fed back to design for improvements.

Space heating in homes is often scheduled using a timer/programmer, which allows occupants to control when the heating system comes on and when it goes off. The controls of the space heating also often include a thermostat, which controls the temperature in the home. The occupants are able to set a comfortable temperature known as the set-point temperature. These settings can also be manually overridden by the occupants to increase or decrease their heating requirements for duration and/or comfort temperature. Space heating behaviours are characterised by the number of scheduled heating periods in a day; the start and end times of heating periods; the heating durations and the heating setpoint temperatures. To date, either survey studies (Shipworth *et al.*, 2010; BRE, 2013a, 2013b; Jones *et al.*, 2016; Guerra-Santin and Silvester, 2017) or measurement studies (Shipworth *et al.*, 2010; Andersen *et al.*, 2011; BRE, 2013b; Fabi *et al.*, 2013; Huebner *et al.*, 2013a, 2013b; Kane *et al.*, 2015; Pritoni *et al.*, 2015) have been used to understand heating behaviours, i.e. identifying scheduled heating periods and set point temperatures. There are limited UK studies that have focussed on identifying manual override heating behaviours (Morton *et al.*, 2016; Bruce-Konuah *et al.*, 2019). In the survey studies, occupants are asked to self-report their heating behaviours in questionnaires or interviews, whilst in the measurement studies, indoor air temperature is normally used to estimate heating behaviours.

The measurement methods often assume that during the heating season when outdoor temperatures are low, an increase in indoor temperature is the result of heating. Previously, Kane *et al.* (2015) presented nine metrics to determine scheduled heating behaviours using both indoor and outdoor temperature measurements. The metrics included identifying: heating days from outdoor temperature; number of heating periods per day through visual inspections of indoor temperature profiles; start and end times of heating periods and hence heating durations from decreases in indoor temperature; as well as setpoint temperatures from maximum temperatures recorded during the analysis period. In addition to using indoor air temperatures, Kane *et al.* (2017) demonstrated the use of radiator surface temperatures and gas consumption measurements (where gas is the primary heating fuel in the dwelling) in estimating when the heating is in operation.

Manual heating override events have only been assessed as part of a questionnaire survey administered to occupants. Occupant surveys are now established assessment methods that complement technical and quantitative performance analysis methods. CIBSE TM62 provides a detailed review and guidance on surveying occupant satisfaction as part of providing insights into operational building performance (CIBSE, 2020b). Regardless of the challenges of occupant surveys, they have shown to demonstrate relationships between built environmental factors and occupant comfort and satisfaction. The Building

Research Establishment (BRE) conducted a questionnaire survey on behalf of the UK Government's former Department of Energy and Climate Change (DECC) (BRE, 2013a). In this survey, households were asked about both their chosen setpoint temperatures and scheduled heating periods at home as well as any additional heating used outside of their scheduled heating periods (BRE, 2013b).

Of the households with a central heating system controlled by a timer to give a regular heating pattern, 60% switched on their heating manually for additional periods of heating at least once a week and 18% did so every day. Shipworth *et al.* (2010) compared heating settings reported through questionnaires and settings estimated from measured temperatures. They did not find any correlation between reported and estimated heating settings even when selecting the more energy-efficient dwellings. This could be because occupants adjust their heating settings fairly frequently that the eventual mean of the settings estimated varies from the reported means. In CIBSE's TM62, it is suggested that occupant dissatisfaction can stem from sticking steadfastly to energy efficiency targets or optimal system set points that do not consequently deliver occupants' expected level of comfort. This is particularly relates to non-domestic buildings where building managers control the environmental conditions through building management systems. Regarding domestic energy modelling, energy performance calculations carried out to demonstrate compliance with building regulations are based on default or standardised operating conditions. According to CIBSE's TM63, the standardised conditions often do not accurately reflect actual operating conditions (CIBSE, 2021). Commonly used building simulation tools such as the Building Research Establishment Domestic Energy Model (BREDEM) assume fixed heating settings (setpoint temperatures: 21°C in living rooms and 18°C in all other zones and heating durations: nine hours on weekdays and 16 hours on weekends) for all dwellings (Anderson *et al.*, 2002). In reality, heating settings vary due to environmental factors (French *et al.*, 2007; Andersen *et al.*, 2009; Guerra Santin *et al.*, 2009; Andersen *et al.*, 2011; Fabi *et al.*, 2013), building characteristics (Guerra-Santin and Itard, 2010; Shipworth *et al.*, 2010; Kane, *et al.*, 2015; Jones *et al.*, 2016) and occupant related factors (Sardianou, 2008; Guerra-Santin and Itard, 2010; Kane *et al.*, 2015; Yang *et al.*, 2015; Jones *et al.*, 2016). Furthermore, predictions of a dwelling's energy demand have been shown to be sensitive to the setpoint and the heating durations used in modelling (Firth *et al.*, 2010; Cheng and Steemers, 2011), with setpoint temperature being the most significant factor influencing space heating energy use. The findings from these studies show that there is a need to improve the input data for energy models so that they best reflect the diversity of occupant behaviour. Increasing our understanding of occupant behaviour in buildings is crucial for improving building simulation results and reducing the performance gap (van den Brom *et al.*, 2018). CIBSE's TM63 provides a guide on the process for achieving this. This includes collecting building data during the operational stage (e.g. indoor environmental quality and controls), identifying performance issues in operating conditions (e.g. actual operating conditions required for comfort), undertaking modelling and calibrating the model (e.g. a model that is a realistic representation of the current operational performance) and creating an in-use baseline (using actual operating conditions).

2 Current study

This paper aims to provide a detailed methodology for identifying scheduled heating periods and manual heating override events in order to present a picture of space heating behaviour in UK homes. Measured indoor and outdoor air temperature will be used to identify the heating season and both scheduled and manual override heating periods. Daily gas consumption profiles will be used to verify and confirm the heating periods identified from the indoor air temperature measurements. Furthermore, estimations of heating settings, i.e. setpoint temperatures and heating durations will be derived from the indoor air temperatures. The study benefits from having a relatively small sample size, where fine-resolution temperature and gas consumption data were available. The paper responds to a key gap in the current body of research that little is currently reported on the frequency and duration of manual heating overrides in UK homes.

3 Data collection

3.1 The dwellings

Measurements were undertaken in living rooms of seven purpose built rented flats, and three rented end-terrace houses located on a new-build housing estate in a town in the South West of the UK. The seven flats were all identical in layout but varied in construction standard. The same applied for all of the three houses. Six of the flats were located on the third floor of a Code for Sustainable Homes (CSH) Level 4 apartment building. CSH Level 4 relates to a 44% improvement over the Target Emission Rate (TER) as determined by the 2006 Building Regulation Standards (BRS). The seventh flat was located on the third floor of a minimum compliance, 2006 Building Regulation Standards apartment building. Two of the end-terrace houses were CSH Level 5 which relates to a 100% improvement over the 2006 Building Regulation Standards. The third house was constructed to the 2006 Building Regulations Standards. Table 1 presents a summary of the dwelling type and their performance standards. An in-depth description of the construction materials and specifications of the structural elements of the dwellings has been presented in Appendix A, Table A.1 in Jones *et al.* (2017). All the dwellings have a gas fired central heating system (GCH) that comprises of a central boiler as the heat generator, a pump and pipework as the heat distributor, individual radiators as the heat emitters and a programmer/thermostat and thermostatic radiator valves (TRVs) for the controls. The thermostat allows multiple heating periods to be scheduled. These scheduled heating periods can also be overridden to turn on/off, increase or decrease the heating period or to change the heating set point temperature. The TRVs allow occupants to control the air temperature in individual spaces. None of the dwellings had mechanical cooling, as a result the indoor temperature depends on the heating setpoint in winter and the air change rate in the summer. The dwellings were equipped with either exhaust air ventilation (EAV) or mechanical ventilation with heat recovery (MVHR) systems to ensure adequate background ventilation is provided.

Table 1: Types and design performance standards of the dwelling sample

Dwelling index	Performance standard	Floor area (m^2)	Airtightness ($m^3/hr.m^3$)	Wall U-value (W/m^2K)	Window U-value (W/m^2K)	HVAC
Flats 1 - 6	Code for Sustainable Homes Level 4	80.5	2	0.10	1.20	GCH, MVHR

Flat 7	2006 Building Regulations Standard	80.5	5	0.24	1.80	GCH, EAV
Houses 1 and 2	Code for Sustainable Homes Level 5	140	2	0.10	0.70	GCH, MVHR
House 3	2006 Building Regulations Standard	140	5	0.26	1.80	GCH, EAV

3.2 Measurements

In each dwelling, an automated monitoring system was installed to capture indoor environmental conditions at 10-minute intervals resulting in 144 indoor air temperature measurements per day per dwelling. The indoor temperature sensor had a measurement range of -20°C to 65°C with an accuracy of ±0.3°C. The sensors were installed in the dwellings by the researchers and were placed away from heat sources (i.e. identifiable at point of installation) and direct sunlight. When the sensors were installed, no secondary heating was evident in the homes. Gas consumption was measured at 30-minute intervals resulting in 48 measurements per day per dwelling.. Outdoor temperature and global solar radiation were measured at 10-minute intervals by a meteorological station which was set up on the housing estate where the dwellings were located. The outdoor temperature sensor had a measurement range of -40°C to 75°C with an accuracy of ±0.3°C and the global solar radiation sensor had a measurement range of 0 to 1800W/m^2 with an accuracy of ±5% of the full scale. All variables were measured continuously from 28th October 2013 to 2nd November 2014 (370 days). The data used in this study were collected as part of a larger Post Occupancy Evaluation (POE) to assess the actual operational performance of the dwellings (Jones *et al.*, 2015; Jones *et al.*, 2016; Jones *et al.*, 2017).

For each dwelling, average daily indoor air temperatures were processed to identify outliers. To the researchers' knowledge, there were no sensor failures that would have caused significant outliers in the dataset. The sensors were calibrated before deployment in appropriate conditions, i.e. away from direct sunlight and other heat or cold sources and all recorded temperatures were within the 10°C to 35°C. Outliers were considered to be temperatures below 10°C, indicating the possibility of the sensor being moved very close to an open window or vent or a thermal bridge area, and temperatures above 35°C indicating the placement of the sensor very close to a temporary heating source (e.g. portable electric heater). Temperature changes of more than 7°C within 30 minutes were considered errors as this may also indicate proximity of a temporary heating source. These outliers were removed from the dataset before analysis.

The outdoor air temperature was assessed to identify the days that dwellings were most likely to be heated, i.e. where an increase in indoor temperature is due to the heating system. During the identified heating period, the living room temperature was used to determine when heating systems were in operation, both in scheduled and manual modes and the gas consumption data was used to verify the method for identifying the heating periods.

4 Description and calculation of heating behaviours

4.1 Estimating heating days

Heating days have been identified through both internal temperatures and external temperatures (Shipworth *et al.*, 2010; Huebner *et al.*, 2013a; Kane *et al.*, 2015; Yang *et al.*, 2015). Published heating degree days in the UK are also calculated to a base external temperature of 15.5°C (Carbon Trust, 2012). This is the temperature below which it is assumed that heating is necessary to increase indoor air temperatures to comfort temperature and it is generally used for most buildings. In Huebner *et al.* (2013a), they recorded indoor and external temperatures for a 92-day period between November 2007 and January 2008 and found no day in the data analysis that external temperature exceed 15.5°C. They considered all the days in their study as "heating days". For the current study, this base temperature of 15.5°C was selected as the cut-off criteria below which the heating systems were turned on in the dwellings. As stated by Huebner *et al.* (2013a), it should be noted that for some homes on some days close to 15.5°C, incidental gains such as heat gains from cooking may maintain internal temperatures without the heating system being on, leading to false positive results. Based on a cut-off temperature of 15.5°C, the identified heating season in this study was a 181-day period between November 2013 to April 2014 (129 weekday and 52 weekend days). As shown in Figure 1, all the days in the identified period were classified as heating days and the average daily temperatures were below 15.5°C. Average daily outdoor temperature ranged from 3.6°C to 14.3°C with an average of 8.5°C. Within this period, 71.5% (128 days) had average daily outdoor temperatures below 10°C. Although there were some days in the remaining months (May-14 – Oct-14) that met the criteria for heating, those days were not included due to the impact of thermal history (Nicol *et al.*, 2012). Furthermore, May 2014 and October 2014 were considered to be transition seasons as the seasons change to a warmer or cooler season.

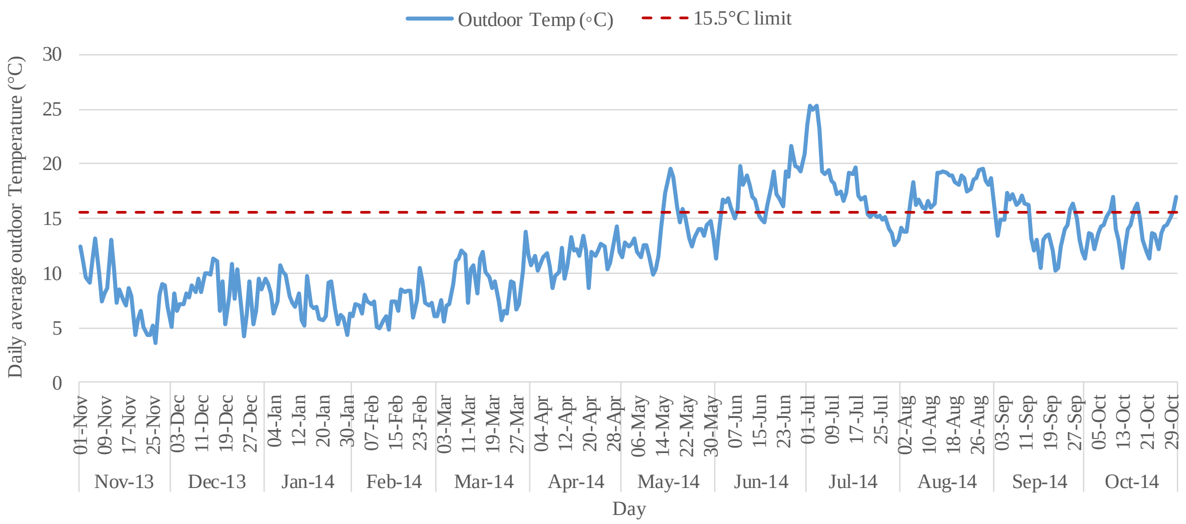

Figure 1: Average daily outdoor temperature during the monitoring period

To verify the selected heating season, the average hourly living room air temperature profile was plotted against outdoor air temperature and solar radiation for the identified heating season (01 Nov 2013 - 30 April 2014) and the non-heating season (01 May 2014 – 31 Oct 2014). Figure 2 shows the profiles in one of the dwellings in the heating season (left) and non-heating season (right). As expected, in the heating season the outdoor temperatures and solar radiation were noticeably lower than that occurring in the non-heating season. The profiles also give an indication of the use of the central heating system in this dwelling. The peaks in indoor temperatures in the mornings (between 07:00 and 11:00) and evenings (between 17:00 and 21:30) do not match the peaks in outdoor temperature and solar radiation, which are in the afternoon (between 12:30 and 15:30). In the non-heating season there is no evidence of the use of a central heating system to increase the indoor air temperature. The indoor air temperatures seem to remain fairly constant throughout the day. This could be an indication of the effectiveness of the thermal performance of the dwelling's fabric. The dwelling is constructed to Code for Sustainable Homes (CSH) Level 5, which is characterised by low U-values and high airtightness and designed to reduce overheating.

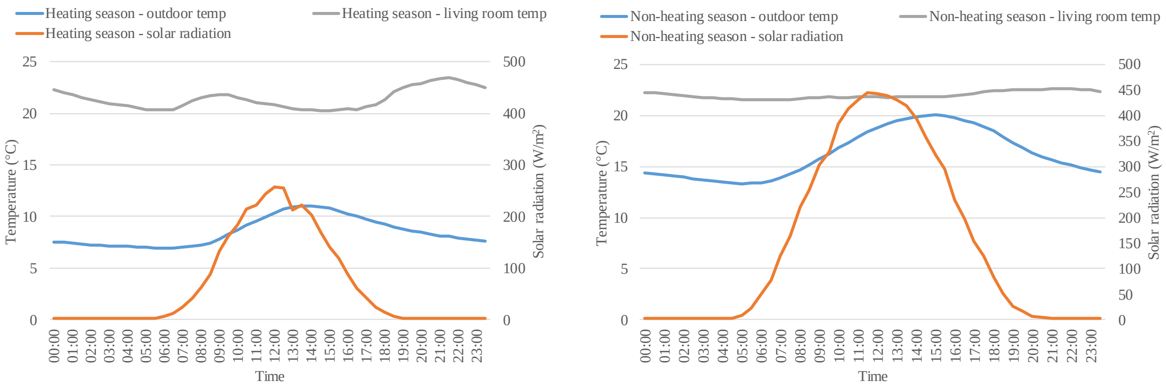

Figure 2: Average hourly indoor and outdoor air temperature and solar radiation recorded in a dwelling during the heating season (left) and non-heating season (right)

4.2 Estimating scheduled heating periods

Active heating periods are times when the heating system is supplying heat to the dwelling. During the winter months, when external temperatures fall below 15.5°C, BREDEM models assume that the heating systems must bring the living room to the 21°C comfort temperature. As applied by Shipworth *et al.* (2010) for this analysis, it is also assumed that, for the majority of the cases, living room temperatures only increased when the heating system was in use. The measured living room air temperatures were translated into statements regarding whether the heating system was on or off based on Equation 1.

$$T_t - T_{t-1} \geq 0.3°C \qquad (1)$$

Where T_t is the living room air temperature at time t and T_{t-1} (°C) is the living room air temperature at time $t-1$(°C).

Figure 3 is a graphical display of the half hourly changes in the living room air temperature in a flat. The data has been split between the weekdays and weekends. Each data point represents the change in the living room air temperature between time, *t* and *t*-1. Each day is represented by a data point, hence at each half hour there are 129 data points for weekdays and 52 data points for weekend days. The continuous line is the 0.3°C temperature increase that indicates the minimum increase in the air temperature at which the heating system is turned on. Based on Kane *et al.*'s (2015) description for the start and end of the heating period, scheduled heating durations were estimated. The start of the scheduled heating period was assumed to be the first 30-minute period for which the temperature was at least 0.3°C higher than the previous 30-minute period (i.e. when the heating is on) for at least 10% of the total days in the heating season. Similarly, the end of the scheduled heating period was determined as the last 30-minute period for which the temperature increase was at least 0.3°C compared to the next 30-minute period (heating turned off) for at least 10% of the total days of the heating season. Based on these statements, the scheduled heating periods were estimated for the dwellings. Figure 4 is the corresponding scheduled heating periods for weekdays and weekends in the Flat. The dashed line on the graphs indicate the 10% cut-off proportion. To verify the estimation of these scheduled heating periods, gas consumption data profiles were added to the graphs (blue line). As a significant proportion of gas is used for space heating in dwellings, the gas consumption profile is an appropriate indicator of when the central heating system is in use. As expected, the gas consumption profile followed the estimated active heating profile.

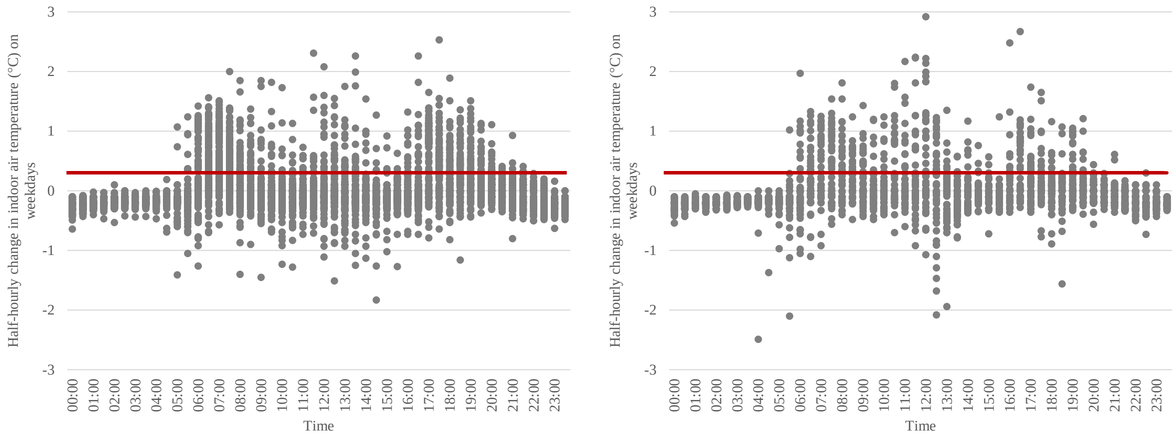

Figure 3: Half-hourly living room air temperature changes on weekdays (left) and weekends (right) in a Flat

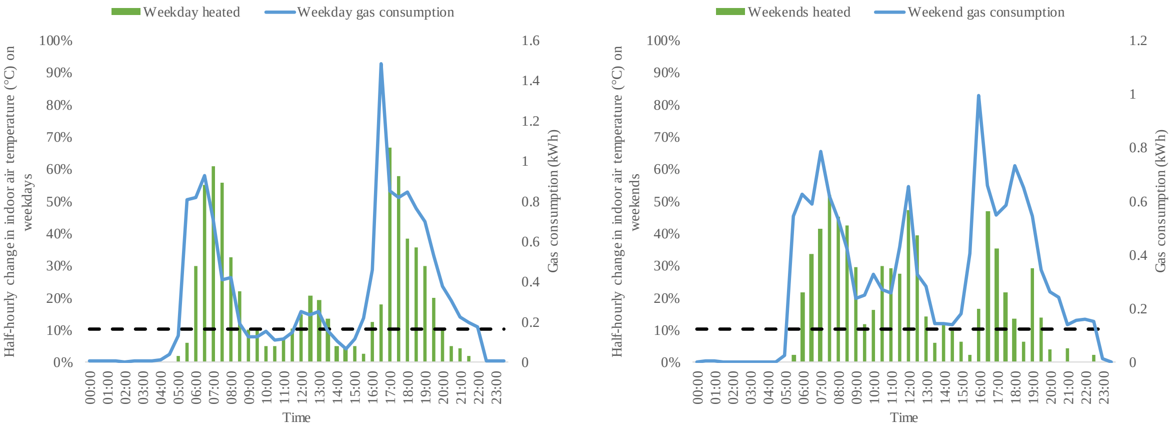

Figure 4: Estimated daily scheduled heating profiles and gas consumption on weekdays (left) and weekend (right) in a Flat

4.3 Estimating manual override heating periods

Manual override events were defined as departures from the estimated scheduled heating times, i.e. when the heating system was turned on outside of the scheduled on/off heating periods. Within the heating season, these occurred at times where the heating was on (i.e. when living room air temperature at time *t* was at least 0.3°C higher than at time *t*-1) for less than 10% of the heating days. For example, in the Flat's heating profile presented in Figure 4, on weekdays, manual overrides were identified to occur between 05:00 and 06:00 when the indoor air temperature increased by at least 0.3°C but for less than 10% of the heating days. Manual overrides were again identified between 10:00 and 11:30, 14:00 and 16:00 and 20:30 and 22:00. At the weekends, manual overrides were identified at 05:30, 13:30, between 15:00 and 15:30, at 18:30 and on three occasions after 20:00.

4.4 Identifying heating setpoint temperatures

A thermostat is designed to turn the gas boiler off when the room temperature reaches the thermostat setpoint. This process is cycled, with the boiler being turned on again when the temperature drops below setpoint and off again when the setting is reached, until the programmed heating duration is reached. Hence, the heating setpoint temperature has been assumed to be the maximum temperature reached during scheduled heating periods (Shipworth *et al.*, 2010). Based on this assumption, the maximum temperature recorded during the identified scheduled heating periods were taken as the setpoint temperatures.

5 Results

5.1 Heating periods

There were variations in heating profiles between the ten dwelling sample used in this study and within each dwelling, there were variations between the weekday and weekend heating days. Across the dwellings, the average number of heating periods per day was 2.2 (SD = 0.8) on weekdays and 2.7 (SD = 0.5) at the weekends. Of the ten dwellings, two had a single heating period on weekdays, four had double and the remaining four had three (i.e. multiple). On weekend days, three dwellings had double heating periods and the remaining seven had three heating periods.

Figure 5 shows examples of heating profiles in three of the dwellings (House 2, Flat 3 and Flat 6). The weekday heating profiles are in the left column and the weekend heating profiles are in the right column. In House 2 (Fig. 5 top), the weekday profile matches the assumptions used in BREDEM, i.e. double heating periods, one in the morning and one in the afternoon/evening. On the weekend heating days, the double heating profile is not as distinct as the weekday profile as there are times in the late mornings where there is enough active heating to represent a scheduled period. In Flat 3 (Fig. 5 middle), there are multiple heating periods on weekdays but double at the weekends. The early morning heating period is not seen in the weekend and this could be because of changes in the household's routines. In Flat 6 (Fig. 5 bottom), there seems to be a more consistent heating profile throughout the week than in the other dwellings. There is a clear single heating period occurring from 09:30 to 13:00 on weekdays and 09:00 to 13:00 on weekends. There is some additional heating in the evening and on weekends.

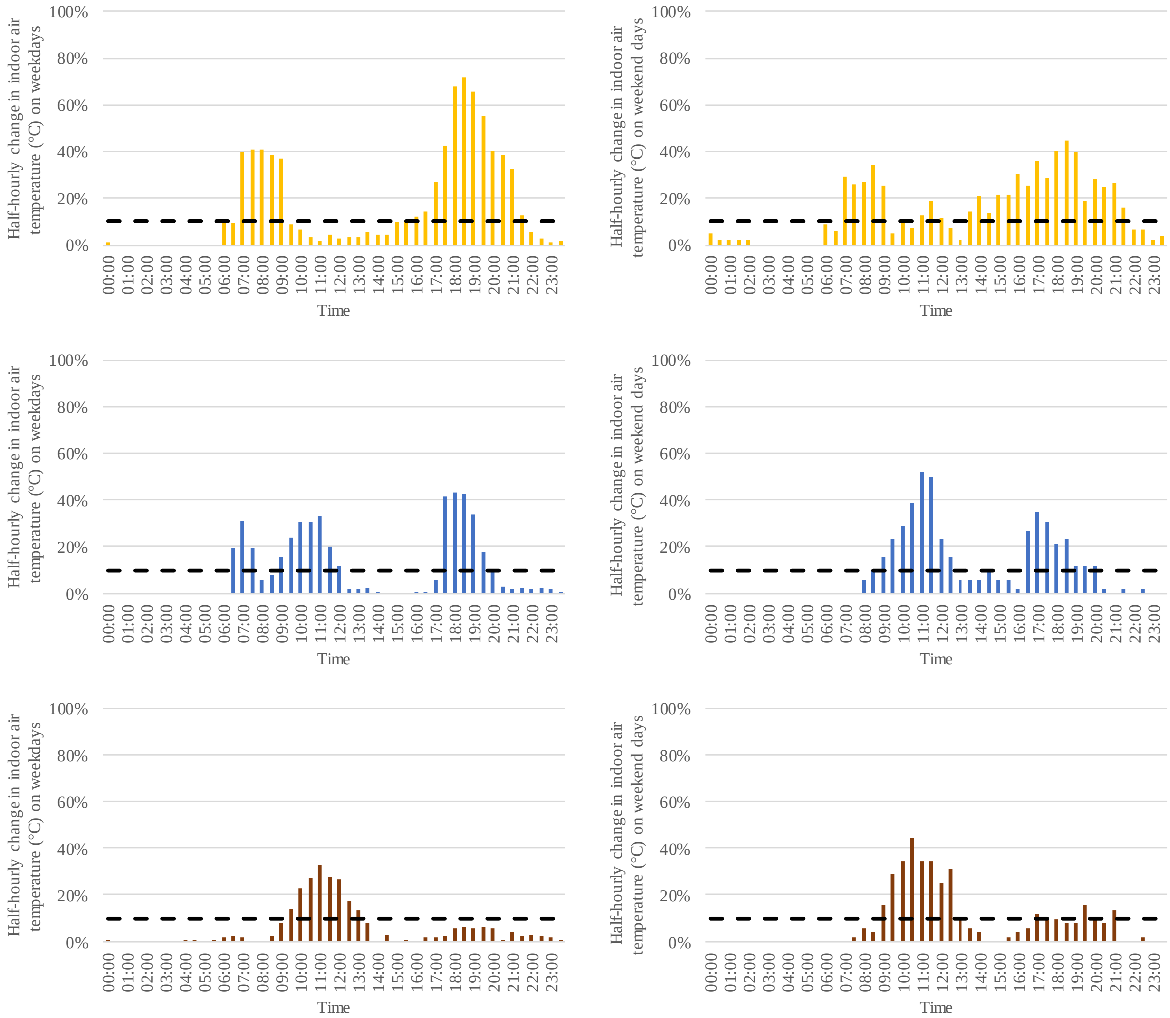

Figure 5: Variation in daily heating periods in the dwellings (top – House 2, middle – Flat 3, bottom – Flat 6) and on weekdays (left) and weekends (right)

Manual heating overrides were identified in all ten dwellings. For example in House 2 (Figure 5) on weekdays, there were manual overrides between the two scheduled heating periods (between 09:30 to 14:30) and again after the second scheduled period from 22:00 to midnight. The additional heating lasted between 30 minutes and two hours. On the weekend heating days, there were manual overrides from midnight to 02:00 and again between the scheduled heating periods during the day with durations between 30 minutes and 1.5 hours. Similarly in the Flats 3 and 6, as can be seen in Figure 5, there were manual overrides outside the scheduled periods. In Flat 6, it seems that manual overrides were used to heat the dwelling in the weekday evenings for a small percentage of the heating days. The results of the calculations suggest this dwelling was not heated much in the evenings during the heating season.

5.2 Scheduled heating durations

Heating durations were calculated for the scheduled heating periods. The durations were taken as the time between the first 30-minute period for which the temperature increase was at least 0.3°C for 10% or more of the total days in the heating season and last 30-minute period for which the temperature increase was at least 0.3°C for 10% or more of the heating season days. Table 2 presents the estimated mean daily heating durations in all the dwellings on weekdays and weekend heating days. On weekdays, the mean daily heating durations ranged from 4 h to 11.5 h with a mean of 8.8 h (SD = 2.1 h) on the weekend days, heating durations ranged from 5.5 h to 13 h with a mean of 9.8 h (SD = 2.4 h).

Table 2: Estimated mean heating durations of scheduled heating periods in all dwellings on weekdays and weekend heating days

Dwellings	Mean weekday heating duration (h)	Mean weekend heating duration (h)
Flat 1	9.5	8.5
Flat 2	8.0	9.5
Flat 3	7.5	8
Flat 4	9.5	7.5
Flat 5	7.5	12
Flat 6	4.0	5.5
Flat 7	10.5	11.5
House 1	11.5	11.5
House 2	10.5	13
House 3	9.5	10.5

The dwellings that had one scheduled heating period per day on weekdays, had the heating on for an average of 5.8 h. When two heating periods were scheduled on weekdays, the average heating durations were 4.5 h and 5.8 h in the first and second periods respectively and at the weekends, the durations were 5.7 h in the first period and 3.7 h in the second period. When multiple heating periods were scheduled, on weekdays the durations were on average 1.9 h in the first period, 3.1 h in the second and 3.9 in the last period and on weekends, they were 2.9 h, 3.1 h, and 3.9 h in the first, second and last periods respectively.

In all the dwellings, manual overrides of the scheduled heating settings added a minimum of 0.5 h of heating to the scheduled heating durations on both weekdays and weekends. Table 3 presents the additional maximum heating duration from manual overrides of the scheduled settings in all the dwellings. On average, additional heating through manual overrides added 2.4 h to the weekday heating duration and 1.5 h to the weekend heating duration.

Table 3: Maximum additional heating durations from manual overrides of scheduled heating settings

Dwellings	Additional heating on weekdays (h)	Additional heating on weekend (h)
Flat 1	2.0	1.0
Flat 2	2.0	1.5
Flat 3	2.0	1.5
Flat 4	2.0	1.5
Flat 5	6.0	3.0
Flat 6	2.0	1.5
Flat 7	1.5	0.5
House 1	1.5	1.5
House 2	2.0	1.5
House 3	3.0	1.5

5.3 Estimated heating setpoint temperatures

The mean estimated setpoint temperature in the scheduled heating periods was 21.2°C (SD = 1.3°C) on weekdays and 21.4°C (SD = 1.4°C) on the weekends. Setpoint temperatures varied across all the dwellings. Table 4 presents the estimated mean weekday and weekend setpoint temperatures in each dwelling.

Table 4: Estimated mean heating setpoint temperatures in the scheduled heating periods on weekday and weekend heating days

Dwellings	Mean weekday setpoint temperature (°C)	Mean weekend setpoint temperature (°C)
Flat 1	20.9	21.7
Flat 2	21.2	20.9
Flat 3	22.0	22.7
Flat 4	19.2	19.1
Flat 5	21.5	20.8
Flat 6	20.9	21.3
Flat 7	22.2	23.2
House 1	22.7	22.7
House 2	22.8	22.2
House 3	19.0	19.3

There was also variation between estimated setpoint temperatures in the daily heating periods. In households with double and multiple heating periods, the estimated setpoint temperatures in the first heating period were always lower than those in the subsequent heating periods on both weekdays and weekends. The average estimated setpoint temperature achieved in the single heating period was 21.2°C. In the households with double heating periods, the average weekday setpoint temperatures were

20.6°C and 22.1°C in the first and second heating periods respectively. On weekend days, the estimated average setpoint temperatures were 22.0°C in the first heating period and 22.7°C in the second period. Similarly, in the households with three heating periods, the setpoint temperatures achieved increased in each heating period. On the weekdays, the setpoint temperatures were in the order, 20.4°C, 21.0°C and 22.1°C and on the weekends, they were in the order, 20.2°C, 20.9°C and 21.8°C.

6 Discussion

6.1 Heating season and daily heating periods

An indirect calculation method based on outdoor and living room air temperature was used for establishing space heating behaviours in this study. It enabled the identification of the heating season, daily scheduled heating periods and manual heating overrides used in dwellings. The method identified a continuous six month heating season from November to April based on an outdoor air temperature limit of 15.5°C which is also the base temperature for calculating heating degree days for most buildings in the UK (Carbon Trust, 2012). This is close to the 2011 Energy Follow-Up Survey findings that found that majority of households have close to a six-month heating period (BRE, 2013b). However, currently the Standard Assessment Procedure (SAP), the methodology used by the Government to assess and compare the energy and environmental performance of dwellings, uses an eight month (October to May) heating season in its calculation (BRE, 2013b).

The result obtained in the current study provides evidence that the eight month heating season (October to May) currently used in SAP may be overestimating the heating season by up to two months and thus the space heating energy demand of the homes. This finding relates to modern, new build housing and not to the general UK housing stock, i.e. including older, inefficient housing. It is also important to consider that assumptions used in energy models are often set to demonstrate compliance with benchmarks and targets rather than attempting to model actual behaviour and energy demands. This finding is corroborated by previous studies (BRE, 2013b).

Based on the methodology implemented, an examination of the changes in temperatures at night-time (between 00:00 and 05:59) identified that none of the dwellings investigated had scheduled heating periods during the night. In general, during this time period, the indoor temperatures fell in the homes due to heat loss. This finding is perhaps expected as it can be assumed that occupants are sleeping and therefore choose to not heat their homes at this time. As well as examining the temperature profiles, household's gas use was used to verify the method for identifying heating periods.

The scheduled heating periods identified in each dwelling gives indications of the occupant heating behaviour and occupancy patterns. Firstly, scheduled daily heating periods varied between the dwellings and between weekdays and weekends suggesting that occupants are actively using their thermostats to control their heating. They may be doing this to correspond to their occupancy patterns and their household routines. If it is assumed that a dwelling is only heated when it is occupied, those dwellings which are occupied only in the mornings and evenings during weekdays will tend to have double heating periods. A first scheduled heating period will coincide with waking up times (starting from around 06:00) and a second heating period will coincide with returning home times (starting from around 16:30). Short, multiple heating periods were the most common at the weekends and this could be because occupants are more likely to be home throughout the day on Saturdays and Sundays. Using multiple heating periods, occupants are able to reduce their heating durations and hence their heating energy by not heating continuously during the day. Also, eight out of the ten dwellings are CSH Levels 4 and 5, which are characterised by significant improvement in fabric performance, reducing heat loss through infiltration. With short heating durations, the dwellings are able to retain the heat for longer, keeping the occupants thermally comfortable.

6.2 Daily heating durations and setpoint temperatures

The average scheduled weekday and weekend heating durations were 8.8 h and 9.8 h respectively. These results sit in-between those previously reported in studies that used indoor air temperature measurements (Shipworth *et al.*, 2010; Kane *et al.*, 2015). Shipworth *et al.* (2010) reported a weekday duration of 8.2 h and weekend duration of 8.4 h and Kane *et al.* (2015) reported an average daily heating duration of 12.6 h (without making a distinction between weekdays and weekends). The heating durations in each identified heating period were also estimated. The results showed that in the households that scheduled only one heating period on weekdays, the average heating duration was 5.8 h whereas those that had their heating on twice per day had it on for 4.5 h and 5.8 h in the first and second periods. The results for the single scheduled heating period differs considerably from that derived from indoor temperature measurements reported in the EFUS (BRE, 2013b). The EFUS reported a heating duration of 14.5 h, however, this was based on measurements taken in a one month period only (January 2012). They also found that in households that heated twice per day, the first heating period was approximately 2 h long and 6 h in the second period on weekdays (BRE, 2013b).

The average estimated setpoint temperatures on weekdays and weekends were 21.2°C and 21.4°C respectively, These findings are again comparable to those reported by Shipworth *et al.* (2010) (21.1°C), and Kane *et al.*, (2015) (20.9°C) from their measured indoor temperature data. In the EFUS, the estimated mean setpoint temperature from temperature data was lower at 20.2°C. In the households with double and multiple heating periods, setpoint temperatures in the first heating periods were lower than the subsequent periods. In the households with double heating periods, the average difference between the estimated setpoint temperatures in the first and second heating periods on weekdays was 1.5°C and on weekends, 0.7°C. In the households with multiple heating periods, there was a difference of 0.6°C between the first and second and 1.1°C between the second and third heating periods on the weekdays. On the weekends, the differences were 0.7°C and 0.9°C. It could be that occupants purposefully set different setpoint temperatures in the different heating periods. Conversely, the selected setpoint temperature may not be reached due to the shorter heating duration in the first heating period. In the households with multiple heating periods, although the heating periods have similar durations, there is still a difference between the setpoint temperatures, particularly between the second and the third heating periods. In the households with double heating periods, on weekends the average heating duration in the second period (3.7 h) is shorter than that of the first period (5.7 h) but there is still an increase in the setpoint temperatures achieved. A possible explanation to this is that the temperature at the start of the second and third heating periods were higher than that at the start of the first heating period. Hence, it does not take long for the indoor air temperature to reach the selected setpoint.

6.3 Manual heating override events

From the calculation method used in the current study, manual heating override events were identified in all ten dwellings. In this study, on weekdays, manual overrides added between 0.5 h and 2.4 h to the scheduled heating duration and on weekends, 0.5 h to 1.5 hours of additional heating was added. The results obtained in the current study is in agreement with the findings reported from the EFUS (BRE, 2013b). Out of the respondents of the EFUS, 60% of the households with a central heating system controlled by a timer to give a regular heating pattern reported that they manually override their setting for additional heating at least once a week where the additional heating would add up to two hours to the regular heating duration. Energy models, such as the SAP, and building performance simulation tools, use fixed heating periods (e.g. SAP uses weekday: 07:00 to 09:00 and 16:00 to 23:00, weekend: 07:00 to 23:00) based on assumed occupancy schedules. Outside these specified time periods, the heating system is assumed to be off. The results from the current study show that even if a household has a fixed double heating pattern as outlined above, manual overrides in homes are prevalent and therefore assumptions for heating behaviour are likely to be inaccurate leading to poor estimations of energy and indoor environmental conditions. The application of fixed heating profiles are therefore unlikely to capture the diversity in heating behaviours observed in most homes.

6.4 Applications for the research

The research reported in this paper should be of interest to a number of key groups, including, energy modellers, energy supply companies and energy distribution network operators as well as local authority and social housing associations and government policy makers.

Findings from this research demonstrate that households manually override their scheduled heating periods to demand additional heat. This is particularly important for energy modellers who often use fixed heating schedules for modelling the energy and indoor environmental performance of buildings. Manual override events are unlikely to be reflected in the fixed heating profiles and will result in limitations in capturing the diversity of heating behaviours observed throughout a day.

The results provided in this paper will also be valuable for energy supply companies and energy distribution operators who need to understand the profiles and temporality of heating energy demand. It could be useful for informing decisions about transitions to future energy systems with a high proportion of low carbon heat sources. For example, regarding improvements or changes to electricity networks, until battery storage becomes commonplace, electricity generation from renewable sources has to match demand. With manual override events, the electricity network must be designed to match these short-term demand peaks.

Furthermore, the findings obtained in this work can be used by local authorities, social housing associations and government policy makers to target demand side energy efficiency response interventions. Interventions can be aimed at increasing the understanding of heating behaviours at home and their impact on heating energy demand. Future demand side interventions may require flexible heating behaviours and the first step to investigating the flexibility of heating behaviours is to understand how households are currently heating their homes.

6.5 Limitations

The methodology presented in this study is based on using indoor air temperature measurements to determine scheduled heating periods and manual overrides and also to estimate set point temperatures. This method does however have a limitation as from the indoor temperature alone, it is not fully clear whether increases in the temperature are due to the operation of the heating system or other heat sources such as secondary heating or internal heat gains from occupancy and household activities. To address this, daily average solar radiation profiles were plotted against daily average outdoor temperature and indoor air temperature profiles. The mismatch in the peaks in the outdoor temperature and the indoor air temperature gave an indication that the increase in indoor temperature was not due to solar heat gains. During the heating season, the peaks in indoor temperature clearly occurred in the mornings and evenings. An examination of the indoor air temperature during the non-heating season showed no peaks in the profiles, i.e. fairly constant indoor temperature throughout the day. This gives an indication of the effectiveness of the fabric standards of the dwellings. The dwellings were constructed to CSH Level 4 and 5 standards, which are characterised, by low U-values and high air tightness to reduce solar heat gains. Another measure used to the address the uncertainty of using indoor temperature was using 30-minute gas consumption measurements. The gas consumption profiles were found to provide a good indication of the start and end times of the heating period, which were consistent with those identified using the indoor temperature measurements. In between the scheduled heating periods, gas consumption decreased significantly but was not zero, as there was still some heating due to the manual overrides and also domestic hot water (DHW) was provided by the gas central heating system. Gas consumption was minimal at night, where there were no scheduled heating periods. These verification methods provided assurance that the increase in indoor temperature were due to the heating system and no other sources of heat.

The heating operation behaviour methodology presented is based on a small sample of 10 UK dwellings. These dwellings were constructed to higher performance standards compared to exiting dwellings and they were all rented. They are therefore not representative of the wider UK housing stock. Despite this limitation, to the author's knowledge, a measurement approach for identifying manual heating override events has not yet been used. There is incremental improvement in the energy performance of new dwellings driven by the gradual tightening if the building regulation alongside initiatives and incentives to improve the existing stock. It therefore makes sense to start the development of occupant behaviour methodologies and models for dwellings constructed to the current minimum performance standards as the baseline. Nevertheless, a larger national-scale study of heating behaviour, representative of the UK housing stock, would be a valuable extension to the current work and could be used to validate the findings of the current study. Other factors that should be included in a larger study are household types and occupancy patterns. These are parameters that will have an impact on household gas consumption and heating behaviours.

6.6 Future work

To date, manual heating override events in UK dwellings have only been recorded through self-reported survey questions (BRE, 2013b). To the authors' knowledge, a measurement approach for identifying manual heating override events has not yet been used. The advent of internet-connected heating controls and its inherent centralised data collection will provide a new stream of data, which will include real time data on heating settings, i.e. on/off times, setpoint temperatures, gas consumption. These will therefore provide future studies with a means for direct measurement of heating behaviours. Analysis of data from smart heating controls have been presented in studies by Hanmer *et al.* (2018) and Huchuk *et al.* (2018). The first observation from these studies is the scale of the data. Hanmer *et al.* (2018) obtained a dataset of temperature setpoints from smart thermostats installed in 337 UK homes. They examined the householder's interaction with the controller directly, hence, it was possible to see exactly when the heating settings were changed. This feature will make it possible to accurately determine and distinguish between scheduled and manual override heating events. Huchuk *et al.* (2018) studied a dataset consisting of more than 10,000 connected thermostats installed across North America spanning multiple years. The thermostats were connected to environmental sensors which recorded environmental data (indoor and outdoor temperature and indoor relative humidity) and heating and cooling settings (setpoint temperatures, durations and scheduled and override events). The use of this type of data source means that issues such short study length, limited sample size and difficulties in data collection are resolved.

Currently, internet-connected thermostats are unlikely to be representative of the wider UK housing stock and therefore early findings obtained from such studies will be difficult to extrapolate to other households. However, as adoption of this technology in homes become more commonplace, information from the smart controls will be valuable for expanding on the knowledge and understanding of occupant heating behaviours given the range of differences that exist at individual household level.

The ten dwellings investigated in this study are new-build properties and should therefore achieve current standards as set by the building regulations. This means that the methodology developed in this work may better capture occupant's heating behaviour in new homes or those which have undergone refurbishment (i.e. the future housing stock), as it could be imagined that heating operation studies undertaken in older dwellings may well be affected by factors such as higher air leakage rates. Equally, household types and occupancy patterns will affect heating behaviours. Further work is therefore required to establish the diversity and safety factors that should applied for different house types and households types to develop more reliable heating schedules to be used in building performance simulation.

7 Conclusions

This paper provides a method for estimating a heating season, scheduled heating periods and manual overrides and heating settings (heating durations and setpoint temperatures). Data was recorded at 10-minute intervals for a one year period and the results are based on a subset of six months of data which was identified as the heating season. The dwellings are new builds constructed to at least the 2006 Building Regulation standards (with eight constructed to higher Code for Sustainable Homes building performance standards). The results obtained in this study are therefore relevant for the future of housing construction including refurbishment of existing dwellings with the aim of reducing energy consumption and emissions from the housing sector.

From the outdoor temperature data recorded on site, the identified heating season was from 01 November 2013 to 30 April 2014. This was a continuous period where daily mean outdoor temperature was less than 15.5°C on all the days. The selected heating season excluded the days in the transition season (October and May) where daily mean outdoor temperature was less than 15.5°C on some of the days. During the selected heating season, there was a mismatch between the peaks in indoor air temperature and outdoor temperature. This indicates that the elevation in indoor air temperature was not due to solar heat gain but possibly the use of a heating source inside the dwelling.

The indoor temperature method used to identify scheduled heating periods and manual override events in this study proved reliable for describing heating behaviour. The method used a criteria for temperature increase over 30 minutes to define when the central heating system is supplying heat to the dwelling and a criteria for percentage of days when the temperature increase occurs to define whether it is a scheduled heating period or a manual heating override.

The method was validated using 30-minute gas consumption data collected in each of the dwellings. The results of the study showed that occupants used the programmable thermostats installed in their homes to control their heating behaviour, i.e. set daily regular, multiple heating periods and setpoint temperatures and manually override the settings for additional heating when needed. There were some variations in the settings used on weekdays and weekend heating days. Overall, the estimated mean weekday and weekend setpoint temperatures were 21.2°C and 21.4°C respectively. This result is similar to the 21°C recommended by the World Health Organisation (WHO) as a comfortable indoor temperature, and to prevent potential health effects.

The mean estimated scheduled heating duration was 8.8 h on weekdays and this was increased by up to an average of 2.4 h through the occupants manually overriding the settings. At the weekends, the mean duration of scheduled heating periods was 9.8 h and it was increased by up to 1.5 h through manual overrides. These results show that the current energy modelling tools such as BREDEM overestimates the heating durations on the weekends. Even with the additional heating provided through manual overrides, the total weekend heating duration estimated in this study is significantly lower than that specified for domestic heating energy prediction.

The research presented in this study could be used in occupant heating behaviour research to better describe control of heating systems and heating settings in order to provide more realistic profiles of household heating behaviour. In addition it could be used to better inform the assumptions of heating preferences used in energy models which could result in more accurate predictions of domestic space heating demands. It should be noted that the results presented in this paper, particularly relating to manual heating overrides are obtained from a study of ten UK dwellings and are therefore not representative of the wider housing stock. A larger, national-scale study of manual heating override behaviour would be a valuable extension to the current study and could also be used to further validate the findings of this study.

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