Heating behaviour in English homes: An assessment of indirect calculation methods

T. Kane*, S.K. Firth, T.M. Hassan, V. Dimitriou

School of Civil and Building Engineering, Loughborough University, Loughborough, LE11 3TU, UK

ARTICLE INFO

Article history:
Received 20 July 2016
Received in revised form 21 January 2017
Accepted 21 April 2017
Available online 27 April 2017

ABSTRACT

Heating behaviours, such as timer and room thermostat settings, are a key influencing factor in energy demand in homes. However they are difficult to measure directly in existing housing with standard heating systems and controls. To overcome this, several indirect methods have been developed in previous research which estimate heating behaviours using sensor measurements of temperatures and energy demands in the home. This work assesses seven of these heating behaviour indirect calculation methods through a comparative study based on sensor data recorded in 20 English homes over a five month period. The results show that methods based on room air temperatures estimate mean daily heating durations between 6.7 and 11.4 hours per day, based on radiator surface temperatures between 2.9 and 3.3 °C per day and based on gas consumption for 4.4 h per day. Estimated thermostat setting based on peak whole house temperature ranged between 20.3 °C and 20.8 °C but a 5 °C temperature range was found when applying the methods to different room temperatures. Of the methods tested, the radiator surface temperature method was found to be the most appropriate for calculating heating behaviours over time and a set of guidelines for the future application of indirect heating behaviour calculation methods is provided. The findings highlight the need for future studies to directly measure heating behaviours in homes in order to further improve the development of indirect heating behaviour calculation methods.

© 2017 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

1. Introduction

There are over 22 million dwellings in England [1]. Natural gas and electricity are predominantly used to heat English dwellings throughout the winter months to avoid uncomfortably cold internal conditions. In 2013 it was estimated that the energy content of the fuel used for space heating in dwellings was 4188MWh [2] which accounted for approximately 12% of the UK’s total energy consumption that year. Consequently dwelling space heating energy use is one of the sectors targeted for emissions reduction as a part of the drive to a low carbon economy and to meet the UK Government’s 80% CO2 emissions reduction targets [3].

Space heating energy use is driven by the thermal properties of the building, the characteristics of the heating system in use and occupant behaviour. Heating behaviours, how occupants' use and control their heating systems to provide warmth to their homes, have a significant impact on overall energy use [4–6]. A better understanding of heating behaviours is required for four reasons; (1) how people control their heating has a significant impact on how much energy is consumed in individual homes [7,8]; (2) building energy models and simulation tools use heating schedules as inputs and consequently a better understanding of heating behaviour will reduce model error [5,9]; (3) heating system and control technologies are constantly evolving and it is essential that as this happens new systems are able to meet the needs of users and to provide the comfort levels that they require at the right times [10] and; (4) in the coming decades it is likely that space heating in our homes will become electrified which will have a significant impact on the electricity grid demand management (in particular the times of the day when peak heating energy use occurs) [11,12]. Heating behaviours such as timer settings, use of override, actual thermostat setting and TRV settings for existing ‘non-smart’ heating systems are very difficult to measure over time (as the settings on these devices cannot easily be captured by traditional sensors).

This paper investigates indirect heating behaviour calculation methods using data collected in a sample of 20 English homes. Detailed data collection and monitoring were carried out resulting in over 100 measurement variables per home. The dataset is, to the authors’ knowledge, one of the most comprehensive to be used in heating behaviour studies on an individual home basis. Drawing from the literature seven indirect methods for calculating heating behaviour based on sensor data were identified. A comparison of
2. Heating behaviour in English homes

2.1. Typical UK heating systems

This work was undertaken in the UK and consequently the heating system described here is a typical UK domestic heating system as found in over 90% of homes [13]. It should be noted, however, that the insights into heating behaviours and their calculation methods are of interest to researchers, policy makers and technology developers in all countries with temperate climates where space heating is required during the winter. Additionally, the techniques discussed in this paper may have the potential to be adapted for calculating cooling durations and set point temperatures in hotter climates where energy use for air conditioning is more significant.

Fig. 1 shows a schematic of a typical UK heating system. A heating supply loop filled with water is used to distribute heat around the building. A boiler, most commonly powered by natural gas, provides the heat to the water in the loop. A pump circulates the water in the loop to individual radiators in each room. The water flow to individual radiators can be controlled using thermostatic radiator valves (TRVs) which are fitted to each radiator. The boiler and pump are often controlled using a central timer or programmer, which is used by occupants to set the times when heating is required, and a room thermostat, which turns the boiler on and off depending on indoor room temperature during the scheduled heating period.

Table 1 describes the components, processes/outcomes, heating behaviours/settings and the secondary factors which all influence the operation of domestic heating systems in the UK. The components are the physical elements that comprise the heating system. Processes/outcomes are the functions that are undertaken by the heating system and the resultant effects of these functions. Settings/heating behaviours are how occupants control the heating system to achieve the desired indoor temperatures. Internal heat gains are the heat gains caused by occupant behaviours which are not directly related to heating. This illustrates the complexity of heating systems, their controls and the challenges in monitoring their performance and the heating behaviours which relate to them.

It should be noted that there are dozens of timers/programmers and thermostats in use in UK homes many of which have complicated functions such as time set-back, occupancy monitoring, weather or price signal controls which vary thermostat and timer settings according to factors such as changes in external weather conditions or energy costs [14,15]. This work does not study all possible combinations of heating systems and their components, but focuses on the most common heating system configurations and associated heating behaviours in UK homes.

2.2. Literature review

A significant body of work in occupant behaviour measurement and modelling has been undertaken as daily changes in occupant behaviours are important inputs in building energy simulation [16]. Much of this work however has been focused on office buildings [17,18] and there is a lack of evidence of daily modelling inputs for domestic dwellings. To date understanding of heating behaviours has come from either surveys or measurement studies.

2.2.1. Survey methods

Survey methods have been used to ascertain the thermostat setting and heating duration used in dwellings. Shipworth [19] found, for UK homes, that there was no statistical difference in reported thermostat setting between 1984 and 2007. The mean thermostat setting for 1984 and 2007 were 19.3 °C and 19.6 °C respectively. This result differed slightly from a similar US study which stated that reported thermostat setting increased by 0.5 °C between 1985 and 2002 (however this result was not tested for statistical significance) [20]. Guerra-Santin et al. [21] reported thermostat settings according to different household types, higher set-point temperatures and longer heating durations were found for seniors and families compared to adults living alone. Jones et al. [22] found that reported heating durations for weekdays and weekends were 9.5 h and 11.2 h respectively and that the mean reported set-point temperature was 20.5 °C. Research has shown that there is no relationship between reported (based on survey methods) and estimated thermostat setting (calculated using measured data) [23,24]. There are four possible reasons why no correlation is found: (1) occupants are unaware of the settings they use; (2) thermostat setting is estimated based on temperatures in living spaces but thermostats are often placed elsewhere; (3) there is inherent error in the temperature sensors and consequently there are uncertainties related to the calculated values or; (4) the calculation methods are incorrect. The authors are unaware of any survey research which has reported other heating behaviours or considered daily changes in heating behaviour.

2.2.2. Measurement methods

To date the authors are aware of only two studies which directly measure heating behaviours [25,26]. Andersen et al. [25] monitored the TRV setting in 13 homes it was found that TRV set point was related to outside air temperature, relative humidity and wind speed. The set-points reported for different homes for weekdays and weekends were all within 1 °C of 24 °C. Pritoni et al. [26] monitored smart thermostats installed in over 200 rooms in university halls of residence, ‘set-points’ were discussed relative to occupied and unoccupied periods but were not reported in the text. Several papers reporting heating behaviours using indirect calculation methods using sensor data collected in homes have been published. Martin and Watson [27] estimated the heating duration in 59 UK homes using radiator surface temperatures sampled every 20 min. The mean heating duration was found to be 8.8 h per day, with a significant variation of between 2 and 22 h per day. Weekends were found to be heated only marginally longer than weekdays. Energy Follow Up Survey (823 homes) used room temperature measurements to derive heating durations and reported the 95% confidence interval for homes with central heating to be 8.8–9.5 h per day in homes with regular heating periods and 9.8–11.3 h for homes without regular heating [28]. Longer heating periods were observed for homes without central heating. Shipworth et al. [29] estimated thermostat setting and heating duration in a sample of 358 homes. The calculations were based on room temperature measurements taken every 45 min between 1st November and 31st January. The mean heating duration was calculated to be 8.4 h on weekends and 8.3 h on weekdays. The average thermostat setting was found to be 21.1 °C. Again, a significant amount of variation was found between homes for both heating duration and thermostat setting. Heubner et al. [29] used the same dataset to calculate mean heating duration. A sample of 248 homes was selected and average heating duration was calculated using temperature rises and falls over the course of the day. Mean heating duration was approximately 10 h per day. A large discrepancy between actual heating duration and the standard heating behaviours commonly assumed for building simulation models was highlighted. Kane et al. [30] calculated nine heating practice metrics including heating duration, timer set-
settings and achieved temperature for a sample of 249 homes. The metrics were calculated using room temperature data measured every hour between 1st December and 28th February. The mean heating duration was 12.6 h which was longer than reported in other studies. Average achieved temperature, as a proxy for thermostat setting, was estimated as 20.9 °C, which was comparable to the thermostat setting calculated by Shipworth et al. [23]. Hunter et al. [31] reported results for heating duration across two winters from 14 homes in Ireland based on data collected using a ZEM30 wireless sensor which measured the electricity consumption of the oil-fired central heating boiler in hourly intervals. The mean heating duration was 6.2 h per day which is shorter than reported in other studies. Total number of heating hours per month was also reported and showed some variation in heating length relating to external conditions, i.e. in the mild shoulder months (spring and autumn) the total number of heating hours was less than in the cold winter
months. Ren et al. [32] used cluster analysis and found six patterns of demand temperatures from data collected in 62 homes in the USA between January and March. The clusters were based on whether the demand temperature was stable or varied, the majority of homes having a varied high or mid demand temperature. French et al. [33] assessed the length of the heating season in a sample of 397 homes in New Zealand and found that average heating season ranges from 8.6 months to 5.5 months in locations with different climates. Temperatures in living rooms and bedrooms during occupied hours were reported but other occupant heating behaviours were not assessed. Peffer et al. [15] monitored indoor temperature and thermostat settings at 15 min intervals in 96 homes in the US, it was found that the household occupants tended to change heating settings on a daily basis but specific heating behaviours were not reported. Again the authors are unaware of any study to date that has reported heating behaviours calculated on a daily basis and how these change over time. The papers using indirect data use different measurement techniques and calculation methods. Consequently, it is hard to compare their results. Data from a growing number of monitoring studies has and will continue to become available over the coming years. These and other temperature monitoring studies have reported internal temperature conditions in homes but not heating behaviours [34–37]. Using these data sets it should be possible to apply the methods previously used to estimate heating behaviours. To date, however, no publication has compared multiple indirect calculation methods for estimating heating behaviours and consequently, it is not possible to quantify the limitations of the methods which have previously been applied.

3. Data collection

The dataset used in this work was collected by the REFIT project, a Research Councils UK collaborative project carried out by Loughborough University, the University of East Anglia and University of Strathclyde. Twenty homes were recruited in 2013 to take part in a study of Smart Home technologies and agreed to several data collection activities. A detailed building survey was carried out by researchers. The survey included questions on the building fabric, glazing, lighting, appliances, heating system, heating controls and many other factors. The survey was conducted on a room-by-room basis in each dwelling and floor plans were created at the dwelling and room levels. A series of interviews were conducted with the occupants over an 18 month period during which at least six individual visits were made to each home. Over 40 sensors and Smart Home devices were placed in each dwelling (the larger homes had more) to collect measurements of internal environmental conditions, energy consumption at the whole-house and appliance levels, occupancy and occupant behaviour. The sensor monitoring resulted in over 100 different measurement variables from each of the 20 homes, leading to over 100,000 data points per house per day. Despite the intrusive nature of the research none of the homes left the study before the end of the monitoring period on the 30th April 2015. The data from the REFIT project is available as open access [38].

3.1. Recruitment and composition of the 20 homes

The homes were recruited using leaflet drops and email. Sampling was undertaken using a two by two sampling matrix based on the criteria: (i) households with or without children and; (ii) households who were comfortable or not comfortable with new technologies. Five homes were recruited for each quadrant in the sampling matrix. During the initial contact potential participants were asked a series of questions to establish their position in the sampling matrix and whether their home was suitable for the study. For example, the sensor installations required that the gas meter was not situated in the basement and that the home had a broadband internet connection. 35 contacts were made requesting further information about the project, of these 27 undertook the initial screening interview. Recruitment visits were made to 23 homes of which 20 were selected to take part in the study. All of the homes were located in or around Loughborough, UK, which enabled easy access to the homes by researchers.

The first home visit undertaken for research purposes was for the monitoring installation and technical building survey. After this a series of social science interviews and user centred design activities were carried out with the homeowners before and after the homes were upgraded with Smart Home technologies. For more information about the social science and design related research related to this project see [39–41]. This paper focuses on the data that was collected as a result of this first visit before the homes were upgraded; later publications will report on the impacts of the Smart Home devices on energy consumption and occupant behaviour.

Table 2 shows a summary of the characteristics of the dwellings and the occupants for the 20 homes which were recruited. The sample was dominated by detached dwellings. This was partly related to the constraints of the monitoring equipment, which prevented the selection of terraced homes where the gas meter was located in the basement. As most of the dwellings were detached they have high floor areas, an average of 135m², compared to the national average of 94 m² [13]. Given the range of construction types, construction ages and floor areas, a significant variation in the heat loss characteristics of the dwellings can be expected. We recognise that this sample is not representative of the UK housing stock, instead our aim was to test how well the indirect heating methods apply to these 20 homes. The 20 home sample was chosen to allow detailed monitoring which is too expensive to collect in larger samples. This approach is common in the field of building performance monitoring to reduce overall monitoring costs and allow for complex multidisciplinary research design [42–45].

A further limitation of the sample is related to the dominance of detached dwellings in the sample, these homes are likely to have high overall thermal capacitances and high envelope heat losses. As a result the indirect calculation methods might perform differently for dwellings of different built form. However, given that the previous applications of the indirect calculation methods do not differentiate between built form it is deemed valid to test them on this sample.

All of the homes were heated with gas-fired boilers, supplying hot water to wall-mounted room radiators. Gas was the main heating fuel for all of the homes. Control of heating was provided by room thermostats, timers and Thermostatic Radiator Valves (TRVs). All of the homes had TRVs fitted to at least one radiator. Four homes had TRVs fitted to all radiators; this was unexpected as typically one radiator is required to remain open all of the time to ensure the pump can be in use when required. Secondary heating was present in 18 of the homes although occupants reported that daily use (during winter periods) should be expected in only four of the homes.

3.2. Choice of measurement variables and sensor placements in the 20 homes

The four measurement variables used in this analysis are room internal air temperatures, radiator surface temperatures, gas consumption and external air temperature. Sensors were placed in the homes for the duration of the study to record these measurement variables on a regular basis. The data used in this analysis was chosen as it has been used previously to infer heating behaviours, i.e. room air temperatures and radiator surface temperatures will rise when the heating is in use and gas is the main fuel used space heating.
### Table 2
Household characteristics of the 20 study homes.

| Characteristic                        | Description |
|--------------------------------------|-------------|
| House type                           | Detached (16), semi-detached (3), mid-terrace (1) |
| Construction type                    | Cavity walls (15), Predominantly Solid wall (5) – three of the solid wall homes had cavity wall extensions and one house had both solid and cavity walls in the original construction |
| Construction age                     | Before 1900 (2), 1900–1929 (2), 1930–1949 (11), 1950–1966 (3), 1967–1975 (5), 1976–1982 (1), 1983–1990 (3), 1991–1995 (1), after 2003 (2) |
| Floor area                           | Mean: 135 m², Range: 78–275 m² |
| Occupants                            | The number of occupants living in the dwellings ranged from one to six. Ten of the homes had children under 18. Nine homes were occupied by two people. |
| Boiler                               | All 20 homes have gas-fired boilers |
| Room thermostat position             | 17 homes had room thermostats. These were located in the following room types: Entrance hall (9), Dining room (4), Living room (2) and Kitchen (2) |
| Thermostatic radiator valves (TRVs)  | TRVs were fitted to 100% of radiators (4) 80% or more radiators (8), between 80 and 50% (5), less than 50% (3) |
| Secondary heating fuel type          | 18 homes had some form of secondary heating. The fuel source for this secondary heating was: electricity (3), gas (10), solid fuel (6)b |

*a Numbers in brackets following a description item give the number of homes in the sample with this characteristic.  
b One home had secondary heating of more than one fuel type.

---

**Fig. 2.** A selection of the monitoring equipment used in the project (left, Hobo pendant, Hobo U12 and iButton sensors; right, a pulse logger on a gas meter).

Fig. 2 shows examples of the sensors chosen to collect these measurement variables. Room indoor air temperatures were monitored using a combination of Hobo pendant UA-001-64 and Hobo U12-012 sensors manufactured by Onset [46]. The sensors have a measurement resolution of 0.03 °C, are accurate to ±0.35 °C and have a measurement range of between 0 °C to 50 °C [46]. The Hobo sensors were installed in each room and logged air temperatures at 15 min or half hour intervals. The logging interval was chosen to ensure a reasonable level of detail [previous studies have logged at intervals of 45 min [23] and one hour [30]] while maintaining the memory life of the logger. Hobo sensors have been used in previous temperature monitoring studies and have proved to be reliable and robust [30]. The sensors were usually placed on shelves or surfaces around shoulder height and care was taken to ensure that sensors were placed away from heat sources and direct solar radiation (i.e. near windows) in order to avoid misleading readings. Limited battery life and memory of the sensors meant that the sensors were replaced midway through the project. Prior to installation temperature sensors were calibrated by Tempcon Ltd [47] and found to be accurate within ±0.4 °C. After the sensors were collected from the homes a sub-sample of the sensors were calibrated, all of which were still found to be within the manufacturer’s specified error.

Surface temperatures of radiators were measured using Maxim Integrated iButton DS1922L temperature sensors [48]. The iButton sensors had a measurement resolution of 0.0625 °C, an accuracy of 0.5 °C and an operating range of –40 °C to +85 °C [48]. A logging interval of half hour intervals was chosen as this was deemed sufficient to identify the use of the radiator at a reasonable resolution. Given the available memory in the sensor this meant that the sensors would need replacing every six months. Visits were organised by the research team to retrieve the sensors and replace them with new ones throughout the study. The iButton sensors were fixed onto the radiators using heavy-duty tape, so the sensor maintained contact with the radiator surface. In most cases the sensors were positioned at the back of the radiators, in the centre towards the top of the back surface, so they would not be visible to the householders and less likely to be disturbed.

There are complex regulations surrounding the monitoring of gas meters owned by National Grid which owns the majority of gas meters in the UK [49]. For more detail on the regulations see the industry recognised documents IGE/GM/7a [50] and IGE/GM/7b [51]. Consequently, gas consumption was recorded using an external company which exchanged the existing gas meters in the dwellings for new meters compatible with their bespoke pulse loggers [52]. All twenty homes in the sample had new gas meters installed in this process. Gas volume measurements were recorded by counting the pulse output, which relates to 0.01m³ of gas, over each half hour time interval. Data was downloaded via mobile communications on a daily basis and emailed to the research team. It was discovered during installation that two of the homes in the sample had a poor mobile signal and were not suited to the gas monitoring solution. However one of these homes agreed to have a standalone Enica Opti-Pulse logger [53] installed which collected a comparable dataset and is used in this analysis.

Given that the previous studies used Hobos to measure indoor temperatures and externally sourced external air measurements, we followed a similar approach. External air temperature was monitored at the Loughborough University weather station, which was
within 20 km of all of the homes and 3 km of 18 of the homes. It was assumed throughout the study that the homes experienced the same external climate conditions as recorded at this weather station as recommended [54].

3.2.1. Data cleaning and preparation

The raw sensor data was imported into an Access database and a combination of SQL queries and Visual Basic for Applications code was used to clean and prepare the data for analysis. The data cleaning steps were:

- Selecting the sensor data only within the analysis time period of 1st February and 30th June 2014
- Converting all time steps to half hour intervals
- Excluding sensors where errors were found

The monitoring period was chosen for two reasons: (1) it was before any of the homes were upgraded with Smart Home heating controls and consequently represents a sample of homes with heating systems which are comparable to those in the majority of English homes and; (2) it includes both winter heating and transition months so that changes in heating behaviour over time can be assessed. Though some room temperature measurements were taken at fifteen minute intervals which would give a more accurate insight into heating system operation, half hour data was the highest resolution which was available across all of the data sets. Consequently, the use of half hour data enabled comparability between the different data streams.

After the sensors were downloaded the data was checked to ensure that it was error free. The temperature data was plotted in weekly periods so that errors could be identified. Database queries were run to highlight any sensors which recorded temperature readings lower than 5 °C or higher than 30 °C. These two methods highlighted temperature traces with unusual patterns. Sensor measurements were removed when data was deemed to be influenced by excessive heat gains which did not reflect usual heating system operation or when a sensor was malfunctioning i.e. recording temperatures lower than the external air temperature. To ensure that data was consistent for the whole analysis period, where erroneous data was identified all of the data collected for that room was excluded. Data from seven rooms was deemed to be erroneous. 202 Hobo sensors had useful data which enabled analysis of temperatures from 173 rooms.

The heating behaviours calculated here can be applied to any room temperature measurement. However, it might be of interest to understand the average temperature in the whole house. As room sizes vary considerably a dwelling temperature which is a volume weighted whole house average temperature use used.

\[
Dwelling\ temperature\ (W_T)\ at\ each\ time\ step\ is\ 
\sum_1^n \frac{T_{Room} \times V_{Room}}{V_T}
\]

Where, \(n\) is the number of rooms where temperature data is available; \(T_{Room}\) is the half hourly room temperatures measured in individual rooms; \(V_{Room}\) is the volume of the individual room; \(V_T\) is the total volume of the rooms where data is available.

It was much harder to definitively identify erroneous iButton data due the magnitude of temperature swings. One focus was to detect sensors which had partially detached from a radiator, however, this was impossible as partially detached sensors have a very similar profile to data collected on a radiator which has a low TRV setting. Consequently, data from only two sensors was removed from the dataset because unusually low temperature readings were identified. This left data available for analysis from 350 sensors and 236 radiators.

Volume of gas consumed measured in \(m^3\) was collected. To convert this into energy use it was assumed that the calorific value of gas 39.3 (which was the average calorific value of gas supplied to the East Midlands for the analysis period) and was constant throughout the analysis period [55]. The standard conversion from \(m^3\) to kWh of gas multiplies the volume of gas consumed by an industry standard conversion factor (1.02264), which accounts for air pressure, and by the calorific value of the gas and then divides by 3.6 which is the kWh conversion factor.

Gas consumed in each half an hour interval is

\[
G \times c \times CV = \frac{3.6}{T}
\]

Where, \(G\) is the volume of gas consumed; \(c\) is the industry standard conversion factor (to account for air pressure); \(CV\) is the calorific value.

Gas consumption data was checked by calculating daily energy use totals, initially some of the data was found to be 100 times higher than expected. This was an error in the data sent to the researchers and was fixed early on in the data collection resulting in no data loss. Annual gas consumption in dwellings in the East Midlands (where these properties are situated) is approximately 12,300 kWh per year [56]. The average gas consumption for the 19 homes reported here is 5296 kWh, as most of these dwellings are detached the four month totals are plausible.

Fig. 3 shows a ‘data map’ of the final, cleaned sensor data used for the analysis in this paper. Gas meter, radiator temperature sensors and space air temperature sensors placed in the 20 study homes resulted in nearly 3 million data points. One climate sensor was used for all homes resulting in 7200 temperature readings. Due to the complexity of the monitoring carried out some of the data streams were incomplete. There were three reasons why data was missing; (1) sensors were not placed until shortly after 1st February 2014; (2) sensors stopped logging because the memory was full and; (3) poor mobile signal resulted in data not being downloaded from loggers. The percentage of days where data was missing from the three monitored data streams were less than 0.5% for room air temperature, 6% for radiator surface temperature and 6% for gas consumption data. This data loss is expected to have a minimal impact on results.

4. Description of heating behaviours and their calculation methods

The room air temperatures, radiator surface temperatures and gas consumption measurements were used to infer heating behaviours in the 20 homes. Although timer settings is a key heating behaviour, many of the previous calculation methods have reported ‘heating durations’ which can be a combination of either active heating times or timer settings. For clarity in this paper, all heating period calculations are referred to as ‘active heating times’ and the derivation of timer settings from active heating times is considered beyond the scope of this paper.

Two heating behaviours were calculated: (1) the active heating times, the times when the heating is active and the boiler is supplying hot water to the radiators (the total number of active heating hours each day is the heating duration) and; (2) the estimated thermostat setting, the temperature set-point on the room thermostat (if present in the dwelling). The analysis of the cleaned sensor data was carried out using Microsoft Access and Microsoft Excel software. SQL queries and Visual Basic for Application code was used within Access to manipulate the data and perform the majority of the calculations. Excel was used predominantly to create figures and tables based on the results generated in Access, and was also used for some calculations where necessary.
4.1. Calculation of active heating times

Five methods for the identification of active heating times were used. Fig. 4 shows the measured sensor data for an example day (21st Jan 2014) for a single home and is used as an aid in describing the methods. The increase in room air and radiator surface temperatures and gas consumption at 13:00 correspond to the heating on time, heating is then on until approximately 22:30.

4.1.1. Room temperature methods

Method 1 is based on room air temperature and assumes that during the winter when external air temperatures are low a rise in indoor air temperature is the result of heating. This method was first used by Shipworth, et al. [23] based on data collected every 45 min. The method was applied unchanged and can be expressed as follows (Eq. (3)).

\[ \text{Heating is active at time } t \text{ if } (T_{\text{room},t} - T_{\text{room},t-1} > 0) \]  

Where, \( t \) is a half hour period; \( T_{\text{room},t} \) is the room air temperature at time \( t \) and \( T_{\text{room},t-1} \) is the room air temperature at the time step before time \( t \).

Method 2 is a development of Method 1 first used by Kane [57]. The method aims to consider periods of thermostatic control by assuming that if the temperature drops less than 0.05 °C the heating is still active. If heating remains constant for three time steps heating is assumed to turn off. This was adapted from the original method which used hourly data (Eq. (4)).

\[ \text{Heating is active at time } t \text{ if } \begin{cases} (T_{\text{room},t} - T_{\text{room},t-1} > 0) \text{ or } (T_{\text{room},t-2} - T_{\text{room},t-3} > 0 \text{ and } T_{\text{room},t-1} - T_{\text{room},t} > -0.05) \end{cases} \]  

Where, \( T_{\text{room},t} \) is the room air temperature at time \( t \); \( T_{\text{room},t-1} \) is the room air temperature at the time step before time \( t \) and \( T_{\text{room},t-2} \) is the room air temperature at the time step before time \( t-1 \).

Method 3 is based on the method developed by Heubner et al. [29] using 45 min data. To account for periods of thermostatic control the method assumes that a change of state of heating, i.e. turning from off to on or vice versa occurs after a cumulative temperature change greater than 0.75 °C is observed over as many time steps as necessary. This method cannot be expressed using a simple equation so for a complete explanation see [29].

4.1.2. Radiator method

Method 4 is based on radiator surface temperature and as with room temperature assumes that higher radiator temperatures result from heating (Fig. 4).

Method 4 is based on work published by Martin and Watson [27]. The original method was based on data collected at 20 min intervals and assumed that a 2 °C increase or decrease in radiator surface temperature related to a change of state of heating. In addition to this the heating is always off when the radiator surface temperature is below 18 °C and always on when the radiator surface temperature is above 35 °C. As data was collected at 30 min intervals in this study, the method was adapted to a temperature increase of 3 °C rather than 2 °C (Eq. (5)).

\[ \text{Heating is active at time } t \text{ if } \begin{cases} (T_{\text{rad},t} - T_{\text{rad},t-1} > 3^\circ C) \text{ or } T_{\text{rad},t} > 35^\circ C \end{cases} \]  

Unless \( (T_{\text{rad},t} - T_{\text{rad},t-1} < -3^\circ C) \) or \( T_{\text{rad},t} < 18^\circ C \)

Where, \( T_{\text{rad},t} \) is the radiator surface temperature (°C) at time \( t \) and \( T_{\text{rad},t-1} \) is the radiator surface temperature (°C) at the time step before time \( t \).

It is noted that the radiators do not act uniformly. Some radiators maintain a high temperature throughout the heating period, other radiators heat up to much lower temperatures and then start to cool while the heating is still active, this is likely due to thermostatic radiator values (TRVs). Thus to infer heating times using radiator surface temperature radiators with active TRVs should be avoided. This method was originally applied to the first radiator in the heating loop, however, this may be fitted with a TRV so in this work the method is applied to the maximum radiator temperature.
at each time step (Method 4a) and the radiator which is not fitted with a TRV when applicable (Method 4b).

4.1.3. Gas method
Method 5 is a new method introduced in this work. Gas consumption appears to provide a good indicator of heating times in Fig. 4. However, for those homes which also use gas for domestic hot water heating, cooking and secondary heating it may prove difficult to discern if the gas consumption measurements relates solely to space heating. The summertime base load of gas consumption can be used to deduce an average gas load for water heating and cooking. This could be subtracted from an average wintertime gas load to estimate the average winter time space heating load. However, for the indirect heating calculation methods a half-hourly gas consumption is required to determine the start and end times of heating periods, so such a method is not suitable here. Fig. 4 shows that 8.7 kWh of gas is consumed between 13:00 and 13:30, then as the heating continues, the half-hourly energy use drops to between 3 and 5 kWh until the last half an hour of heating. During the last half hour (22:00 to 22:30) only 1.7 kWh is consumed.

The maximum power output of a domestic boiler ranges between 24 and 40 kW [58]. If a 32 kW boiler runs for five minutes at full power, the energy use is 2.5 kWh, however, most modern boilers modulate to ensure high efficiency even at low flow rates. Consequently, this method reflects the patterns seen in the data and assumes that heating was active in a half an hour period if more than one kWh of gas was consumed during that time (Eq. (6)).

\[
\text{Heating is active at time } t \quad \text{if } G_t > 1
\]  

(6)

Where, \(G\) is gas consumed in a half an hour interval in kWh at time \(t\).

4.2. Estimated thermostat settings

4.2.1. Peak temperature when heated
As the thermostat is designed to turn the boiler off when the room temperature reaches the thermostat setting, previous work has assumed that thermostat setting is the highest temperature reached when the heating is active [23]. Method 6 takes this approach and calculates thermostat setting for every day when the heating is active at least once during the day. The daily thermostat setting is calculated for each day as the maximum air temperature recorded when the heating is active.

\[
\text{Daily thermostat setting is}
\]

\[
\text{Maximum}(T_{\text{air},1}, T_{\text{air},2}, \ldots, T_{\text{air},n})
\]  

(7)

Where, \(T_{\text{air},i}\) is the air temperature at the time of the \(i\)th occurrence of active heating during each day \(n\) is the number of active heating time periods in each day.

4.2.2. Average temperature when heated
Method 7 assumes that the estimated thermostat setting is the average of all of the temperatures when heated each day. This method which is was first used by Kane et al. [30] and was termed the demand temperature to reflect the limitations of using only peak temperatures to estimate thermostat setting. It describes the equivalent thermostat setting if the heating system was 100% responsive and heated the room to a constant temperature.

\[
\text{Daily thermostat setting for a single day is}
\]

\[
\text{Mean}(T_{\text{air},1}, T_{\text{air},2}, \ldots, T_{\text{air},n})
\]  

(8)

Where, \(T_{\text{air},i}\) is the air temperature at the time of the \(i\)th occurrence of active heating during each day, \(n\) is the number of active heating time periods in each day.

Table 3 provides a summary of the seven methods and how they were applied to the data collected in the 20 homes. In some cases it was not possible to apply a method to a home due to the data requirements for the method not being available. For example Method 1b uses the room temperature of a room with a room thermostat installed which was only available in the 12 homes which had room thermostats and Method 4b uses the radiator temperature of a radiator without a TRV fitted which was only available in 16 homes. Given that the different methods are applicable to different numbers of homes, the results are reported for both all homes and for a subset of 10 homes across which all methods could be applied.
Table 3
Summary of the nine methods used to infer times of active heating in this paper and the data upon which they are based.

| Method | Heating practice | Data type | Sensor location | No. dwellings where data is available |
|--------|------------------|-----------|----------------|-------------------------------------|
| 1a     | Active heating   | Room temperature | Living room | 20                                    |
| 1b     | Active heating   | Room temperature | Thermostat room | 12                                    |
| 2a     | Active heating   | Room temperature | Living room | 20                                    |
| 2b     | Active heating   | Room temperature | Thermostat room | 12                                    |
| 3a     | Active heating   | Room temperature | Living room | 20                                    |
| 3b     | Active heating   | Room temperature | Maximum radiator | 20                                  |
| 4a     | Active heating   | Radiator surface temperature | Room temperature | 16                                    |
| 4b     | Active heating   | Room temperature | No TRV radiator | 16                  |
| 5      | Active heating   | Gas | Whole house gas consumption | 19          |
| 6a     | Thermostat setting | Room temperature | Dwelling temperature | 20                                    |
| 6b     | Thermostat setting | Room temperature | Living room | 20                                    |
| 6c     | Thermostat setting | Room temperature | Maximum radiator | 12                                   |
| 7a     | Thermostat setting | Room temperature | Dwelling temperature | 20                                    |
| 7b     | Thermostat setting | Room temperature | Living room | 20                                    |
| 7c     | Thermostat setting | Room temperature | Thermostat room | 12                                   |

5. Results

5.1. Summary of sensor measurements

Fig. 5 summarises the sensor data collected in the 20 homes for the three measurement variables of internal room air temperature, radiator surface temperature and gas consumption. For each home and for each day in the 150 day period a daily mean value is calculated from the half hour readings of dwelling air temperature and gas energy consumption. A daily maximum value is calculated for radiator surface temperature as this is a better indicator of if the heating system was active in a particular day. In Fig. 5 these daily mean or daily maximum values are plotted as box and whisker plots showing (in order) the minimum, 1st quartile, mean, 3rd quartile and maximum values across the 20 homes for each day. The daily means of the external air temperature are also plotted. The mean daily temperature values are similar to those reported in previous publications [23,30] suggesting that the readings taken are plausible.

During winter months, in this case February until mid-April, indoor temperatures are predominantly driven by how occupants heat their homes as heating is used on most days (Fig. 5). Small daily variations in dwelling air temperatures can be observed, these relate to changes in heating settings and external weather conditions. During this time gas consumption is high and mean daily maximum radiator temperatures are consistently around 60°C. Dips in minimum indoor temperatures and radiator surface temperatures relate to periods where individual dwellings are unheated, such as the low radiator temperatures can be seen on a number of days during February. As external air temperatures increase during April and May heating is used less and the variation in dwelling air temperature follows the external air temperature more closely. During this time the greater range between 1st and 3rd quartile values of maximum radiator temperatures suggests that heating is not required every day in every home. This is also reflected in the gas consumption which in some homes is close to zero during this period. Most of the homes are unheated after June 7th. During this time gas consumption is very low and variation is largely driven by hot water heating and cooking. Dwelling air temperature largely follows the pattern set by external air temperature. The inter quartile range of daily maximum radiator temperature is much lower which suggests that in most homes the heating is now not in use.

5.2. Assessment of active heating methods

5.2.1. Total heating duration

The five methods were used to calculate the total number of heating hours for each home (Fig. 6). The room temperature methods (Methods 1, 2 and 3) have the highest active heating hours of the methods studied. The room temperature methods calculated using living room temperatures (Methods 1a, 2a and 3a) identified slightly more heating than methods using thermostat room temperatures (Methods 1b, 2b and 3b). Mean total heating hours for the room temperature methods range from 1696 h (2a) to 949 h (1b). Method 1a (1173 h) and 3a (1122 h) have similar mean total heating hours despite their different calculation methods. Method 2a has a much higher number of mean heating hours (1696) than Methods 1a or 3a, which is caused by Method 2 incorporating thermostatic control into its calculations.

The radiator methods have the lowest mean total heating hours (4a = 419 h and 4b = 386 h), less than half of mean total heating hours compared with the room temperature methods. In one home zero heating hours were calculated by method 4b. This method assumes that if a radiator has no TRV it will always be heating during active heating times. However in this home the radiator surface temperature follows the room temperature closely suggesting that the radiator is constantly turned off. The mean total heating hours calculated by the gas method (599 h) is slightly higher than the radiator methods. This is as expected as Method 5 will classify some non-space heating gas use as heating.

The mean total heating hours discussed here are calculated using different samples because of the availability of data for each of the methods. Consequently, these calculations were repeated for a sample of ten homes where all calculation methods were possible (Table 4). This allowed a more complete comparison and results show that the trends are similar to those observed in Fig. 6.

5.2.2. Daily heating duration

During February, mean daily heating durations ranged from 11.4 h (2a) to 5.9 h (4b) (Table 5). Throughout April, which is a transition month, when heating is not constantly required the radiator temperature methods suggest that the daily duration fell to 2.7 h (4a) and 2.5 h (4b). The room temperature methods remain high, although Method 3 falls from 7.8 h in February to 6.9 h in April. In June, when minimal heating is required, the room temperature methods estimate that heating is still active on average for at least seven hours a day. The gas method predicts less active heating in the
Fig. 5. Daily mean dwelling temperature, daily maximum radiator surface temperature and daily mean gas consumption for 20 homes and daily external air temperature measured between 1st February 2014 and 30th June 2014.

Warmer months but heating durations in June are higher than those recorded by the radiator methods. Daily heating durations were calculated for the highest and lowest 10% of external air temperature days and highest and lowest 10% gas consumption days as measured in individual homes. On the warmest 10% of days the room temperature methods indicate long heating durations (8.4–13.2 h) when the radiator methods show very little heating (0.2 h). During the coldest days this difference decreases and the methods estimate more similar active heating durations. A comparable result is observed in the highest and lowest gas consumption days.

Of the 20 homes discussed here four reported regular use of secondary heating and 16 reported little or no use of secondary
heating. Daily heating durations were calculated for these two sub-groups to assess whether the room temperature methods were more successful at identifying heating durations in dwellings where secondary heating was used as this would not be identified by the radiator methods. Daily heating durations were marginally lower in the homes where secondary heating is used according to all methods and consequently the results are inconclusive.

5.2.3. Relationship with external air temperature

As external air temperatures increase the gas and radiator methods show that daily heating durations decrease. To further explore this relationship the mean daily heating durations (the mean of the daily heating durations recorded in each home) for three methods (1a, 4a and 5) were plotted against daily external air temperature (Fig. 7). The radiator and gas methods show a strongly linear relationship ($R^2 > 0.75$). The room temperature method has a less strong linear relationship ($R^2 = 0.25$) and shows two distinct parts; below $10^\circ$C daily heating durations are relatively constant (around 8 h) but above $10^\circ$C they start to increase with increasing external air temperature. This effect has been observed in previous work [30] and suggests that the room temperature methods should only be applied at external air temperatures below $10^\circ$C.

5.2.4. Identification of unheated days

The five active heating calculation methods were also used to identify unheated days. In this work an unheated day is a day where zero active heating hours are recorded. In the winter unheated days are uncommon, even when homes are unoccupied, because of fears of water pipes freezing. As the external temperature increases, however, more unheated days are expected as heating is no longer required.

The percentage of unheated homes according to each method was calculated for each day of the study period and plotted over time (Fig. 8). The room temperature methods identified few unheated days (Methods 1 & 2 = 1%) because, even on cold days when no heating is used, solar gains or heat gains from people or appliances may result in small air temperature increases which the methods identify as active heating. Method 3 appears to be more successful than Methods 1 and 2 in identifying unheated days (3a = 17% and 3b = 21%) due its calculation method requiring a greater temperature swing before a change of state (i.e. heating off to heating on). The radiator methods (4a and 4b) identify the most unheated days (4a = 31% and 4b = 37%). The gas method (Method 5) identifies less unheated days (12%) than the radiator methods because the gas consumption also includes non-space heating gas use which can be misidentified as space heating. The difference between the radiator and gas methods is less pronounced in the colder months when inactive heating is a result of dwellings being unoccupied (i.e. no gas use for non-space heating purposes) as opposed to warmer days when heating isn’t required but occupants are still present in the home.

5.3. Assessment of thermostat setting methods

5.3.1. Average temperature and peak temperature results

Section 5.2 suggests that Method 4a should be considered the most reliable method for active heating and it is used for the basis for the thermostat setting calculation methods. Fig. 9 shows the results of thermostat setting methods (Methods 6 and 7) using the dwelling air, living room and thermostat room temperatures. The peak temperature method (Method 6) showed mean temperatures from 21.1°C to 20.0°C. The average temperature method (Method 7) gave slightly lower results, with a range of mean temperatures from 19.8°C to 19.1°C. The mean peak temperatures are slightly higher than the average temperatures this reflects the fact that in many homes the peak temperature is reached towards the end of the heating period [29,57]. The estimated thermostat settings for both Methods 6 & 7 are slightly higher in living rooms and lower in the thermostat room. This is probably because some thermostats are located in rooms with low occupancy such as hallways.

Table 6 shows estimated thermostat settings calculated using Methods 6 & 7. During February estimated thermostat setting ranges between 18.5°C (Method 7a) and 21.3°C (Method 6b). As external air temperatures rise the estimated thermostat settings
Table 5
Total heating hours and daily heating duration for the 20 homes calculated for the period 1st February 2014 and 30th June 2014 based on all nine calculation methods.

| Room temperature methods | Radiator temperature | Gas method methods |
|--------------------------|----------------------|--------------------|
|                         | Living room | Living room | Living room | Thermostat Room | Thermostat Room | Thermostat Room | Maximum | No TRV |
| 1a                       | 2a         | 3a          | 1b          | 2b              | 3b              |                 |         |       |
| Data available for analysis (no. of homes) | Feb-14  | Mar-14     | Apr-14      | May-14          | Jun-14          |                 |         |       |
| 20                       | 20         | 20          | 20          | 12              | 12              | 12              | 20      | 16    |
| 20                       | 20         | 20          | 20          | 12              | 12              | 12              | 20      | 16    |
| 20                       | 20         | 20          | 20          | 12              | 12              | 12              | 20      | 16    |
| Daily heating duration (hours) | All homes, whole period | Mar-14 | Apr-14 | May-14 | Jun-14 |                 |         |       |
| 7.6 (±0.6)               | 11.4 (±0.7) | 7.5 (±1)    | 6.7 (±0.9)  | 11.2 (±1.6)     | 7.4 (±2.1)     | 3.3 (±1.3)    | 2.9 (±1.5) | 4.5 (±1.5) |
| 7.1 (±0.5)               | 10.9 (±0.7) | 7.3 (±0.9)  | 6.7 (±0.8)  | 11 (±1.2)       | 7.6 (±1.3)     | 5 (±0.9)      | 4.2 (±1.3) | 6.3 (±1.1) |
| Lowest 10% external air temperature days | 7.6 (±2.2) | 11.2 (±2.9) | 7.9 (±3.8)  | 7.2 (±2.1)      | 11.5 (±2.9)    | 7.8 (±4)      | 6.9 (±3.2) | 6.8 (±3.9) | 8.7 (±4) |
| Highest 10% external air temperature days | 9.9 (±1.9) | 13.2 (±1.8) | 11.1 (±6.6) | 8.4 (±2.2)      | 13.1 (±4.1)    | 10 (±7.2)     | 0.2 (±0.6) | 0.2 (±0.5) | 1.2 (±1.1) |
| Lowest 10% gas use days* | 7.3 (±1.1) | 10.5 (±1.3) | 7.7 (±3.2)  | 6 (±1.4)        | 10.3 (±2.5)    | 5.8 (±4.4)    | 0.1 (±0.2) | 0.1 (±0.2) | 0.3 (±0.5) |
| Highest 10% gas use days*| 8.2 (±0.9) | 12.1 (±1.2) | 9.1 (±1.7)  | 7.8 (±1.2)      | 12.2 (±1.7)    | 8.8 (±2.5)    | 7.6 (±1.4) | 6.6 (±2.2) | 9.8 (±1.8) |
| 16 homes where secondary heating is not used (Feb-14) | 7.7 (±1.2) | 11.7 (±1.4) | 7.6 (±2.8)  | 6.8 (±1.6)      | 11.7 (±2.5)    | 7.6 (±4.4)    | 3.6 (±1.9) | 3.4 (±2.1) | 4.7 (±2.2) |
| 10 Households with children | 7.7 (±1.5) | 11.6 (±1.8) | 7.4 (±3.6)  | 6.7 (±1.8)      | 11.3 (±3.1)    | 7.3 (±5)      | 2.9 (±2.3) | 2.4 (±2.4) | 4 (±2.2) |
| 10 Households without children | 7.6 (±1.6) | 11.2 (±1.9) | 7.5 (±3.9)  | 6.7 (±2.4)      | 11.1 (±3.6)    | 7.5 (±6.5)    | 3.7 (±3)   | 3.4 (±3.8) | 4.8 (±3.1) |

* As measured in individual homes.
increase. In June estimated thermostat settings range between 21.4°C and 22.1°C. This trend is also seen in the highest and lowest 10% external air temperature days. The lowest and highest 10% gas use days are less clear, which reflects the fact that very few homes are heated on the days with will low gas use and consequently there is significant uncertainty in the results. Homes where secondary heating is used frequently have slightly higher estimated thermostat settings but this result should be treated with caution due to
the small sample size this it is based on. Calculations were made for homes with and without children as it was expected that homes with children would be heated to higher temperatures, however, little difference can be observed between the calculated thermostat settings.

5.3.2. Assessment of calculation methods over time

To assess how the methods perform on days with differing external climate conditions daily estimated thermostat setting was plotted against daily external air temperature (Fig. 10). Each point on the figure shows the mean daily thermostat setting calculated across the homes using Methods 6 & 7. On the coldest days the difference between the estimated thermostat settings is approximately 4 °C (ranging from 18 °C to 22 °C). As expected the peak temperatures are higher than the average temperatures. The temperatures measured in the living room are slightly higher than those measured across the whole dwelling and in the thermostat room, perhaps because this is where the occupants are likely to spend most of their time. At slightly higher external temperatures around 10 °C, the difference between the calculation methods becomes smaller. The highest mean thermostat setting is still approximately 22 °C but the lowest values are closer to 19 °C. Above external air temperatures of 15 °C all estimated thermostat settings appear to rise which suggests that they start to be influenced by external air conditions.

6. Discussion

6.1. Comparing indirect methods for estimating heating behaviours

As Smart Home and Smart Metering technologies become more common new data streams will become available. This study has gathered examples of Smart Home data from 20 homes and is consequently well placed to comment on the usefulness of this data for understanding heating behaviours. The complexity of heating systems means that developing indirect heating behaviour calculation methods, which do not directly measure heating behaviours, is challenging.

Room temperatures measurements are a common part of Smart Home technologies [59], but our findings show that room temperature methods predict heating durations of three to five hours per day longer than radiator methods. This difference is partly related to the effects of boiler cycling. As radiators cool the radiator methods record that the boiler is inactive however the radiator temperatures may still be high and heat is dissipated into the room increasing or maintaining the room temperature. The result is that for each heating period and during times when the thermostat temperature is maintained, the air temperature methods record the heating as active while the radiators methods do not. This difference between calculation methods suggests that during the coldest months the temperature methods may be more suitable for calculating the timer settings, i.e. the boiler on and off times selected by the occupant, while the radiator temperature and gas methods are more successful at identifying times when the boiler is active.

Radiator temperatures are unlikely to be part of a Smart Home system. Programmable TRVs include air temperature sensors which may record temperatures that resemble a combination of room air and radiator surface temperature but these may not be available to download. The roll out of Smart Meters will ensure that good quality gas data becomes more available. This will enable more accurate estimates of heating active times but, unless the non-space heating portion of the gas consumption is disaggregated it is unlikely to be accurate during transition months. A new method which uses both air temperature and gas consumption data could be developed to overcome the limitations of using single data streams described above.

6.2. Measurement and calculation uncertainty

All sensor measurements are subject to error and consequently care should be taken when interpreting their results. This is likely to be a bigger problem with Smart Home data streams, when sensor resolution may only be 0.5 °C [59]. However, the nature of the calculation methods for identifying times of active heating may counteract this limitation resulting from this measurement resolution as the methods are largely based on temperature change and not relative temperatures. The radiator method is particularly robust as a 3 °C swing is required before a change of state is recognised. The time interval of the measured data, however, does cause uncertainty. This work was based on data collected at half hour intervals and consequently, all of the daily heating durations reported here are subject to a measurement error ±1 h as it is not possible to know at what point in the half an hour interval
the heating turned on or off. The previous temperature monitoring studies used longer time intervals and therefore have greater uncertainty. In addition to this duration uncertainty, none of the methods applied here are able to reliably identify subtle changes to occupant settings such as timer override or changes to thermostat settings.

The estimated thermostat setting methods have also been shown to have a high level of uncertainty. Firstly they are based on an estimate of when the heating is active and second using a single heating active method a 4 °C difference between Methods 6 & 7 was seen. Some of this variation is related to the location of the temperature sensor that is used in the calculation. Most previous studies on heating behaviours are based on living room temperatures, however in this sample; only 10% of the homes had a room thermostat located in the living room. Thermostat settings calculated based on temperatures measured in the rooms where the thermostat is located are not comparable between homes because of differing room functions i.e. some thermostats were located in living rooms while others were found in hallways which tend to be heated to lower temperatures. While temperatures based on whole house averages or living rooms are more comparable they are perhaps more closely related to the occupants’ comfort or demand temperatures and not the settings actually used.

In addition uncertainty relating the temperature measurement the calculation of thermostat setting using sensor data is flawed in some cases as in some homes the thermostat setting is never reached. Furthermore, due to variation in the quality of heating controllers and the effect of radiant temperature recorded by the sensors the room temperature often increases until the end of the heating period [57]. Peak temperatures are particularly sensitive to sensor error or misplacement compared to average temperatures as a single spot temperature is more influenced by short spikes in temperature related heat gains or solar irradiation. This is a concern when there is already a high level of uncertainty in the result based on the number of assumptions required. While the logic behind using the daily peak temperature when heated to estimate thermostats has flaws as described above, the use of average temperature when heated was never designed to predict the thermostat setting.

Steady state modelling techniques often assume that the ‘thermostat setting’ is reached instantly when the heating system is turned on and then remains perfectly constant until the heating is turned off [30]. In this specific case the thermostat setting is equivalent to the average temperature when heated. In real homes, however, the thermostat setting is only reached after the room temperature rises slowly over time. The average temperature when heated is consequently influenced by a number of factors including the heating duration, dwelling heat loss characteristics and the thermostat setting (if reached). Assessment of thermostat setting is consequently a complex problem and although this work has advanced the field by assessing a number of calculation methods it is unlikely that accurate thermostat setting estimation is possible using secondary data.

New advanced thermostats directly log the settings which their users choose. This would provide more accurate measurements and remove the need for heating behaviours to be calculated indirectly from sensor data. However, such advanced thermostats are only present in a small proportion of homes at present and the ability to access any data is limited. There is also a growing number of datasets which include sensor data similar to the data used in this analysis which present an opportunity to assess heating behaviours in statistically significant samples, consequently the methods used in this work will need to be applied for some time to come.

6.3. Additional occupant behaviours

As discussed above, using indirect sensor data to estimate heating behaviours has serious limitations. There are, however a number of additional complicating factors relating to the additional occupant behaviours which impact on room temperature but are not heating behaviours. Curtain, window and door opening change the air flow between rooms and the internal and external space. Heat gains from cooking and electrical appliances can also influence temperatures measures. All of these factors impact room temperatures and consequently will reduce the accuracy of the temperature methods. The radiator and gas methods are not directly influenced by room temperatures, however, their accuracy can be reduced in homes where secondary heating is used. In these homes single rooms may be heated but the radiators will not be in use and therefore heating durations will be underestimated. These additional complicating factors highlight again the level of detail required to fully understand how homes are heated. This level of detail is difficult and costly to gather in large samples and is further evidence of the need to continue to undertake both large scale representative and smaller more detailed surveys.
6.4. Guidelines for researchers

The discussion above has highlighted a number of limitations to using indirect data to estimate heating behaviours, however, all of the indirect methods for calculating heating durations are valid but it is important that care is taken when using these methods. Consequently, to aid researchers in applying the methods described here on other datasets the following recommendations are proposed:

- Room temperatures (Methods 1, 2 & 3) should only be applied on days when the mean external air temperature is lower than 10 °C.
- If gas consumption (Method 5) data is to be used to accurately identify active heating, gas consumption used for non-space heating gas use should be disaggregated.
- If the calculations carried out are sensitive to unheated days (including the estimate of thermostat setting) only the radiator methods should be applied.
- All daily heating durations are subject to a potential error of twice the length of the monitoring interval. In this case the error for all daily heating durations is ±1 h.
- Estimated thermostat settings is extremely uncertain and a large variation is expected based upon the method chosen and the air temperature which it is applied to.
- When estimating room thermostat settings only days with a mean external air temperature lower than 14 °C should be used.
- The limitations and error relating to the measurements and the calculation methods must be considered when reporting results. This should include discussion of the complexity of both heating systems and the additional uncertainty related to occupant behaviour.
- In large studies where it is not possible to measure temperature in every room care should be taken to ensure that misleading results are not reported as the living room will not always be the location of the room thermostat.

7. Conclusions

Detailed monitoring was carried out in 20 homes during the winter and spring of 2014. Seven indirect heating behaviour calculation methods were used based on room temperature, radiator surface temperature and gas consumption measurements. The three heating behaviours of active heating times, heating durations and room thermostat temperatures were calculated and the differences between the indirect calculation methods assessed. The main conclusions from this work are:

1. A significant variation was found between all of the indirect heating behaviour calculation methods suggesting that a high level of uncertainty exists when using indirect measurements to calculate heating behaviours in the home. Future studies which aim to further understanding of heating behaviours must collect direct measurements of heating behaviours from smart heating controls so that the indirect methods can be fully assessed. This will ensure that they can be applied in homes with ‘non-smart’ conventional heating systems and controls.

2. The methods for identifying times of active heating estimated significantly different amounts of active heating across the 5 month period under study. The methods based on room temperatures identified 900–1600 h of heating over the monitoring period, compared to 400–450 h for the radiator temperature methods and 500 h for the gas method.

3. The room air temperature methods were successful at predicting active heating times during the coldest winter months but are poor predictors of active heating in warmer months. This is evidenced as they predict active heating when there is no gas use (Table 5). This is likely due to the tendency to misidentify heat gains as heating.

4. Overall the gas method works well, however it over predicts heating durations during warmer months when radiator temperatures do not rise because of non-space heating gas use. This is because the method misidentifies gas consumption for domestic hot water as heating.

5. Radiator methods appear to be the most reliable as they avoid the problems of the methods above. This is shown in their ability to successfully identify unheated days (Fig. 8). A maximum radiator surface temperature (Method 4a) is preferred because single radiator readings (Method 4b) are subject to potential errors if the radiator is switched off.

6. On the coldest days the mean estimated thermostat setting ranged between 18 °C and 22 °C with the peak temperature method (Method 6) being slightly higher than the average temperature method (Method 7). It was found that all thermostat methods were subject to considerable uncertainty.

Further detailed monitoring studies should measure more parameters that are important in understanding when heating occurs but also why occupants are heating at those times. Specifically additional measurements of the thermal comfort indicators should be measured and reported; wind speed, relative humidity and clothing. Additional detail is also required to assess the exact proportion of energy use that is associated with secondary heating and to better understand the heating behaviours relating to the use of secondary heating. To do this accurately detailed information about window and door opening is also required to ensure that heating flows in and out of the house and well as between rooms can be considered. In larger more representative studies where it is not feasible to monitor a complete set of energy and thermal comfort parameters care should be taken to measure the room temperature in both the living room and the room where the thermostat is located.

Acknowledgements

This work has been carried out as part of the REFIT project (‘Personalised Retrofit Decision Support Tools for UK Homes using Smart Home Technology’, £1.5m, Grant Reference EP/K0024571/1). REFIT is a consortium of three universities – Loughborough, Strathclyde and East Anglia – and ten industry stakeholders funded by the Engineering and Physical Sciences Research Council (EPSRC) under the Transforming Energy Demand in Buildings through Digital Innovation (BuildTEDDI) funding programme. For more information see: www.epsrc.ac.uk and www.refitsmarthomes.org.

References

[1] ONS (2011) UK Census data 2011. Office for National Statistics, London http://www.ons.gov.uk/ons/guide-method/census/2011/index.html.
[2] DECC, Energy Consumption in the UK, Department of Energy and Climate Change, London, UK, 2015.
[3] DECC, Climate Change Act 2008, Department of Energy and Climate Change, London, UK, 2008.
[4] S.K. Firth, K.J. Lomas, A.J. Wright, Targeting household energy-efficiency measures using sensitivity analysis, Build. Res. Inf. 38 (1) (2010) 25–41.
[5] S. Wei, R. Jones, P. de Wilde, Driving factors for occupant-controlled space heating in residential buildings, Energy Build. 70 (2014) 36–44.
[6] O.G. Santin, Behavioural patterns and user profiles related to energy consumption for heating, Energy Build. 43 (10) (2011) 2662–2672.
[7] K. Gram-Hansen, Residential heat comfort practices: understanding users, Build. Res. Inf. 38 (2) (2010) 175–186.
[8] K. Steemers, G.Y. Yun, Household energy consumption: a study of the role of occupants, Build. Res. Inf. 37 (5–6) (2009) 625–637.
[9] V. Cheng, K. Steemers, Modelling domestic energy consumption at district scale: a tool to support national and local energy policies, Environ. Model. Software 26 (10) (2011) 1186–1198.
