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Measuring the potential of zonal space heating controls to reduce energy use in UK homes: The case of un-furbished 1930s dwellings

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ABSTRACT

A matched pair of 1930s semi-detached houses, in original condition and un-refurbished in terms of energy efficiency, were employed to measure the energy savings that might result from the use of zonal space heating control (ZC). The houses were adjoined and had the same synthetic, yet realistic, occupancy schedule, the same new central heating system, and were exposed to the same weather conditions. In one house the space heating was controlled conventionally (CC) according to minimum requirements in UK Building Regulation Part L1B for existing dwellings, whereas in the other house ZC was used to heat the rooms only when they were 'occupied'. Over an 8-week winter test period, the house with ZC used 11.8% less gas despite 2.4 percentage points drop in average daily boiler efficiency. Although zonal control reduced the mean indoor air temperature of the whole house by 0.6 °C, it did not reduce the average air temperature in rooms during the hours of active 'occupancy'. Normalisation and extrapolation of the results shows that, compared to CC, ZC could reduce annual gas demand for space heating by 12% in most regions of the UK, and that ZC would be a more effective energy efficiency measure in homes in the cooler, more northerly regions of the UK.

1. Introduction

This paper presents, what is believed to be, the first controlled comparative study of zonal heating control (ZC) systems in UK houses. Such systems have the potential to reduce the fuel used for space heating, which accounts for 66% of all energy use in the UK residential sector [1]. Since energy demand in the residential sector is responsible for 25% of the UK's greenhouse gas emissions (GHGE), it would be difficult to meet the UK's target of 80% reduction in the total GHGE by 2050 compared to 1990 levels without reducing emissions from houses [2].

Central heating, which allows the households to simultaneously heat all the spaces of their home, is found in 90% of UK homes. Nearly one third of these homes have condensing combi gas boilers, which is the fastest growing type of boilers installed in the UK [2]. The control system for a central heating system with a combi boiler that complies with UK Building Regulations for existing dwellings [3] includes: a programmable room thermostat (PRT), usually located in the main living area or hallway, thermostatic radiator valves (TRV) fitted to each radiator except the radiator in the space where a PRT is located, and a by-pass valve usually located in the boiler (Fig. 1). However, 70% of the existing UK housing stock do not reach the minimum levels of controls specified in the current Building Regulations: 33% do not have room thermostats, which could cause excessive room temperatures; 40% have no TRVs, which means there is no individual control of temperatures in different rooms and therefore the whole house is often heated to the same temperatures [4,5]; and more dramatically, 4% of houses with a boiler have no controls at all [4].

To the best of the authors' knowledge, there is no published peer-reviewed information on the energy wastage due to poor controls in UK homes. Research in the US, has shown that 6.2% of total primary energy in the US is wasted for heating or cooling unoccupied living rooms during the night [6]. The same study also

Abbreviations: ASHRAE, American Society of Heating, Refrigerating and Air-Conditioning Engineers; CC, conventional control; DECC, Department of Energy and Climate Change; CIBSE, Chartered Institution of Building Services Engineers; GHGE, green house gas emissions; HDD, heating degree days; HT, heating trial; IRR, internal rate of return; LPHW, low pressure hot water; MRT, mean radiant temperature; NPV, net present value; PRT, programmable room thermostat; PTRV, programmable thermostatic radiator valve; TRV, thermostatic radiator valve; WGC, weekly gas consumption; ZC, zonal control.

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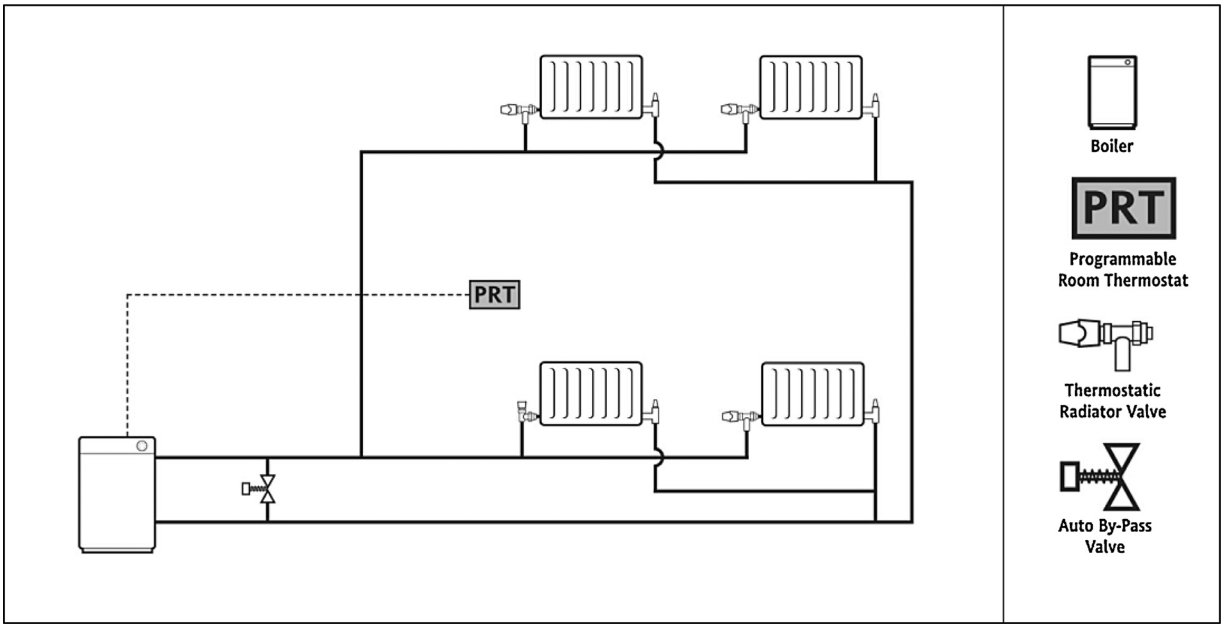

Fig. 1. Schematic of a standard gas-fired, low pressure hot water (LPHW), central heating system with a combi boiler [3].

estimated that 9.7% of total primary energy is wasted by heating or cooling the bedrooms during the 4 h of a day when occupants are likely to be in the living rooms [6]. Together these figures amounts to a total of 15.9% of wasted primary energy for heating or cooling unoccupied spaces of a typical US home [6] and suggests that it might be possible to reduce the energy demand for space heating in centrally heated houses by controlling the delivery of heat on a room-by-room basis.

Since 2010, two-zone heating control has been mandatory in the UK for every new home which is not open plan [7], though this is not obligatory in the case of existing dwellings. Going further, wireless technology and the availability of more powerful batteries, have led controls manufacturers to develop systems that enable room-by-room Zonal Control (ZC) of space heating, which means that rooms may be heated only at the times they are occupied and to the level needed; thus reducing the volume of the house that is being heated. Although market deployment is in its infancy, this is a rapidly developing area with many new systems emerging. The main components of such systems are the battery operated programmable thermostatic radiator valves (PTRV) which replace normal TRVs and have motorised valves to either enable or disable the hot water flow through the radiators according to a set-point temperature and time schedule. These can be set on the PTRVs themselves, via a central controller which communicates wirelessly with the PTRVs, or even remotely via a mobile phone or computer in some products.

The paper introduces the Loughborough Matched Pair 1930 test houses (LMP1930); an adjoining pair of semi-detached homes with synthetic occupancy. The homes enable all the influential factors including the weather, occupant behaviour and heating system characteristics to be kept the same for both houses while one is heated with ZC and the other with conventional control (CC). This allows small differences between the energy demands of the two homes to be isolated and the resulting temperatures to be measured. The experiments were conducted over a single winter period. Then, based on the experimental data, an empirical model is developed to predict the annual space heating energy savings that could result from installing ZC in houses in different regions of the UK. The cost benefit is investigated by employing a discounted cash flow analysis and projected future residential gas prices. The research starts to answer questions such as: how much energy could zonal heating controls save in UK houses? Will rooms with ZC be warm enough when occupied? Will the energy savings pay back the cost of installing the controls? and does the effectiveness of ZC depend on UK location?

2. Experimental facility

2.1. Test houses

LMP1930 test houses which are a pair of adjoining semi-detached homes were employed to measure the energy savings from ZC. The houses, which are typical family homes of the 1930s period, are located in the East Midland's town of Loughborough, UK. Semi-detached houses are the most common house type in England representing 26% of the housing stock with over 30% built between 1919 and 1944 [8]. However, semi-detached house layouts and construction methods remained largely unchanged from the 1930s through to as late as the 1960s [9].

The test houses had the same geometry, size and construction and had not been significantly modified since they were built (Table 1, Fig. 2). Therefore, both were single glazed, with un-insulated cavity external walls, and no floor or loft insulation. In contrast, many UK homes have been refurbished, such that in 2011, of the 3.6 million UK homes built between 1919 and 1944, only 4% had no loft insulation, only 6% were still fully single glazed, and only 28% had uninsulated cavity walls [10].

Internal dimensions of the test houses were measured at the beginning of this study and their plans were drawn (Fig. 3). Each house had a total floor area of 91.2 m^2 (including both floors) and a total volume of 240 m^3. Each house had three rooms located on the ground floor including living room, dining room and kitchen plus a hallway and four rooms on the first floor including three bedrooms and a bathroom plus a WC and a hallway (Fig. 3). Each house was equipped with an identical low pressure hot water (LPHW) central heating system consisting of a 30 kW condensing combi boiler (Worcester Greenstar 30 CDi combi), identical Eco-Compact radiators sized to suit each room, and a Horstmann wireless C-stat 17-B programmable room thermostat located in the hallway. The

Table 1
Summary of construction elements of the test houses, their areas and approximate *U* values.

Element	Description	Total area (m^2)	U-value (W/m^2 K)[a]
External walls	Brick cavity	81.6	1.6
Floor (except kitchen)	Suspended timber	40.2	0.8
Floor (kitchen)	Solid floor	5.4	0.7
Roof	Pitched roof covered with clay tiles	45.6[b]	2.3
Windows	Single glazing with wooden frames	20.7	4.8
Entrance doors	Wooden	3.4	3.0
Party walls	Brick Cavity with closed air vents	42.2	1.6
Internal partitions	Solid Brick covered with gypsum plaster	56.1	2.1

[a] Approximate U-values from UK Government's Standard Assessment Procedure for energy rating of the existing dwellings (RdSAP) [11].
[b] The horizontal, not pitched, area.

Fig. 2. Views of the two test houses: front, south-facing (left) and back, north-facing (right).

boilers were less than seven years old. The radiators were installed by an independent contractor and the C-stat, which replaced the standard thermostat, by the research team, both in 2014. The fronts of the houses faced south and the windows are unshaded except for those on the West facade of House 1 and the East facade of House 2; these windows were covered by 50 mm of Polyisocyanurate (PIR) insulation boards to minimise the effect of different morning and afternoon solar heat transfer. Moreover, original open fire places in both houses were blocked to avoid unnecessary air leakage.

2.2. Characterisation of the houses

Characterisation tests were carried out to evaluate and compare the thermal performance of the test houses. These tests consisted of a standard blower door test in accordance with ATTMA Technical Standard 1 [12] and a standard co-heating test as described by Wingfield et al. [13].

The blower door tests were carried out on the same day (3 July 2013) for both houses. During the tests, the openings of the passive ventilation, extractor fan in the kitchen and original open fire places were sealed and all drainage traps were filled by water, as required by the standard test protocol; during the heating trials though these openings were unblocked, as they would be in an occupied house. Thus the measured air leakage rate does not measure the in-use ventilation rate of the dwelling.

The co-heating tests were conducted simultaneously in the two test houses during the period of 23 November to 1 December 2013. Electrical fan heaters, located in each room, were used to maintain a nominal internal air temperature of 25 °C in each room for a period of 9 days, plus 2 days of pre-conditioning. The heat output of each fan heater was controlled using a thermostat located in the centre of each room, 1.5 m above the floor level. The thermostats were shaded from direct sunlight and the hot air from the fan heaters. Circulation fans were used in each room to mix the air and reduce stratification; the doors to all rooms were left open. The electrical energy supplied to each house was measured at the meter (see Section 2.4). The internal air temperature of every room was measured at 1 min. intervals using calibrated thermistors (see Section 2.4). Minutely outdoor air temperature and hourly global horizontal solar irradiance during the test period were sourced locally (see Section 2.4).

The "Siviour" linear regression method [14] was used to calculate the solar-corrected heat loss coefficient of each house by plotting $Q/\Delta T$ against $S/\Delta T$ for each day of the test where:

Q: average daily measured power consumption (W),
ΔT: average daily air temperature difference between indoor and outdoor (°C),
S: average daily global horizontal solar irradiance (W/m^2)

The resulting slope of the plot is the solar aperture R in m^2 and the Y intercept is the solar corrected total heat loss coefficient in W/K.

The results of the characterisation tests are presented in Table 2 and show that the two houses had very similar airtightness values and that the overall heat loss coefficients were within 6%. This is remarkably similar performance, especially given the uncertainty of co-heating tests, which may be greater than 10%[1] [14]. An estimate of the background air infiltration rate, for the houses in the blower door test state[2], can be achieved by dividing the air change rate at 50 Pa by 20 [15]; which gives 1.04 ach and 1.07 ach for Houses 1 and 2, respectively. The test houses were less airtight compared to the average for UK houses of a similar age. For example, the mean air leakage rate of 58 dwellings built between 1930 and 1939 reported in the Building Research Establishment's database,

[1] In National House Building Council's (NHBC's) review of co-heating test methodologies [14], solar corrected whole house heat loss coefficients found by 6 independent co-heating tests conducted by different project partners ranged from −17% to +11% of the calculated steady state heat loss based on as-built dimensions and specific fabric element *U*-values and infiltration rates [11].
[2] I.e. with the large purpose made openings blocked.

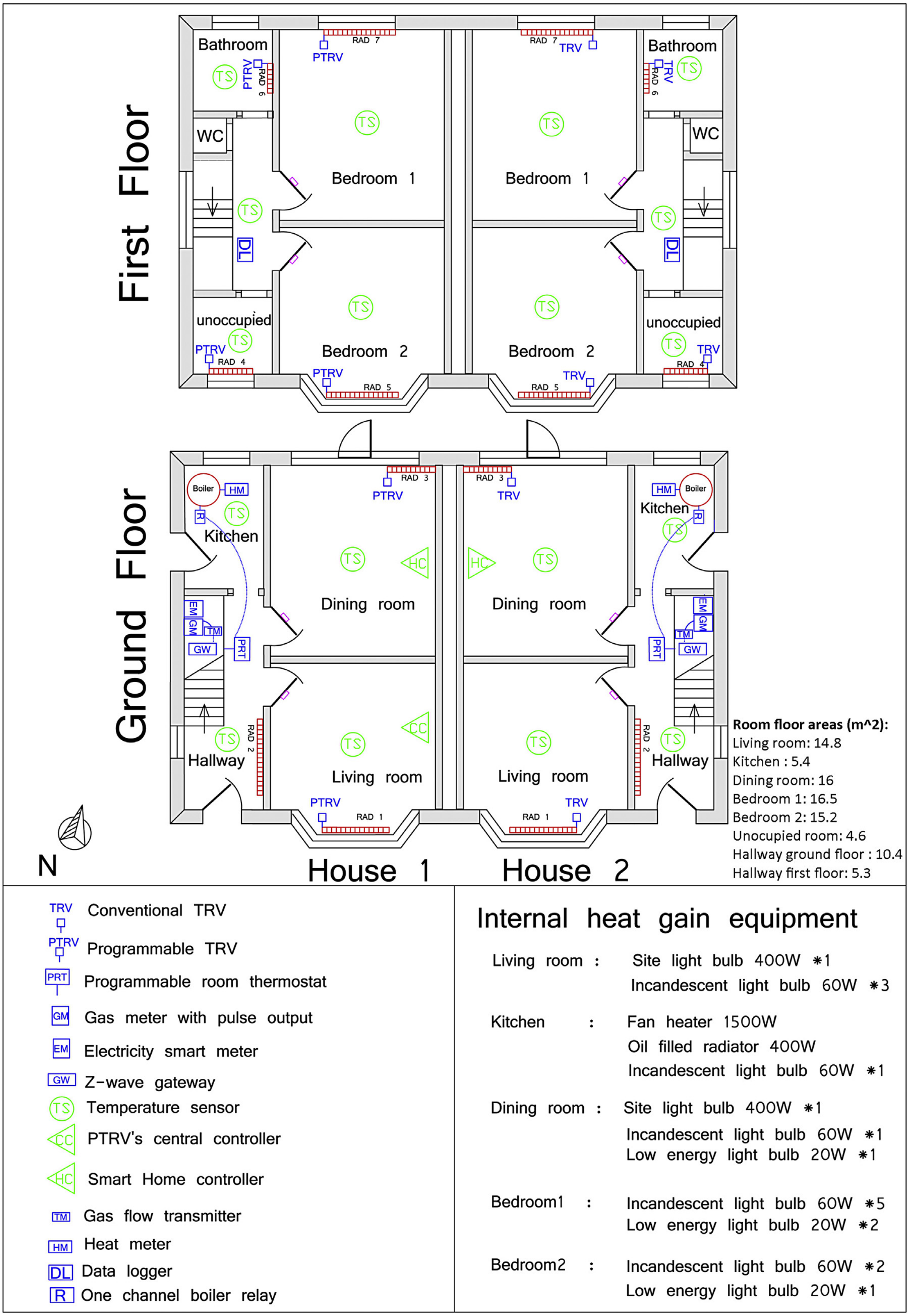

Fig. 3. Test house schematic plans with heating systems, synthetic occupancy and environmental monitoring equipment as configured during heating trial 1, for heating trial 2 the PTRVs with their central controller were swapped with TRVs in the opposite house.

Table 2
Summary of the house characterisation test results.

Performance measure	House 1	House 2	% difference
Total heat loss coefficient (W/K)	382	361	+5.6%
Air leakage ($m^3/h\,m^2$ surface Area @ 50 Pa)	20.76[a]	21.39[b]	−2.9%
Infiltration rate (ach)	1.04	1.07	−2.9%
Solar aperture (m^2)	9.9	11.8	−16%

[a] Equals to 21.5 ach @ 50 pa.
[b] Equals to 22.1 ach @ 50 pa.

which is one of the largest and most comprehensive sources of information on the airtightness of UK dwellings, was 15.9 ach measured at 50 Pa [16].

Notwithstanding the similarity in the homes, in order to minimise any effects of the small differences, the control strategies were switched between the two houses half way through the testing, as described in Section 3.

2.3. Synthetic occupancy

Synthetic occupancy was used to represent heat gains from people, domestic equipment and lighting, internal door opening/closing and window blind operation. The same occupancy profile was mimicked in both houses using a z-wave smart home automation controller: Vera 3 [17].

The chosen occupancy profile represented a family of two working adults, and two school-aged children. The time periods when heat gains occurred in each space were set according to Porritt [18] as derived from the Time Use Survey 2000 which recorded, in ten minutely slots, the daily activity of over 6000 households as a representative sample of the population of households and individuals in the UK [19] (Table 3). Although the occupancy patterns were the same for all the weekdays, for the weekends bedroom occupied periods were extended by 1.5 h thus shifting morning gains in other rooms 1.5 h later compared to the weekdays. During the day time (09:00 to 16:00 hrs on weekdays and 10:30 to 16:00 hrs on weekends) all the occupants were assumed to be out of the house. Evening occupancy patterns were the same for all days of the week including weekdays and weekends (Table 3).

Tables published by the American Society of heating Refrigeration and Air conditioning Engineers (ASHRAE) [20] were used to estimate the heat output rates from occupants, equipment and lighting. Each house was assumed to have a refrigerator in the kitchen which was rated at 60 W, a 150 W modern LCD TV in the living room and a computer or game console in the children's bedroom with 100 W heat output. Cooking gains were 1.6 kW for period of one hour during the evening, 160 W for the 30 min breakfast period and no cooker use at lunch time. The total amount of heat required at any time and in each room was delivered using a series of incandescent, halogen and low energy light bulbs, oil-filled radiators or fan heaters (Fig. 3). These were controlled from the home automation controller using z-wave enabled plugs to produce the repeating weekday and weekend total heat gain profiles (Fig. 4). The actual total heat gains produced in each room were identical in each house and within 10% difference of the total estimated values calculated from the ASHRAE tables (Table 3) [20]. This was due to the sizes of heat emitters that were available (Fig. 3). Variations in the electricity supply voltage also resulted in small differences in the heat gains achieved; however, this discrepancy was also the same for both test houses.

Each room was deemed to be 'occupied'[3] when there was at least one occupant present and assumed be 'unoccupied' at all other times (Table 4). The internal doors of the living room, dining room and bedrooms 1 and 2 (Fig. 3) were operated using actuators controlled by the home automation controller. These doors were scheduled to be closed when the room was 'occupied' and open otherwise (Table 4). The internal door of the kitchen was open at all times whilst the doors of the unoccupied spare bedroom, the bathroom and the two doors to the outside, were closed at all times.

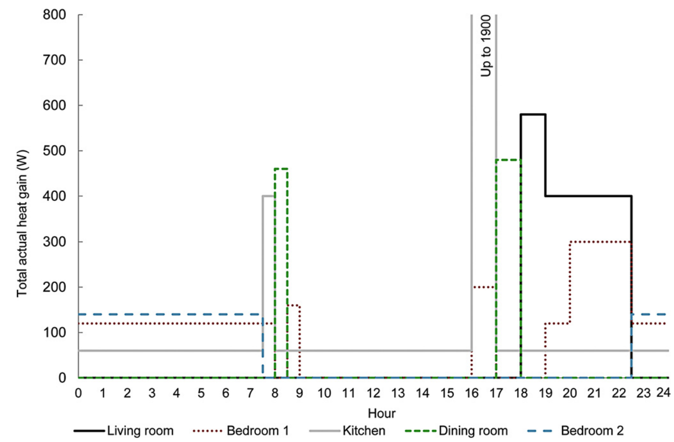

Fig. 4. Total actual heat gains in different rooms of a house during a weekday.

All windows were fitted with internal roller blinds. The blinds in the living room and bedrooms 1 and 2 were opened every weekday at 08:00 hrs and at 09:30 hrs on Saturday and Sunday. All blinds were closed at 16:00 hrs every day. The blinds in the dining room, bathroom and kitchen which all were facing north and the unoccupied spare bedroom were always remained closed during the heating trials[4].

Aspects of occupancy that were not mimicked include outside door openings, window opening, domestic hot water use, bathroom heat gains and occasional electrical usage such as dish washers, clothes washing and kettles. Windows and doors could not be simulated due to security concerns. The potential heat gains from hot water use and occupants in the bathroom were considered to be negligible as any heat produced was assumed to be transferred directly to the outside by extract fans or window openings or drainage. Most importantly however, as both houses were operated in the same manner, the measured difference in heating energy demands was not affected. The possible effects of different occupant behaviour on the heating energy impacts of ZC are discussed later (see discussion).

[3] Throughout, 'occupied' means that the room had synthetic occupants present.

[4] The assumption of blinds in the dining room, kitchen and bathroom being always closed might not reflect the behaviour of real occupants. The blinds will reduce radiative and convective heat losses but, as these rooms were all facing north, the closed blinds have negligible effect on solar gains. The net effect is the same in both houses.

Table 3
The timing and magnitude of internal heat gains presented in different rooms of both houses during each trial.

Room	Time of day weekday	Time of day weekend	Gain source: estimated rate (W)	Total estimated gains (W)	Total actual gains (W)
Kitchen	07:30–08:00	09:00–09:30	Morning cooking: 160 Adult cooking: 189 Fridge: 60	409	400
	16:00–17:00	16:00–17:00	Evening cooking: 1600 Adult cooking: 189 Lighting: 54 Fridge: 60	1903	1900
	All day	All day	Fridge: 60	60	60
Living room	18:00–19:00	18:00–19:00	TV: 150 Lighting: 30 Adult seated: 108*2[a] Children seated: 80*2[a]	556	580
	19:00–22:30	19:00–22:30	TV: 150 Lighting: 30 Adult seated: 108*2[a]	396	400
Dining room	08:00–08:30	09:30–10:00	Hot food: 18 *4[a] Adult seated: 108 *2[a] Children seated: 80 *2[a]	448	460
	17:00–18:00	17:00–18:00	Hot food: 18 *4[a] Lighting: 30 Adult seated: 108 *2[a] Children seated: 80 *2[a]	478	480
Bedroom 1	08:30–09:00	10:00–10:30	Children seated: 80 *2[a]	160	160
	16:00–17:00	16:00–17:00	Lighting: 30 Children seated: 80 *2[a]	190	200
	19:00–20:00	19:00–20:00	Lighting: 30 Child seated: 80	110	120
	20:00–22:30	20:00–22:30	Lighting: 30 Children seated: 80 *2[a] Computer: 100	290	300
	22:30–08:00	22:30–09:30	Children sleeping: 54*2[a]	108	120
Bedroom 2	22:30–07:30	22:30–09:00	Adult sleeping: 72 *2[a]	144	140

[a] Multiplied by the number of people.

2.4. Instrumentation

Identical instrumentation was used in each house. Indoor air temperature was measured throughout the testing period, in each room, at 1 min intervals, using U type thermistors. These were located in the volumetric centre of each room and shielded from any direct sunlight using aluminium sheets.

The surface temperature of each radiator was measured at 10 min intervals using I-button temperature loggers [21]. They were attached to the centre of each radiators surface using adhesive tape.

Table 4
Weekday and weekend 'occupied' hours with the number of hours each room was heated to the set-point or set-back temperatures and, for ZC, the PTRV set-point and set-back temperatures, and for CC, the TRV position.

Room	Weekday 'occupied' hours	Weekend 'occupied' hours	ZC				CC	
			Set-point (°C)	Set-back (°C)	Hours heated to the set-point (WD[a],WE[b])	Hours heated to the set-back (WD[a],WE[b])	Hours heated to the set-point (WD[a],WE[b])	TRV level (1–6)[c]
Living Room	18:00–22:30	18:00–22:30	21	16	5, 5	5.5, 12	10.5, 17	4
Dining Room	08:00–08:30 17:00–18:00	09:30–10:00 17:00–18:00	19	16	2.5, 2.5	8, 14.5	10.5, 17	3
Kitchen	07:30–08:00 16:00–17:00	09:00–09:30 16:00–17:00	–	–	–	–	–	–
Bedroom 1	19:00–22:30 22:30–08:00 08:30–09:00 16:00–17:00	19:00–22:30 22:30–09:30 10:00–10:30 16:00–17:00	19	16	8.5, 10	2, 7	10.5, 17	3
Bedroom 2	22:30–07:30	22:30–09:00	19	16	2, 3.5	8.5, 13.5	10.5, 17	4
Bathroom	07:30–08:00 08:30–09:00 19:00–20:00	09:00–09:30 10:00–10:30 19:00–20:00	21	16	3.5, 3.5	7, 13.5	10.5, 17	4
Un-occupied bedroom	–	–	12	–	10.5, 17	–	10.5, 17	1

[a] WD–weekdays.
[b] WE—weekends.
[c] The TRV settings provided the same set-point temperatures in each room as the set-points with ZC.

Table 5
Accuracy of the equipment and uncertainty in values used.

Equipment/values used	Parameter measured/calculated	Accuracy/uncertainty	Source
U type thermistors	Air temperature	±0.2 °C	Manufacturer stated accuracy
Data logger	Air temperature	0.1%	Manufacturer stated accuracy
I-buttons	Radiator surface temperature	±0.5 °C	Manufacturer stated accuracy
Gas meter	Volume of gas	±2%	[28]
Gas calorific value	Energy of gas	±1.5 MJ m^{-3}	[29]
Heat meter	Boiler heat output	±2%	Manufacturer stated accuracy

Boiler heat output was measured at 1 min intervals using a heat flow meter consisting of Supercal 531 energy integrator [22] programmed for 10Wh per pulse, Superstatic 440 flow meter [23] installed at the return water going to the boiler and Pt500 temperature sensors inserted into 1/2" BSP pockets both at supply and return water pipes to the boiler.

The volume of gas consumption for the boiler was measured every 10 min at the supply company gas meter of each house using an intrinsically safe pulse counter. The gas consumption (in kW h) was then calculated using the natural gas calorific value of 39.6 MJ m^{-3} [24] according to the location and test conditions.

Electricity consumption was recorded every 5 min using LED pulse loggers [25] installed on the supply company electricity meter of each house, and at the individual appliance level using Plogg energy meters [26]. This provides a measure of the heat delivered to the houses as electricity[5].

Minutely outdoor air temperature was measured using a thermistor located adjacent to the houses but far away enough to avoid any thermal effects from the external walls. The thermistor was shaded from direct solar radiation and the sky and was shielded to protect it from rain and moisture. Hourly global horizontal solar irradiance was sourced from Sutton Bonington weather station (8 km away from the test houses) using the MIDAS Land Surface Observation database at the British Atmospheric Data Centre (BADC) operated by the UK Meteorological Office [27].

Data logging at each house was carried out using a DT 85 Datataker data logger with in-built web server. The recorded data could be accessed online and downloaded at any time.

2.5. Data quality

All the monitoring and synthetic occupancy equipment had been tested both in the laboratory and in situ prior to the start of the heating trials. All the temperature sensors used were calibrated by the research team before and after the experiments using a temperature controlled water bath. The accuracy of the equipment and the uncertainty in values used for this study is indicated in Table 5.

To check that the homes were operating as required, even though they were not accessed during the heating trials, the web access function of the data loggers was used every day to check the quality of data and to detect any unanticipated problems. In addition, Internet Protocol (IP) cameras, which were located in the living room of each house, were used to check the operation of some synthetic occupancy equipment such as internal door or window blinds opening/closing and the lighting status. Checking the data on a daily basis was particularly useful on an occasion during the heating trial 2 when it was found that there was no heat output from the boiler in one of the test houses, and immediate inspection of the test house revealed a leak in the pipes; which was quickly fixed with minimum loss of testing time and data.

[5] All supplied electricity emerges as heat in the house.

3. The control strategies

In one house the space heating was controlled conventionally according to minimum requirements in Building Regulation Part L1B for existing dwellings (conventional control or CC) (Fig. 1). In the other house, ZC was used to heat only those rooms that were occupied, at the time they were 'occupied'. In heating trial 1 (HT1) ZC was applied to House 1 and CC to House 2 then, for HT2, the heating control strategies were swapped with CC in House 1and ZC in House 2. This was done to negate any small differences between the thermal performances of the building fabric of the two test houses (see Section 2.2). HT1 was conducted continuously from 16 February to 15 March 2014. HT2 started on 18 March 2014, was stopped for 1 week due to equipment failure (9 to 15 April) and continued afterwards until 21 April 2014. Thus each heating trial consisted of 4 weeks of reliable data including 20 weekdays and 8 weekend days.

The CC system consisted of the Horstmann wireless programmable room thermostat (PRT) in the hallway and Drayton RT212 TRVs on all radiators (except the one in the hallway) (Fig. 3). This allows the heating system to be operated on a daily schedule using the PRT. The PRT controlled the delivery of hot water to all the radiators simultaneously, although the individual, brand new, TRVs provide some room-by-room temperature control.

During the heating trials, the PRT switched on the heating for 10.5 h per day for weekdays (06:00–09:00 and 15:00–22:30) and 17 h per day during the weekends (06:00–23:00) (i.e. the 'Heating on' periods) and the boiler was switched off during the rest of the day (i.e. the 'Heating off' periods)[6]. There was no set-back temperature during the heating off period (Table 4). This is similar to the heating durations specified in the UK standard calculation method [11] but with each heating period starting one hour earlier. This was because the poorly-insulated house needed a longer time to achieve suitable temperatures for the assumed periods of occupant activity.

Pilot heating trials were undertaken to find, by trial and error, suitable TRV positions for each radiator in order to achieve the comfort temperature specified by CIBSE Guide A [30] for winter comfort: i.e. 21 °C in the living room and bathroom and 19 °C in the bedrooms. In the unoccupied spare room a setting that yielded just 12 °C was used to avoid frost and condensation (Table 4). The TRV settings were left unchanged when they were transferred to the radiators in house 1 for HT2.

For ZC, the whole system 'heating on' and 'heating off' periods were set by the PRT, and were the same as for the CC. The main difference between ZC and CC was that programmable thermostatic radiator valves (PTRV) (Honeywell HR80UK wireless) [31] replaced the normal TRVs in 6 of the rooms (Fig. 3). Room temperature set-points were the same as for CC but set for the 'occupied' hours only (Table 4). However, the PTRVs' central controller was programmed to adjust the set-point temperature of the PTRVs 30 min before each 'occupied' period in order to allow the room to reach

[6] Throughout, 'Heating on' and 'Heating off' periods means the times given here.

the set-point temperature. The set-point temperatures were held whilst the room was 'occupied', but allowed to fall to the set-back temperatures when the heating system was on but the room unoccupied. The set-back temperature was 16 °C in all rooms except the unoccupied spare room for which 12 °C was used (as for CC). When the heating system was off there was no set-back temperature.

Compared to CC, in which all the rooms were heated to their set-point temperatures for 10.5 h during weekdays and 17 h during weekends (i.e. 'Heating on' hours), ZC established shorter periods of time when each room was heated to its set-point temperature (see Table 4).

4. Experimental results

4.1. Comparison of indoor temperatures

The air temperature and radiator surface temperatures varied throughout a typical weekday and weekend according to the heating strategy set on the PRT, but there were distinct room-by-room temperature differences depending on whether CC or ZC was used (e.g. Fig. 5).

In the morning, the radiators started to warm up when the heating came on and with CC continued to emit heat until the set-point temperature was reached. With ZC however, if the room was not 'occupied', the PTRV stopped the flow of water to the radiator when the set-back temperature was reached (see Fig. 5, dining room and living room, morning heating period). If the room remained unoccupied, ZC only provided heat when the air temperature fell below the set-back temperature whereas, with CC, heat was provided to maintain the higher, set-point temperature (Fig. 5, living room, morning on period, bedroom 2 evening heating period). If a room with ZC became occupied during a 'heating on' period, the PTRV would enable flow to the radiator to bring the room temperature up to the set-point (Fig. 5, dining room, living room and bedroom evening heating on periods). It is the difference in the energy needed to achieve the set-point temperature compared to the set-back temperature when the heating is on but rooms are unoccupied, that leads to potentially lower heating energy consumption. The lower the set-back temperature and the shorter the occupied time relative to the heating on time, the more energy ZC might, in principle, save.

The houses exhibited other characteristics common to UK centrally heated homes, especially poorly insulated homes. For example, even though bedroom 2 was 'occupied' from 06:00 hrs to 07:30 hrs and the heating was on, the room failed to reach the set-point temperature with either ZC or CC. In fact, the set-point wasn't reached even after 3 h of heating using CC: bedroom 2 has a particularly large single-glazed bay window. In the middle of the day, when the house was unheated, the temperatures in the north-facing rooms fell: to below the set-back temperature in the case of bedroom 1. In contrast, the solar gain through the large, south-facing window of bedroom 2, and the similarly sized window in the living room, caused the temperatures in the middle of the day to exceed the heating set-point; especially in the house with CC (Fig. 5). In the evening heating period, with both CC and ZC, the living room -, and to a lesser extent the dining room temperatures exceeded the set-point during the occupied hours. This is probably due to the internal heat gains.

Table 6 shows the average air temperature in each room for the 8 weeks trial periods[7]. These are broken down into five different averaging periods: the whole of each day; when the PRT had switched the 'Heating on'; when the heating was on and the space occupied, 'Heating on and occupied'; when the heating was on but the space was unoccupied, 'Heating on and unoccupied'; and, finally, the average during the 'Heating off' hours. The table also gives the floor area-weighted[8] average temperature for the whole house during each of these five periods.

Considering the whole day, the average air temperature of all the rooms and the whole house was lower with ZC than with CC. The temperatures were also lower with ZC during periods when the heating system was on and when the heating system was off. This was because ZC kept space temperatures low when rooms were unoccupied, but provided similar air temperatures to CC (not less than the set-point temperature) when the rooms were actually occupied. During the 'occupied' hours when the heating was on, for both control strategies, the average indoor air temperatures measured in the living room and dining room were higher than their set-point temperature, which is thought to be due to the effect of internal heat gains and closing the doors when the rooms were occupied.

The average air temperature in bedroom 2 was lower than its set-point temperature during the 'occupied' hours especially in the house with ZC. This was because this bedroom was 'occupied' mostly during the night when the occupants were assumed to be sleeping and the heating was switched off (it is usual to sleep in an unheated bedroom in the UK [32]). Therefore, the daily period when the heating was on and the room was 'occupied' and thus heated was too short for the room to achieve its set-point temperature (Table 4).

On a similar basis, the average air temperature in bedroom 1 during the occupied hours was higher than bedroom 2 and close to the set-point temperature because it was 'occupied' for longer each day, when the heating was on, for purposes other than sleeping.

The average air temperatures during the sleeping periods are worth noting. In the house with ZC they were 15.5 °C and 14.3 °C, in bedrooms 1 and 2, respectively, which was lower than the averages of 16.2 °C and 14.6 °C found for CC. Bedroom air temperatures in both homes are thus lower than the CIBSE recommendation for bedrooms of 17 °C. However, Humphreys [33] reports good sleep quality even for bedroom temperatures as low as 12 °C while Collins [34] and Hartley [35] indicate the World Health Organization's bedroom temperature limit of 16 °C to reduce the risk of decreasing resistance to respiratory infections which can occur at lower temperatures [36].

Bathroom average air temperatures were lower than the designed set-point temperature with both ZC and CC during 'occupied' hours. This could be due to an undersized radiator. Also, there were no internal heat gains as it was assumed that in real houses any heat gain produced in this room would be quickly transferred to outdoor via extract fans or window opening (see Section 2.3).

The mean temperatures in the unheated rooms (i.e. unoccupied room and kitchen) were found to be lower for ZC during all the periods of the day. Again this was assumed to be due to higher rates of heat loss and lower rates of heat gain to and from the adjacent rooms in which were cooler in ZC compared to CC. The mean temperature of the kitchen was much higher than all other rooms during the 'occupied' hours (23 °C and 23.6 °C for ZC and CC, respectively). This was clearly due to the considerable heat gains representing cooking activities.

The daily average air temperatures in the circulation areas on the ground floor and first floor were lower in the house with ZC compared to the house with CC. This could again be explained by the lower temperatures in adjacent rooms acting as a heat sink.

[7] This is thus the average of 4 weeks with ZC in House 1 and 4 weeks in House 2, and likewise for CC.

[8] Calculated as: $(T_1{}^*A_1+T_2{}^*A_2+\cdots+T_n{}^*A_n)/(A_1+A_2\cdots+A_n)$ where: T_1 to T_n are the average air temperature of different rooms during each of the 5 periods and A_1 to A_n are the floor area of those rooms

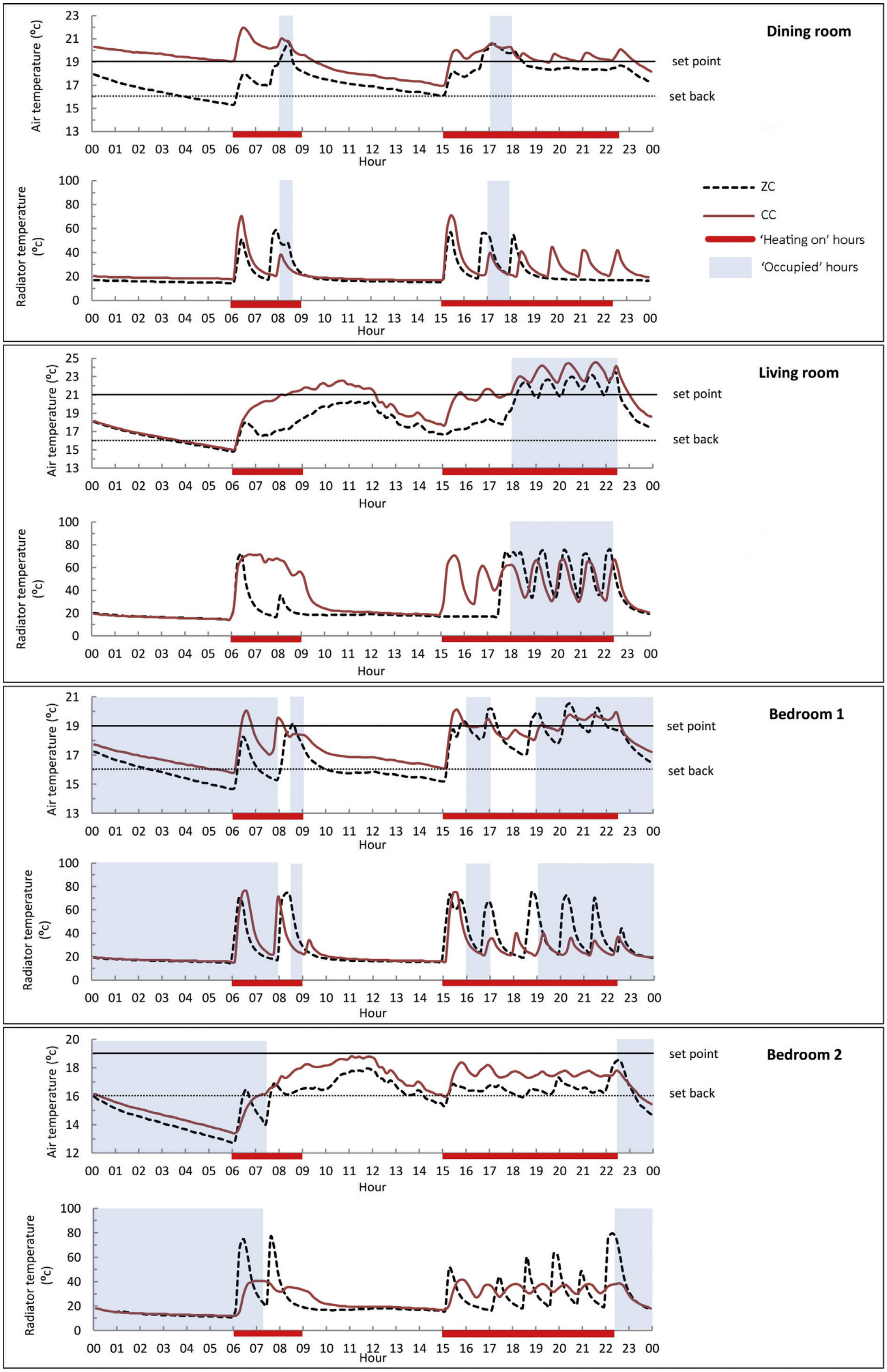

Fig. 5. Air and radiator surface temperature variations in different rooms: heating trial 1, 21st Feb 2014, ZC in House 1, CC in House 2.

It is important to quote the energy savings of ZC when the same level of comfort as CC is being provided. (In this work, it is assumed that indoor air temperature alone is a good proxy for thermal comfort.) However, in this experimental work, it was not possible (or indeed intended) to provide identical temperatures at the same time in the two homes using the different control strategies. The consequence, as can be seen from Table 6, is that the whole house average air temperature during 'occupied' hours was slightly lower

Table 6
Average indoor air temperatures in each room during five different periods, and the spatially averaged whole house temperature.

Room	Whole day		'Heating on'		'Heating on' 'occupied'		'Heating on' 'unoccupied'		'Heating off'	
	ZC (°C)	CC (°C)	ZC (°C)	CC (°C)	ZC (°C)	CC (°C)	ZC (°C)	CC (°C)	ZC (°C)	CC (°C)
Living Room	19.2	20.0	20.3	21.5	22.3	22.5	18.7	20.5	18.0	18.4
Dining Room	18.2	18.7	19.0	19.5	20.4	20.1	18.8	19.4	17.4	17.7
Bedroom 1	18.0	18.3	18.9	19.2	18.9	19.2	18.7	19.4	17.1	17.3
Bedroom 2	17.2	18.2	17.6	19.1	16.3	18.1	17.9	19.3	16.5	17.1
Bathroom	16.5	17.7	17.3	18.9	19.7	19.1	17.2	18.9	15.5	16.4
Unoccupied room	14.8	15.3	14.9	15.5	–	–	14.9	15.5	14.6	15.0
Circulation areas[a]	19.1	19.5	20.3	20.8	–	–	20.3	20.8	17.8	18.1
Kitchen	19.6	20.0	20.7	21.2	23.0	23.6	20.4	20.8	18.4	18.6
Whole house[b]	18.1	18.7	18.9	19.7	19.7	20.1	18.6	19.6	17.1	17.5

The averages are across four weeks with the control system in one house and four weeks in the other house.
[a] Average air temperature in hallways on the ground and first floors.
[b] Floor area weighted average air temperature.

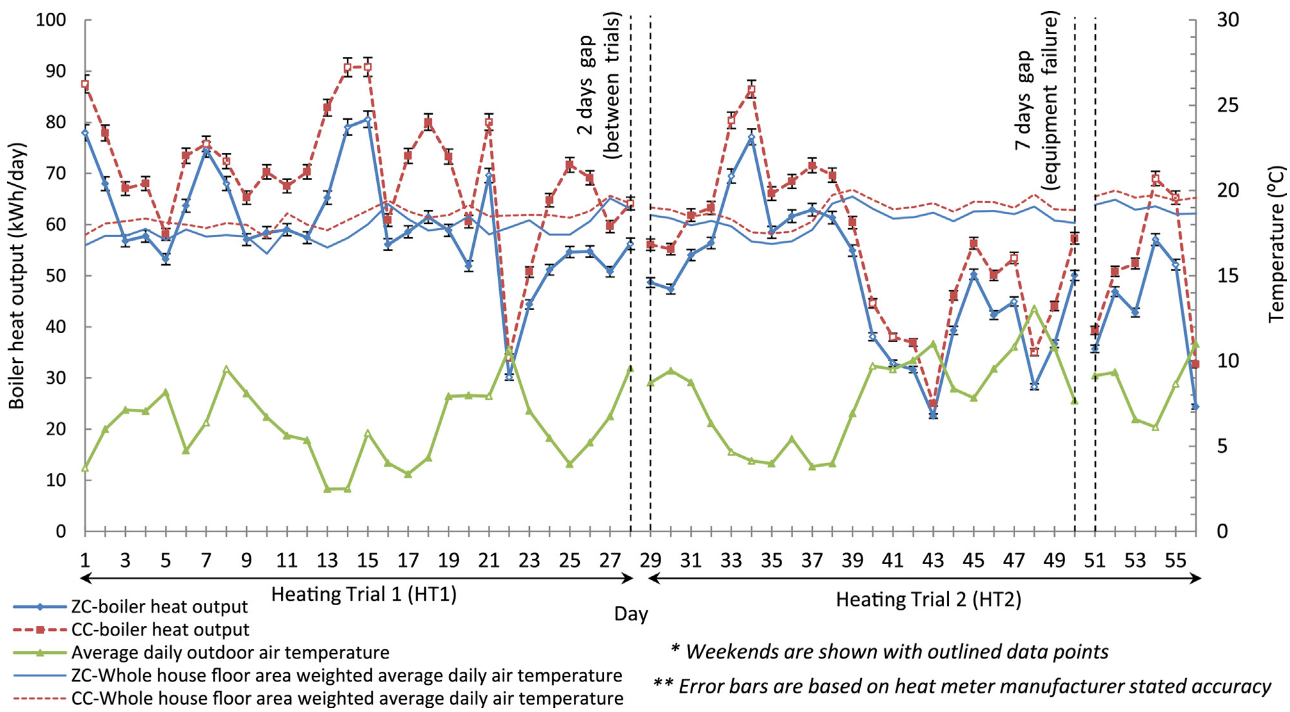

Fig. 6. Measured daily heat output from the boilers during the heating trials 1 and 2 and their error bars (based on manufacturer stated accuracy) together with the average daily outdoor air temperature and whole house floor area weighted average daily air temperature for the houses with CC and ZC.

with ZC (19.7 °C), than it was with CC (20.1 °C). However, the main reason for the whole house average air temperature during the "occupied" hours being slightly lower in ZC compared to CC was that ZC provided lower air temperatures in bedroom 2 which was mainly occupied for the purpose of sleeping as it was discussed earlier.

Considering the hours of 'active occupancy' (i.e. when the occupants are assumed to be present and awake) for the entire 8 weeks of the trials the average air temperatures of the whole house was 21.0 °C for ZC and 20.8 °C for CC. Therefore, on average, for this experiment ZC provided a slightly higher air temperature compared to CC during the time period of most interest (i.e. 'active occupancy'). Therefore, it was assumed that both control strategies provided the same level of thermal comfort to the occupants.

4.2. Heating demand, boiler efficiencies and fuel use

During the heating trials the daily average outdoor air temperature ranged from a minimum of 2.5 °C (Day 14) to maximum of 13.1 °C (Day 48) with an average of 7.1 °C (Fig. 6). As expected, whole house heating demand, as measured by the boiler heat output, was greater on colder days than on warmer days. During the weekends, the heat output was generally higher than for weekdays because the heating was switched on for longer (Fig. 6).

The daily heat output with ZC varied from 22.6 to 80.6 kW h/day with an average of 53.6 kW h/day, while with CC it varied from 25.0 to 90.8 kW h/day with an average of 62.4 kW h/day. On every day of the trials the daily boiler heat output in the house with ZC was lower than the boiler output in the house with CC (Fig. 6). Overall, daily heat output with ZC was between 2.6% (Day 7) and 22.1% (Day 25) lower than with CC, giving a daily average of 14.1% lower heat output.

The efficiency of boilers when operating with ZC was lower than the efficiency of the boilers when operating with CC (Fig. 7)[9].

[9] Uncertainty in daily boiler efficiencies are calculated as the quadratic sum of the uncertainties in calorific value of gas, gas meter and heat meter (Table 5).

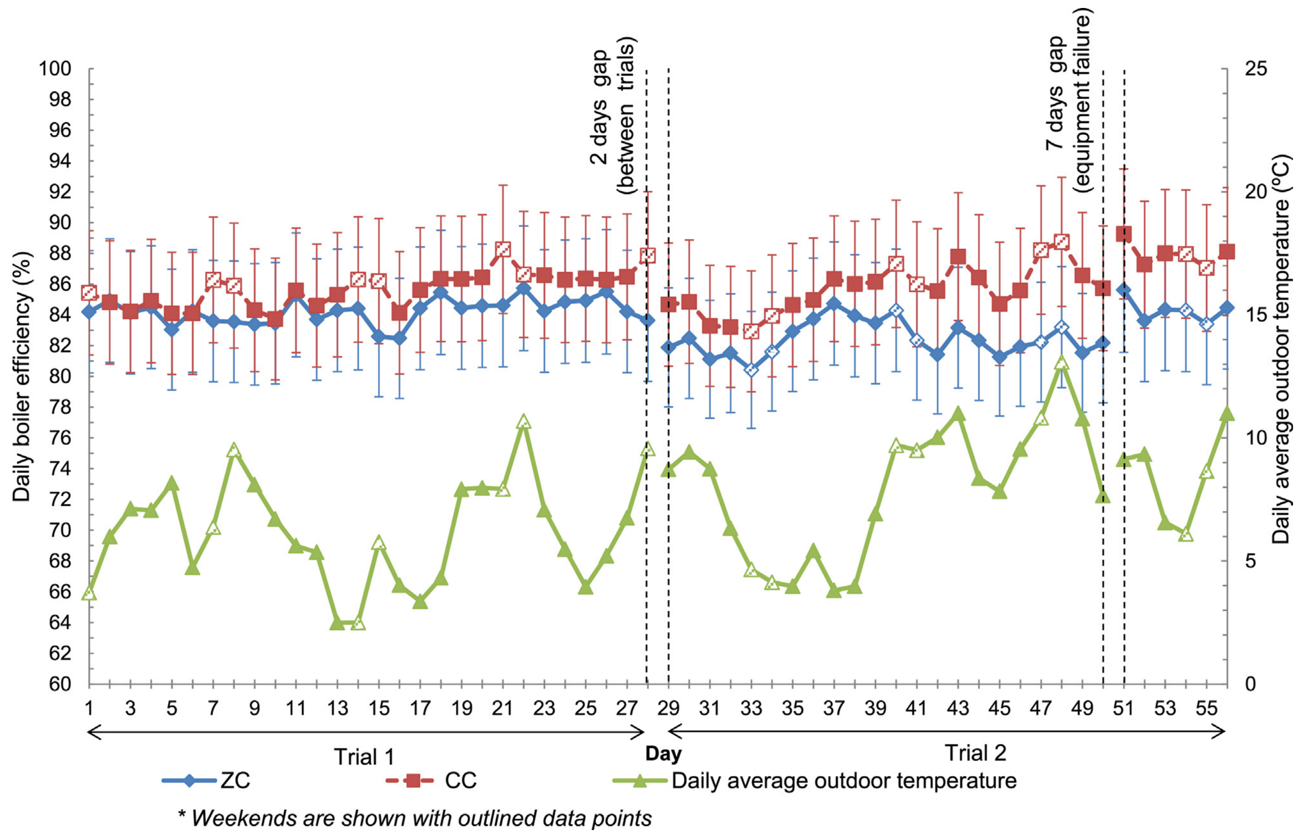

Fig. 7. Daily efficiency of the boilers with zonal control (ZC) and conventional control (CC) in each heating trial with their error bars together with the daily average outdoor temperature.

Table 7
Summary of daily average boiler efficiencies in each heating trial and overall efficiency.

	Heating Trial 1, boiler efficiency (%) Daily average (minimum, maximum)	Heating trial 2, boiler efficiency (%) Daily average (minimum, maximum)	Overall average boiler efficiency (%) Daily average (minimum, maximum)
Zonal control (ZC)	84.2% (82.5%, 85.7%)	82.8% (80.4%, 85.6%)	83.5% (80.4%, 85.7%)
Conventional control (CC)	85.7% (83.7%, 88.3%)	86.1% (82.9%, 89.3%)	85.9% (83.7%, 89.3%)
Difference	1.5pp[a]	3.3pp[a]	2.4pp[a]

[a] Percentage points.

However, the difference was quite small, being on average 1.5 percentage points (pp) less efficient during the first trial (HT1) and 3.3pp less in the second trial (HT2). The larger difference during HT2 is perhaps due to the warmer weather which meant the boiler outputs were less and so they were operating further away from the peak efficiencies for longer[10]. There may also be some small differences between the boilers installed in the two houses as they were less than seven years old.

Averaged over both trials, the efficiency of boilers associated with ZC were 2.4pp less efficient than boilers controlled conventionally (CC) (Table 7). This difference is statistically significant ($p < 0.01$) and is likely to be because boilers with ZC, experienced lower heating loads, and therefore operated further away from the peak load capacity—at which they are most efficient.

The total gas consumption across both heating trials was 11.8% less with ZC than with CC. This resulted from the combination of a reduced heat demand of 14.1% but a reduction in boiler efficiency of 2.4pp. Average daily gas consumption was significantly less ($p < 0.05$) with ZC (64.2 kW h) rather than CC (72.8 kW h). During the 40 weekdays of monitoring, average daily gas consumption was significantly less ($p < 0.01$) in the house operating with ZC (61.8 kW h) rather than the house operating with CC (71 kW h); a difference in gas consumption of 13%. During the 16 weekend days the house with ZC used on average 70.3 kW h/day while the house operating with CC used 77.3 kW h/day; a difference of 9.1%. However, this was not found to be statistically significant; due to relatively small number of weekend days ($n = 16$) for testing any statistical significance. Compared to weekdays, at the weekends rooms are occupied for a greater proportion of the time that the heating is on (Table 4) and the programmable thermostat (located in the hallway) tends to reach the set-point more often with CC than with ZC and so the heating system is cycled off for slightly longer with CC. These results suggest that houses that are more intermittently occupied and which have rooms that are used infrequently might benefit more from ZC than homes that are occupied extensively and for longer (see discussion).

5. Annual heating fuel and cost savings in different UK locations

To extrapolate the measured gas consumptions with CC and ZC to annual values, and to make an initial estimate of the effect of the

[10] At part load, small differences in power output lead to larger differences in efficiency than at, or near, peak load.

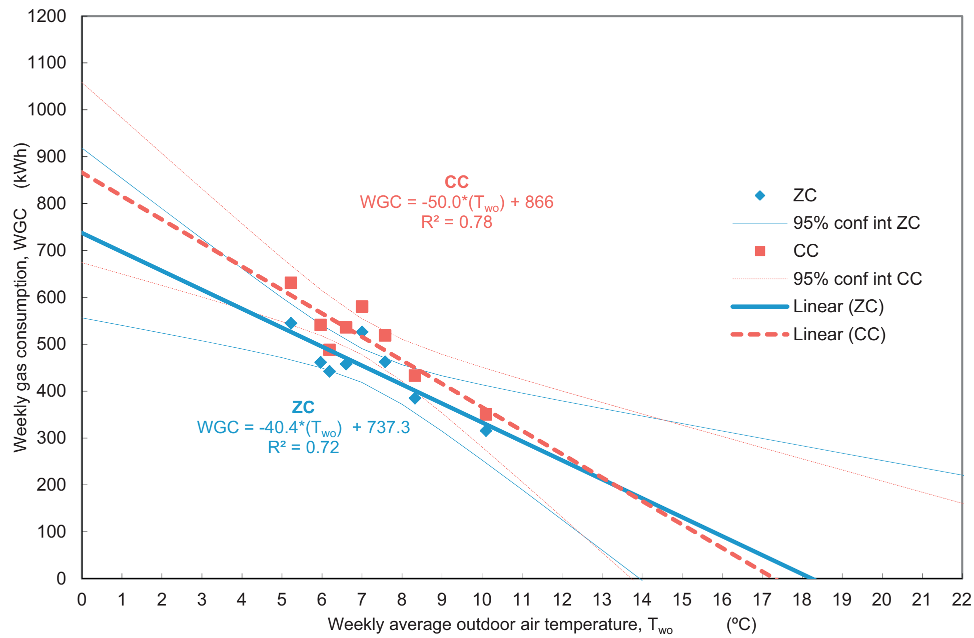

Fig. 8. Weekly gas consumption of the houses with ZC and CC against weekly average outdoor air temperature for 8 weeks of monitoring, best fit lines and 95% confidence intervals.

weather in different parts of the UK, the results were normalised and then extrapolated using a heating degree days (HDD) method. The method was selected as it has substantial benefits over other simplified methods that use mean outdoor temperatures to calculate energy demand such as BSEN ISO 13790 [37] since the "*HDD method accounts for fluctuations in outdoor temperature and can capture extreme conditions in a way that mean temperature methods cannot*" [38].

First, the base temperature (T_{base}) to be used for calculating the HDD was determined using the experimental results and then the relationship between the weekly HDD and the measured gas consumption was determined. This linear relationship was then used to estimate the weekly, and so annual, gas consumption in UK regions with different HDD.

5.1. Relationship between measured gas use and weather conditions

The measured weekly gas consumption (WGC) during the trials was strongly correlated with the weekly average outdoor air temperature (T_{wo}) for both ZC and CC (see Fig. 8, $R_{ZC}{}^2 = 0.72$ and $R_{CC}{}^2 = 0.78$). The linear relationship for the two control strategies was similar, but subtlety and importantly different. The regression lines indicate that for any average weekly ambient temperature below 13.4 °C, ZC will use less gas than CC. During the heating season, say September to April, the weekly average ambient is virtually always below 13.4 °C in all regions of the UK. It is also evident that the energy saved by ZC increases as the weekly average ambient temperature falls.

The base temperatures, i.e. the external temperature at which no heat is needed, is the intercept of line of best fit with the *x*-axis; this was 18.2 °C for ZC and 17.3 °C for CC (Fig. 8). However, the difference in intercepts is perhaps due to the limited range of weekly ambient temperatures to which the two systems were exposed, and thus poor definition of the *x*-axis intercepts. This is reflected in Fig. 8 by the wide 95% confidence intervals for both systems at the *x*-axis intercept. Given this, the same base temperature of 17.8 °C, which is the mean value of 17.3 °C and 18.2 °C, was selected as the base temperature for houses with both ZC and CC. However, the sensitivity of energy consumption predictions to the HDD base temperature

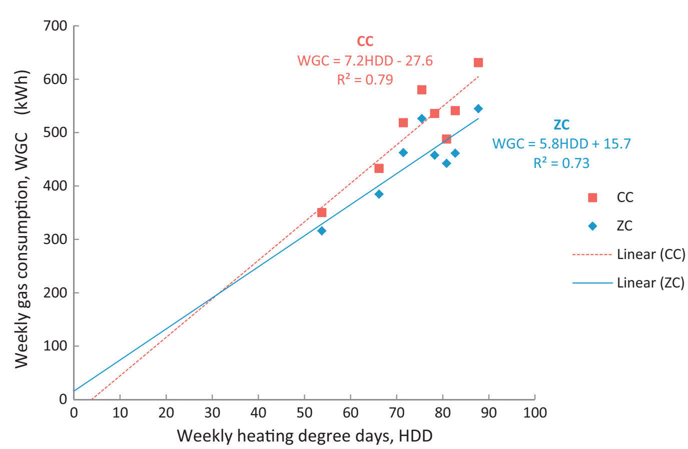

Fig. 9. Measured weekly gas consumption plotted against calculated weekly HDD for the houses with ZC and CC.

was investigated using a lower base temperature of 15.5 °C and a higher base of 20 °C and presented later in Table 8.

The base temperatures for CC and ZC were used to calculate the HDD during the heating trials (Eq. (1)).

$$\text{weekly HDD} = \sum_{\text{day 1}}^{\text{day 7}} \frac{(T_{\text{base}} - T_{\text{out}})_{\text{minutely}_{((T_{\text{base}} - T_{\text{out}})>0)}}}{60 \times 24} \quad (1)$$

The subscript shows that only positive differences are summed and if $(T_{base} - T_{out})_{minutely}$ is negative, then it is set to 0 for that minute in Eq. (1).

Weekly HDD were used in preference to daily HDD because different heating patterns were used for weekdays and weekends. The weekly gas consumption was then plotted against the weekly HDD for each control configuration. Least squares regression analysis was used to determine the equation of the performance line.

There was a strong correlation between the eight measured weekly gas consumption measurements and the weekly HDD for both ZC and CC (Fig. 9. $R_{ZC}{}^2 = 0.73$ and $R_{CC}{}^2 = 0.79$). If the regression was forced through the origin, the correlation remained

Table 8
Estimated gas use for heating the test house, with the same occupancy, in seven different regions of the UK, using either ZC or CC and, the NPV, IRR or financial savings, for both a basic and a luxury ZC systems.

Region (Weather station)	Annual heating energy use CC[a] (kW h)	Annual heating energy use ZC[a] (kW h)	Reduction in heating energy use (%)	NPV after 15 years: Luxury system[b] (£)	IRR Luxury system[c] (%)	NPV after 15 years: Basic system[b] (£)
London	15685	13839	11.8%	−£109	3.4%	£971
(Gatwick)	*14884, 15950*	*13217, 14053*	*11.2%, 11.9%*	*−£214, −£79*	*1.8%, 3.9%*	*£866, £1001*
East of England	15696	13848	11.8%	−£108	3.4%	£972
(Hemsby)	*14875,15963*	*13210, 14064*	*11.2%, 11.9%*	*−£216, −£77*	*1.8%, 3.9%*	*£864, £1003*
Northwest	15805	13936	11.8%	−£95	3.6%	£985
(Aughton)	*14973, 16073*	*13286, 14152*	*11.3%,11.9%*	*−£203, −£65*	*2.0%, 4.1%*	*£877, £1015*
West Midlands	16354	14379	12.0%	−£33	4.5%	£1,047
(Birmingham)	*15460, 16623*	*13667, 14596*	*11.6%, 12.2%*	*−£140, −£2*	*2.9%, 5.0%*	*£940, £1078*
Ireland	16374	14395	12.1%	−£30	4.6%	£1,050
(Belfast)	*15471, 16642*	*13675, 14611*	*11.6%, 12.2%*	*−£139, £0*	*3.0%, 5.0%*	*£941, £1080*
Yorkshire	16507	14503	12.1%	−£15	4.8%	£1065
(Finningley)	*15604, 16774*	*13780, 14718*	*11.7%, 12.2%*	*−£121, £15*	*3.2%, 5.2%*	*£959, £1095*
Scotland	17346	15180	12.5%	£80	6.1%	£1,160
(Aberdeen)	*16334,17616*	*14349,15397*	*12.1%,12.6%*	*−£27, £111*	*4.6%, 6.6%*	*£1053, £1191*

Calculated based on HDD base temperature of 17.8 °C in large regular fonts; Calculated based on 15.5 °C and 20.0 °C in *small italic font*.
[a] For a typical weather year with heating months being October to April.
[b] Based on Department of Energy and Climate Change (DECC) [30] energy & emissions projections central scenario for residential gas prices and discount rate of 5%.
[c] Based on the life span of 15 years for TRVs.

strong and the change in gas consumption per unit change in HDD was very similar (ZC: 6.03 kW h/HDD, $R_{ZC}^2 = 0.73$; CC: 6.85 kW h/HDD, $R_{CC}^2 = 0.79$).

5.2. Extrapolating to different UK locations

The performance lines (Fig. 9) were used to estimate the likely gas consumption for ZC and CC if houses built and occupied in a similar way to those measured, were located in different regions of the UK. The HDD were calculated for seven UK regions using the base temperatures of 17.8 °C for the heating months of October to April. To achieve this, "typical weather year" data from the International Weather for Energy Calculations (IWEC) [39] were used for each region: London, the East of England, the West Midlands, Yorkshire, the Northwest, Northern Ireland and Scotland.

The calculated energy use for heating with each system shows that, regardless of the location, for the particular house and occupancy tested, ZC saves between 11.8% and 12.5% of annual gas consumption for heating compared to CC (Table 8).

The calculations were repeated with different base temperatures of 15.5 °C, which is often used by convention for UK homes [38] and also with 20.0 °C, which, given the set point temperature of 21 °C would seem to be a plausible maximum value. The linear relationship between weekly gas consumption and weekly HDD was determined when these new base temperatures were used and the figures in Table 8 recalculated. The regression coefficients with the new base temperature of 20 °C were very similar to those achieved with a base temperature of 17.8 °C. However, for the base temperature of 15.5 °C the regression coefficients were much poorer ($R_{ZC}^2 = 0.55$, $R_{CC}^2 = 0.63$). It can be seen that the calculated energy savings of ZC is not very sensitive to the base temperature selected (Table 8).

To estimate the impact on annual space heating costs, the Department of Energy and Climate Change (DECC) [40] energy & emissions projections central scenario for residential gas prices was used. A discounted cash flow analysis was conducted, using a modest discount rate of 5%, to calculate the net present value (NPV) after 15 years (assumed lifespan of the system) of upgrading a same size house with conventional heating controls to zonal heating controls in each of the 7 regions. The zonal heating kit is a recently developed system and therefore the life span of the system is not exactly known, however, a typical normal TRV has a life span of 15 years and therefore a life span of 15 years was assumed for the programmable TRVs as well. The cost of batteries with a life span of two years was included in the total price of the system. The internal rate of return (IRR) was also calculated for each region as it is an indication of the discount rate necessary to pay back the investment within the 15 years. Two ZC systems with different capital costs were considered for the calculation of NPV: a luxury ZC system with a touch screen central controller (which costs £1200 including installation costs) and a basic ZC system with no central controller in which PTRVs need to be programmed individually by the household (which costs £120).

The calculations for a heating degree day base temperature of 17.8 °C show that 15 years after upgrading to the luxury ZC system, houses in Scotland will have a positive NPV while the houses in all other regions will have a slightly negative NPV; with the houses in more Southern regions having more negative NPVs (Table 8). This indicates that ZC is a more profitable energy efficiency measure for the homes in the colder more northerly parts of the UK. The IRR calculations show that discount rates of up to about 6% is imaginable for the house in Scotland, whereas the upgrade to luxury ZC would only be financially worthwhile in London at discount rates of below 3.5% (Table 8). In contrast, if households buy the basic ZC system, which is 10 times cheaper than the luxury system, they can save about £1000 (present value) after 15 years, regardless of the location of their house (Table 8).

Calculations using the base temperature of 15.5 °C and 20 °C show that the percentage of energy saved with ZC changed little compared to that calculated using a base temperature of 17.8 °C. The savings remained greatest in the more northerly regions. However, the NPV and IRR were sensitive to the base temperature selected. This is because NPV and IRR are dependent on the reduction in gas use (kW h) with ZC rather than the percentage gas savings. A base temperature lower than 17.8 °C, results in lower annual gas use for both systems, thus lowering the absolute saving with ZC leading to correspondingly lower NPV and IRR values. A higher base temperature resulted in the opposite result. However, irrespective of the HDD base temperature, ZC was found to be a more cost effective in Northern regions of the UK.

6. Discussion

To the best knowledge of the authors, this is the first study that directly measured the impacts of ZC on energy use and indoor air temperatures in UK houses. The side-by-side comparison method adopted in this study is a powerful technique by which the effects of home energy efficiency measures on building energy use and thermal comfort can be independently assessed whilst controlling for the effects of the other influential factors, such as the outdoor weather, occupant behaviour and heating system characteristics. The technique enables relatively small differences in energy demand caused, for example by energy efficiency measures, to be identified. However, the method has rarely been used because paired full-size test facilities are not generally available; they can be expensive to construct or buy, the creation of synthetic occupancy regimens is expensive and time consuming, and the need to match the buildings can also take time. The availability of two, attached, un-refurbished and conveniently located homes offered a unique opportunity to conduct the work reported here.

This is one of the first field studies in the UK in recent times in which synthetic occupancy has been used to mimic people and their use of heating systems and energy consuming household equipment and lights. This approach eliminates the variability in the behaviour of people, which can dominate patterns of domestic energy demand and it allows measurements that are intrusive or potentially damaging to property or occupants. The ability to mimic the occupancy assumptions embedded in household energy models can be helpful for validation purposes. Health and safety concerns may constrain the behaviours that are simulated, for example turning on and off gas ovens and hobs. The automatic opening and closing of doors can pose dangers when researchers are working in the house and the operation of outside windows and doors can compromise security.

A number of assumptions were made in undertaking the experiments which place caveats on the generality of the results. Future work could be undertaken in the test houses to extend our understanding of ZC. The time-of use data was used to set up the 'occupancy' schedules, but the way occupants behave in their houses could be very different. For example, it was assumed that the occupants close the doors of the living room, dining room and bedrooms when they are 'occupied'. This is perhaps the best scenario for saving energy while maintaining comfort with ZC as it minimises the heat transfer from the occupied room to the other rooms. In reality, the occupants might not wish to change their internal door opening habits, even if they know it is the best way to get the most benefit with ZC.

Other assumptions and constraints will also affect the measured energy savings. For example, households could achieve adequate fresh air through infiltration in these leaky test houses and window opening was not mimicked. In practice however, people may choose to open windows or trickle vents even in winter, for example at night in occupied bedrooms. This additional heat loss may extend the time needed to achieve comfort temperatures after the heating has switched on, thus reducing the benefits of ZC. Conversely, heat gains from hot water use, especially in bathrooms, might cause a greater fractional decrease in energy demand with ZC then with CC[11].

The trials assumed a household with two working adults and two children, occupying all the rooms except one, who heat their home intermittently. It was found that ZC provides the greatest benefits with intermittent heating rather than continuous heating. This suggests that, if a house is occupied by a household that spends most of its time in the house which is heated, then ZC would save less energy. However, if that household tended to occupy only one or two rooms, rather than the whole house, then this could increase the energy savings from ZC.

[11] The absolute saving might be the same for both, but this will represent a greater percentage saving for ZC.

In this study, indoor air temperature was taken as a proxy for thermal comfort. Of course, thermal comfort is better assessed using operative temperature, which combines air temperature and mean radiant temperature (MRT) [41]. Although the difference between MRT and air temperature is usually small in well insulated homes, it is likely to be greater in thermally massive buildings which are intermittently heated [41]. Further work is needed to better understand thermal comfort in homes with ZC.

The predicted UK regional energy savings of 11.8 to 12.5% for ZC were based on data collected during a limited 8-weeks trial conducted during the winter which did not include many warm days. This increased the uncertainty in the degree-day approach used to extrapolate the measurements to warmer periods of the year and to other locations. Further trials, in milder weather conditions, would increase confidence in these energy saving estimates.

The forgoing discussion has indicated where there is scope for further useful work in the LMP1930 test houses to explore different occupancy schedules, heating regimes, thermal comfort measures and weather conditions. There are however, matters that might more usefully be explored in other facilities or by other types of study. For example, this study only examined the potential savings from a house with a heating system that already complied with building regulations. If houses have poorly controlled heating systems, i.e. no TRVs, or even no thermostat (PRT), then applying ZC could save considerably more energy.

The savings predicted from the LMP1930 are also only reliable for houses of the same size, type, thermal mass and thermal efficiency. As Utley and Shorrock [42] argue, savings from heating certain spaces instead of the whole house could be higher for a house with poor levels of insulation while it would be lower for a well-insulated house where heat transfer from the heated spaces can often achieve the comfort temperatures throughout the house. However, it is not clear how the savings from ZC would vary in houses with different levels of insulation. Moreover, bigger houses have more zones to be controlled and therefore they need more PTRVs, which could considerably increase the capital cost and payback time of a ZC system.

Despite the experimental limitations, it is clear that retrofitting of ZC to existing houses in the UK offers an opportunity for reducing energy demand for space heating. It is also much easier, cheaper, faster and less-disruptive for the households (but less energy efficient) than other retrofit measures such as external wall insulation, double glazing etc. The study also shows that, upgrading to ZC could be a good investment for the homes in the UK, especially when purchasing the cheaper basic system. However, the cheaper system does not have a user friendly interface with a touch screen central controller. This might influence how much households actually get involved with the control of their heating system and considerably shrink the potential cost savings of installing such systems.

Field trials, probably at a large scale, are clearly needed to investigate occupants' real behaviours and their interaction with the new ZC technology. Such research is currently underway in the wider DEFACTO project [43], with which the study reported here is affiliated. However, even in a large field trial, results are limited only to the homes and households from which the data are gathered. Therefore, dynamic thermal modelling, which can accurately represents inter-zone heat transfer, boiler efficiency, and control switching phenomena, and which can simulate any occupancy and heating regimen, will be employed by the current authors to explore the performance of heating controls more thoroughly.

7. Conclusions

Over an 8-week winter test period in a matched pair of 1930s-era UK semi-detached houses with synthetic occupancy

(LMP1930), zonal control heating was compared with conventional control. It was found that zonal control, compared to conventional control, provided a 14.1% reduction in measured boiler heat output but reduced boiler efficiency by 2.4%. The resultant effect was that zonal control produced an 11.8% saving in gas consumption over the 8-week monitored period, compared with conventional control. This was achieved with little or no reduction in the average air temperature in rooms which were occupied, although during sleeping hours bedroom temperatures were up to 1.8 °C cooler on average with zonal control.

Normalisation of these findings across the UK based on heating degree days, suggests that, regardless of geographic location, zonal control of heating, in houses built and occupied in a similar way to the LMP1930, could save about 11.8 to12.5% of the annual space heating energy, compared to conventional control. Cost analysis suggests that zonal control is potentially a more cost-effective measure in Northern regions of the UK, compared with Southern regions, though it should be noted that financial costs and benefits of upgrading from conventional control to zonal control are subject to many uncertainties, and hence are difficult to determine.

Further studies in the matched pair homes are suggested to enable the effects on energy savings of different occupancy and heating schedules to be investigated. Further work, using a dynamic thermal model calibrated against the measured data, will enable the energy saving potential of zonal controls to be explored more fully.

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