Potential energy savings achievable by zoned control of individual rooms in UK housing compared to standard central heating controls.

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Abstract

Energy is wasted in domestic buildings when rooms that are heated are not occupied. Allowing those rooms to cool reduces the inside – outside temperature difference and therefore rate of heat loss, resulting in an energy saving. This suggests a cost effective way to upgrade an existing modern heating system, especially in older properties where other energy saving possibilities are limited. Assessing the savings achievable requires an analysis of a range of influencing factors, such as house type and age, location and occupancy patterns. Door opening has a major influence due to the impact on air exchange between heated and unheated zones in a house, so this was also considered.

Annual simulations were carried out on dynamic models of the thermal and air flow interactions, for all combinations of influencing factors, to compare the potential energy savings of zoned versus non-zoned control.

Savings of between 12% and 31% were obtained in the case of a semi-detached house model, and between 8% and 37% for a single storey bungalow. The largest percentage savings occurred in older properties, with interconnecting doors kept closed, and for the more intermittent types of occupancy. The average saving obtained for both house types was around 20%.

Keywords

Multi-zone zone zoning control modelling simulation occupancy heating saving energy

1. Introduction

Reducing energy consumption in homes, largely driven by the need to meet carbon dioxide emission reduction targets, is being achieved in new build properties predominantly through higher insulation standards, increased air tightness and more efficient domestic lighting and appliances. However, at least 80% of the building stock that will exist in 2050 is already built (Royal Academy of Engineering 2010), so increasing attention is being paid to finding energy saving solutions for existing properties. Relatively simple and cost effective measures such as loft insulation, cavity wall insulation, weather stripping, and boiler replacement are widely deployed. More costly and invasive demand reduction measures include replacement windows, and internal or external wall insulation. Further measures usually involve the deployment of renewable technologies, such as solar thermal and PV panels, biomass boilers and heat pumps. These solutions are heavily promoted by manufacturers, but are expensive, and significant uptake is driven by government aid programmes such as the Renewable Heat Incentive and the Energy Company Obligation (OFGEM 2016).

Heating controls are a neglected technology in the home, and although there is now acceptance that time and temperature control can reduce energy use, mainly by avoiding unnecessary fuel use, there is a lack of knowledge or understanding as to what technologies and techniques could be applied to obtain the maximum benefit in particular instances. Only in recent years have even the simplest domestic heating controls become a standard for new heating systems in the UK, the minimum installation requiring a single time and temperature control zone for floor areas up to 150 m^2, and two independent time and temperature control zones for floor areas greater than 150 m^2. Thermostatic radiator valves (TRVs) are required on all radiators except in the room where the thermostats are located (HM Government 2013). Even this basic standard level of control does not exist in 70% of UK homes (Consumer Focus, 2012). More advanced thermostats, usually combining time and temperature programming, allow more complex profiles to be accommodated, and this can lead to some additional savings. Until recently, this level of control sophistication was all that could be achieved by automatic control, using standard components available to installers. Recent developments now offer a practical means of controlling the environment in individual rooms in a house.

These technologies allow the thermostatic radiator valve head (the part that actuates the valve) to be replaced by a wirelessly controlled motorised actuator. By this means, every room can be controlled independently, so heating can be turned off in those rooms not in use during parts of the day, or temperatures may be increased in a room without affecting the heat supply to the rest of the property. A central control unit receives the demands from all radiators, and switches the boiler on or off as required to meet the current demand throughout the day. This is a relatively low cost retrofit option in many existing homes, no alterations to pipework and only minimal additional wiring being required. By this means, energy savings should be achievable, compared to single point time and temperature control of the entire heating system.

There remains a substantial proportion of the housing stock for which the more conventional solutions are difficult to apply, due to architectural, location and conservation constraints. In contrast, multi-zone heating system controls suffer no such constraints, and can often be installed as an upgrade to an existing heating system.

The premise under investigation is that a multi-zone control system could offer a means to save energy in many existing properties, as an alternative, or addition to the conventional solutions. The purpose of this paper is to demonstrate a range of potential energy savings achievable by deployment of multi-zone controls for a variety of occupancy patterns in various UK house types, locations, and ages. This will indicate what overall energy saving could be achieved by deploying multi-zone controls in existing housing on a national basis, and lend additional weight to the argument that such systems should receive more recognition and support by government agencies responsible for determining the scope of standard assessment procedures and incentive schemes.

The approach of this study was to use dynamic computer modelling and simulation, using the open source building performance simulation (BPS) package ESP-r (Clarke, 2001), which has been developed over three decades by the Energy Systems Research Unit (ESRU) at the University of Strathclyde and a global community of users. ESP-r is used to carry out all aspects of building performance appraisal within a modelling environment that accounts for thermal energy flows, air flows and climate interactions. To ensure that the simulation results were credible, a validation check was carried out using published data from a monitored site.

2. Multi-zone control behaviour

Multi-zone control in a domestic property achieves energy savings, compared with single zone control, because radiators in rooms that would otherwise be heated can be turned off or adjusted to reduce heat output. The achievable energy saving will depend on the extent to which the temperatures in such rooms fall before heating is again required in those rooms. This in turn is dependent on room location, duration of the off (or reduced temperature setpoint) period, thermal exchange with connected rooms or zones, the overall insulation level of the property, internal gains, solar gains and the external temperature. For example, a room in a semi-detached property with other heated rooms on all sides and below, will not cool down as rapidly as a corner room in a bungalow, and therefore will deliver a lower energy saving if turned off for short periods. Turning the heating off in a room for a longer period will increase the obtainable energy saving per unit time, because a lower average temperature, and therefore lower heat loss to the external environment, will be experienced. A room with an open door into a neighbouring zone will gain heat from that zone as long as the temperature is lower, and this will reduce the energy saving in that room, and increase the energy required to maintain temperature in the connected zone. The potential for energy saving will also be affected by the overall external fabric insulation levels. A well-insulated building will not lose heat very rapidly from a room with no heating, so the potential energy savings will be quite low compared with an older, unimproved property. A similar property in a cooler climatic location would also be expected to achieve greater energy savings (though not necessarily in proportion to its total energy consumption).

The study therefore included variations in parameters that would allow observation of these various effects on the savings due to multi-zone control.

3. Previous Studies

Given the energy saving potential of multi-zone control, it has received surprisingly little attention in the published literature. On the other hand, there are several papers that demonstrate the benefit of simple controls (such as a single thermostat with timed control and TRVs) over poorly controlled systems (e.g. timed boiler on/off control). However, empirical studies are difficult to undertake at a scale that may lead to reliable estimates of savings, and both measurement and modelling studies that have been undertaken show a large range in potential savings. For example, Peffer et al (2011) undertook a review of thermostat studies in North America and found reported energy savings from the use of programmable thermostats varying from zero to 9%. Liao et al (2005) reviewed current practice regarding control of heating systems in residential buildings in the UK and Peeters et al (2008) undertook a similar study in Belgium. In both cases, they demonstrated the inefficiency of many installations, and concluded that overall efficiency is affected markedly by the boiler size, the choice of boiler control, whether weather compensation is applied, and the particular configuration of a control thermostat and TRVs.

Regarding multi-zone control, a detailed experiment was undertaken by Beizaee et al (2015) on a matched pair of semi-detached houses: in one house the space heating was controlled with a single thermostat with timed control and TRVs; in the other, zonal control was used to heat rooms only when they were occupied. More details of the experiment are given in the Model Validation section in this paper where the published data are used as a check on the modelling work. Extrapolating the results to the range of UK climates, it was concluded that zonal control could reduce space heating by around 12% for the un-refurbished 1930's houses that were tested.

Meyers et al (2010) undertook a high level scoping study of the potential energy savings in US residential buildings resulting from better control and increased appliance efficiency. Technologies they considered were programmable thermostats, smart meters and outlets, zone heating, automated sensors, and wireless communication infrastructures. They estimated that in the order of 4.2% of primary energy is wasted by heating and cooling unoccupied houses, 6.2% is wasted by heating or cooling living areas during the daytime, and 9.7% is wasted heating and cooling bedrooms when the house is occupied, but the bedrooms are not being used.

Leow et al (2013) undertook a modelling study on occupancy-moderated zonal temperature control. They developed algorithms that would control different house zones based on occupancy, including demand-response adjustments to heating and cooling based on the prevailing electricity price. They showed, for zoning control (without demand-response load shifting) over a range of climates in the USA, overall savings averaging around 23%, depending on the particular configuration. Potential cooling energy savings were found to be higher than heating energy savings. The reference for the calculated savings was the whole house heated or cooled to the chosen set-point temperatures of 23.9°C for cooling and 21.1°C for heating.

An interesting study on the attitudes of residents to controls was undertaken by Rubens and Knowles (2013). The literature on controls show that potential energy savings are often not achieved due to user factors, particularly the difficulty of understanding controls. However, from an in-depth survey and interviews with 43 householders, they concluded that participants seemed to want more rather than less active involvement in their heating, with a greater degree of control. The participants also wanted to be able to see how their behaviours related to their spending on heating. The authors' analysis suggested that remote and zonal control could be combined, with automation as an optional layer so that users could try it out and build trust in it over time.

4. Model Construction

Two geometrical construction types were included in the study; a typical UK semi-detached property on two floors, and a typical single floor detached bungalow property. This would show up the effect of different zone interactions due to these main construction types.

Four different occupancy patterns were simulated, corresponding to:

Young four person family with two children	(YF)
Four person family with two teenagers	(FT)
Elderly couple	(EC)
Young couple	(YC)

As the authors could not locate any standard heating profiles to represent multi-zone occupancy, these patterns were constructed to represent a range of typical occupancy profiles with different levels of occupancy intensity and variations in timing. For each occupancy pattern, the number of occupants in each zone and the internal heat gains were assigned on an hourly basis according to each profile. These occupancy profiles are shown in Appendix A.

Simulations were carried out for each house with standard heating controls (temperature controlled in each room but only one time programme for the whole house), and with a zoned heating control system with independent time and temperature control in each room. These were called the non-zoned and zoned control strategies respectively. In each case, heat was delivered via radiators in each room with a 50/50 radiant/convective split. Radiators were sized at 1.75kW per zone for the semi-detached house, and 2kW per zone in the bungalow, to ensure a rapid heat up (maximum 30 minutes) to the set point temperatures, which were then maintained by an idealised control, without on/off fluctuations or load influenced deviations from set point. Thermostats in both zoned and non-zoned cases sensed a 50/50 mix of air and mean radiant temperatures. Details of the heating schedules are also shown in Appendix A.

In order to assess the effect of insulation and air-tightness on energy consumption, construction material thermal properties were adjusted to create models that meet minimum building standards corresponding to four age categories as defined by the UK government Standard Assessment Procedure (SAP) (BRE, 2014). These changes in building standards delineate major changes in the level of insulation and airtightness and are used for comparing the energy and environmental performance of buildings of varying ages in the UK by SAP. The age bands chosen were C, F, I and K (England & Wales) and the corresponding fabric properties are shown in Table 1.

Table 1 Property age bands and construction properties

Band	Year range	Wall U-value W/m^2K	Roof U-value W/m^2K	Ventilation rate ac/h
C	1930-49	2.0	2.0	0.5
F	1976-82	1.0	1.2	0.4
I	1996-2002	0.45	0.43	0.4
K	2007 on	0.3	0.3	0.3

U-values are approximate.

Two UK climatic locations were chosen, corresponding to London (Heathrow), England, and Glasgow (Abbotsinch), Scotland. TRY (test reference year) data for these locations were used to ensure representative boundary conditions. The dry bulb temperature, direct normal radiation, and wind velocity data are summarised in Appendix B. Diffuse horizontal radiation and wind direction are also contained in the weather files, and used in the simulations.Figure 1 is a view of the model of the semi-detached property, and Figure 2 a view of the bungalow. Rendered views looking from the south-west, and wireframe views in plan are shown, and for clarity representations of internal thermal mass are not shown.

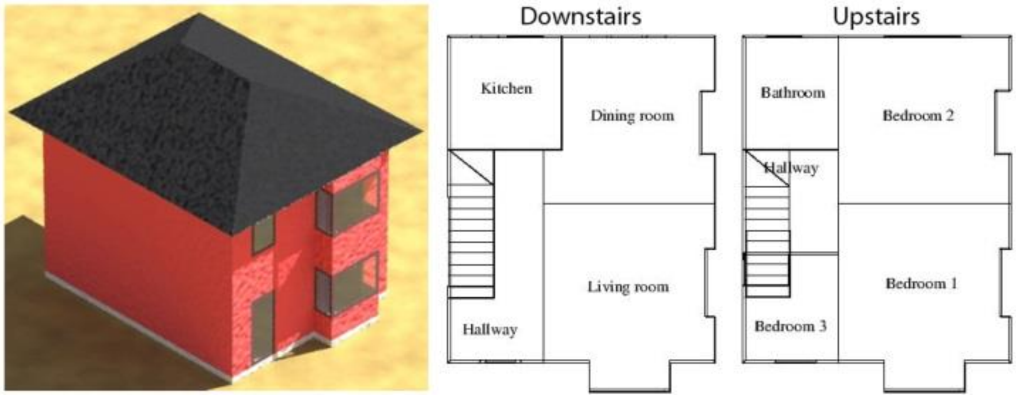

Figure 1 model of semi-detached property

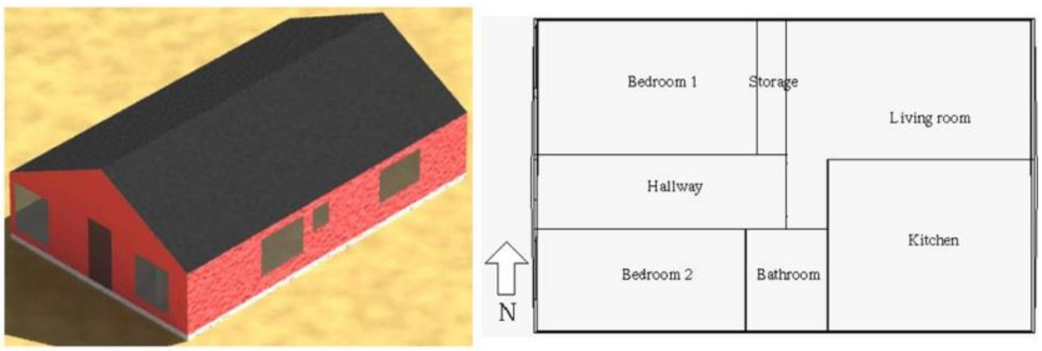

Figure 2 model of bungalow

196 The semi-detached house includes nine separate zones, heated except where indicated:

Z1 Downstairs hallway
Z2 Living room
Z3 Dining room
Z4 Kitchen
Z5 Upstairs hallway
Z6 Bedroom 1
Z7 Bedroom 2
Z8 Bedroom 3
Z9 Bathroom (not heated)

197 The bungalow includes six separate zones, heated except where indicated:

Z1 Bedroom 2
Z2 Hallway
Z3 Bedroom 1
Z4 Living room
Z5 Bathroom (not heated)
Z6 Kitchen

198 The hall heating schedule follows that of the living room. The temperature in the
199 bathroom is free floating.

200 In all cases, the set point temperature in all rooms during heating periods is 20°C
201 operative temperature.

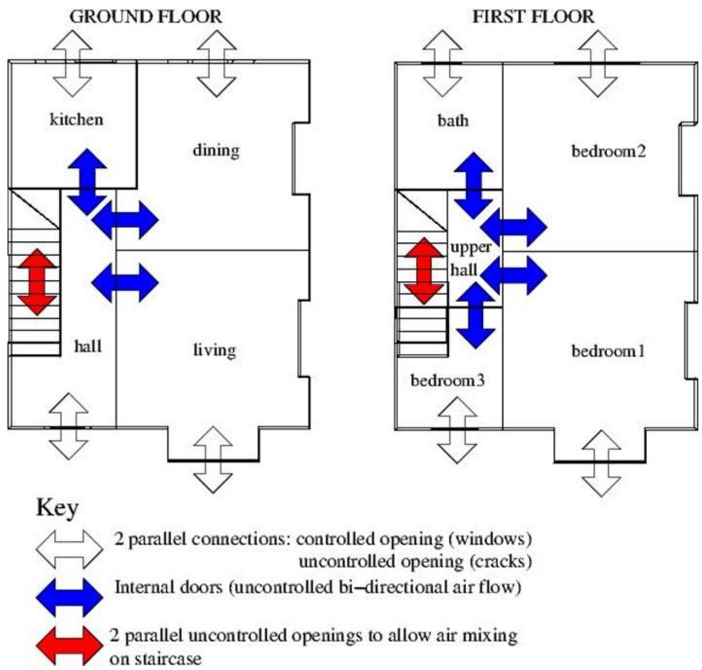

Figure 3 Airflow network for semi-detached house.

The effects of wind and buoyancy on air flows and air exchange between zones are important factors affecting energy consumption in a zoned house. The air flow network used in the model of the semi-detached house is illustrated in Figure 3. For clarity, connections between internal zones representing cracks in "solid" constructions are not shown; these connections generally represent insignificant flows compared to the connections detailed in Figure 3. Bi-directional airflows may occur through doorways due to the combined effects of external wind and internal temperature differences. Windows were modelled as operable, and each was subject to a proportional control such that opening area was linearly proportional to dry bulb temperature in the appropriate zone between 25 and 28°C. Windows were closed at and below 25°C, and fully open (with area of 2.5m^2) at and above 28°C. This was intended to model typical occupant behaviour in preventing rooms from overheating. A similar flow network was constructed for the bungalow model. In the semi-detached house, air will also flow vertically between the ground and upper levels, mainly driven by buoyancy effects. In order to assess the impact of air flow on the performance of the houses, four levels of door opening were modelled, corresponding to average door opening areas of 0, 10, 50 and 100% of full door open area. This was applied to the full door opening area to each room in each house.

5. Model Validation

Numerous extensive validation exercises have been carried out on ESP-r over many years, involving analytical, inter-program and empirical evaluations (Strachan et al, 2008). To build further confidence in the modelling approach, specifically to build confidence in the results of multi-zone simulations, we identified the work of Beizaee et al. (2015) as being of particular significance. Beizaee et al. carried out simultaneous measurements of energy consumption in a side-by-side comparison of two semi-detached properties, one with conventional single zone heating control, and one with a multi-zone system as described above. This experiment demonstrated the potential for energy saving. The details of these properties have been used to create a dynamic simulation model in ESP-r to verify that the computed energy data predicts the energy savings that were observed by Beizaee et al.

The properties were an adjoining pair of semi-detached houses built around the 1930s, typical of UK housing stock of this period. They were located in Loughborough in the East Midlands, England. The properties had not been significantly modified since they were built, and thus had poorly insulated envelopes including single glazed windows, no cavity wall insulation and no loft or floor insulation. Beizaee et al. reported a blower door (pressurisation) test on both properties, finding that both were rather leaky at approximately 21 ac/h at 50 Pa pressure difference.

These properties were very similar to the semi-detached dwelling model that was developed for this study. The validation strategy adopted was to calibrate a variant of the model with the conventional non-zoned control, by adjusting the fabric thermal properties and leakage distribution to achieve reasonable agreement in terms of energy consumption and temperature statistics. The control parameters were then changed to represent the multi-zone controller. Simulations of the calibrated model were then carried out for the periods for which the houses were monitored, using contemporaneous weather data, and internal gain profiles as described by Beizaee et al. The monitoring periods were 16th Feb – 15th Mar, 18th Mar – 8th Apr and 16th Apr – 21st Apr 2014. The predicted savings resulting from the two control options were compared to the measured savings in the side-by-side experiment. Figure 4 compares the model and the measured differences in average temperatures during the heating periods in each zone, with and without zone control. In all cases the differences are negative, due to the shorter heating periods in each zone with zoned control.

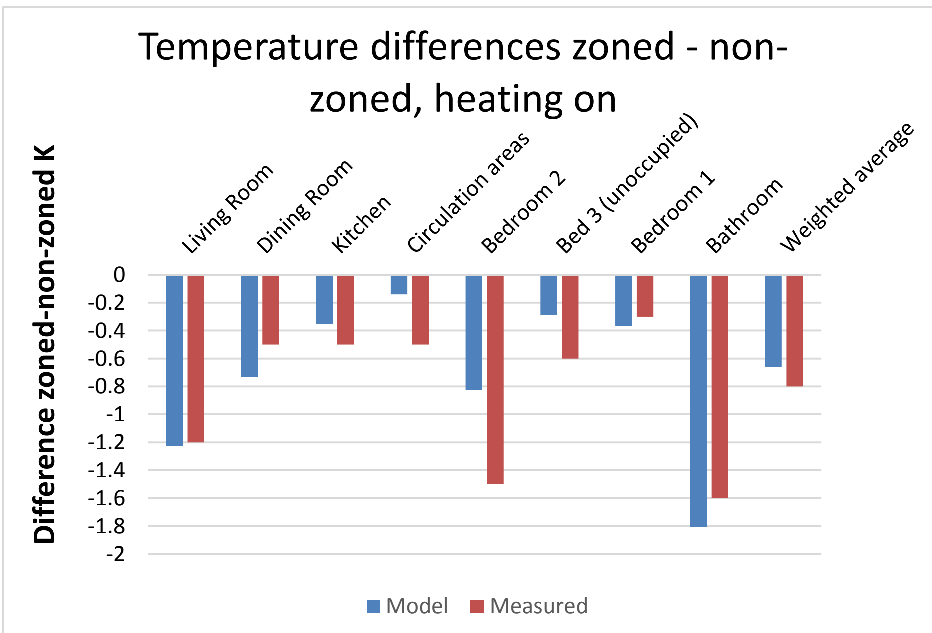

Figure 4 Comparison of temperature differences zoned - non-zoned, heating on

Table 2 shows the results that were obtained by simulation, compared with the measurements by Beizaee et al. of energy consumed over the reported monitoring period. Good agreement was obtained with the measurements, which increases our confidence in the results for the parametric study. As an initial indicator of annual saving potential, the ESP-r simulation estimated an average consumption of 62.6kWh/day with zoning, a saving of 11.8% when compared with the non-zoning case.

Table 2 Comparison of measured and simulated energy consumptions from validation study

	Energy consumption, not zoned	Energy consumption, with zoning	Energy Saving
Beizaee et al. measurements	62.4 kWh/day (average)	53.6 kWh/day (average)	14.1%
ESP-r estimates	62.6 kWh/day (average)	55.2 kWh/day (average)	11.8%
Estimate as % of measured	100.3%	103.0%	83.7%

6. Simulation method

Simulations were carried out for each house type (semi-detached and bungalow), for each of four age bands, for each climate location (Glasgow and London) for each of four occupancy types, and for four door opening percentages (0-100%). Each simulation was carried out for one year.

Thus, a total of 256 annual simulations were run, each with a 24 day pre-simulation start up period in order to eliminate initialisation assumptions, and using 5 minute time steps. The runs were automated using shell scripts in a UNIX environment.

7. Simulation Results

Results comparing internal operative temperatures across all simulation runs are presented for a typical one week winter period. Results comparing energy consumptions are presented for the annual result.

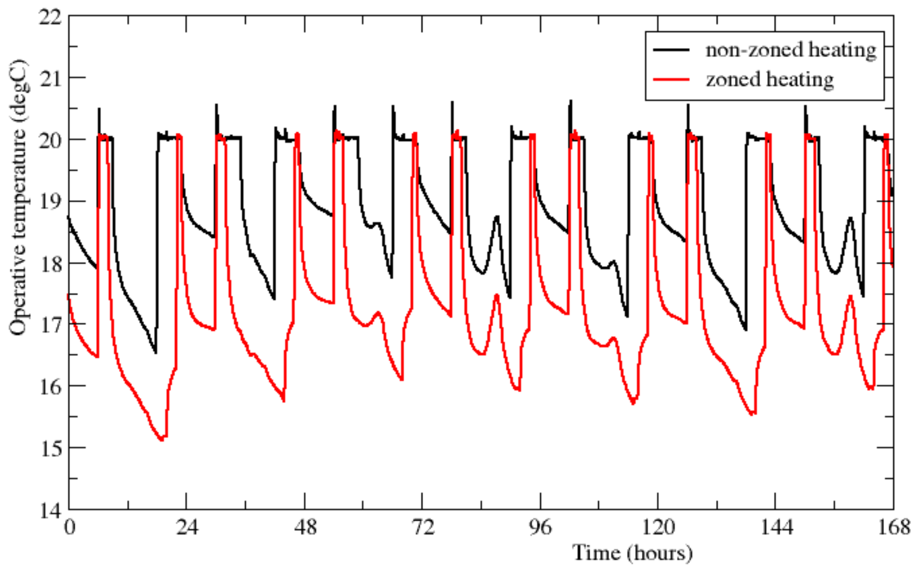

Figure 5 Typical operative temperatures over a winter period in the bungalow

Figure 5 shows the operative temperatures in bedroom 1 in the bungalow model, for YC occupancy, age band K, London climate, doors closed, with and without zoning over a seven day winter period. Providing heat only during the much shorter occupied periods (zoned heating) results in lower temperatures during the unoccupied periods and thus an energy saving compared to the non-zoned case.

Figure 6 shows the effect of occupancy (YF, FT, EC and YC as described in the Model Construction section) on the average living room temperature during occupied hours in the semi-detached house for the non-zoned case. For each occupancy type, the average temperature is shown as a function of climate (Glasgow or London), and house construction age band. For each case, a range of four values is plotted corresponding to four door opening percentages (0, 10, 50 and 100%).

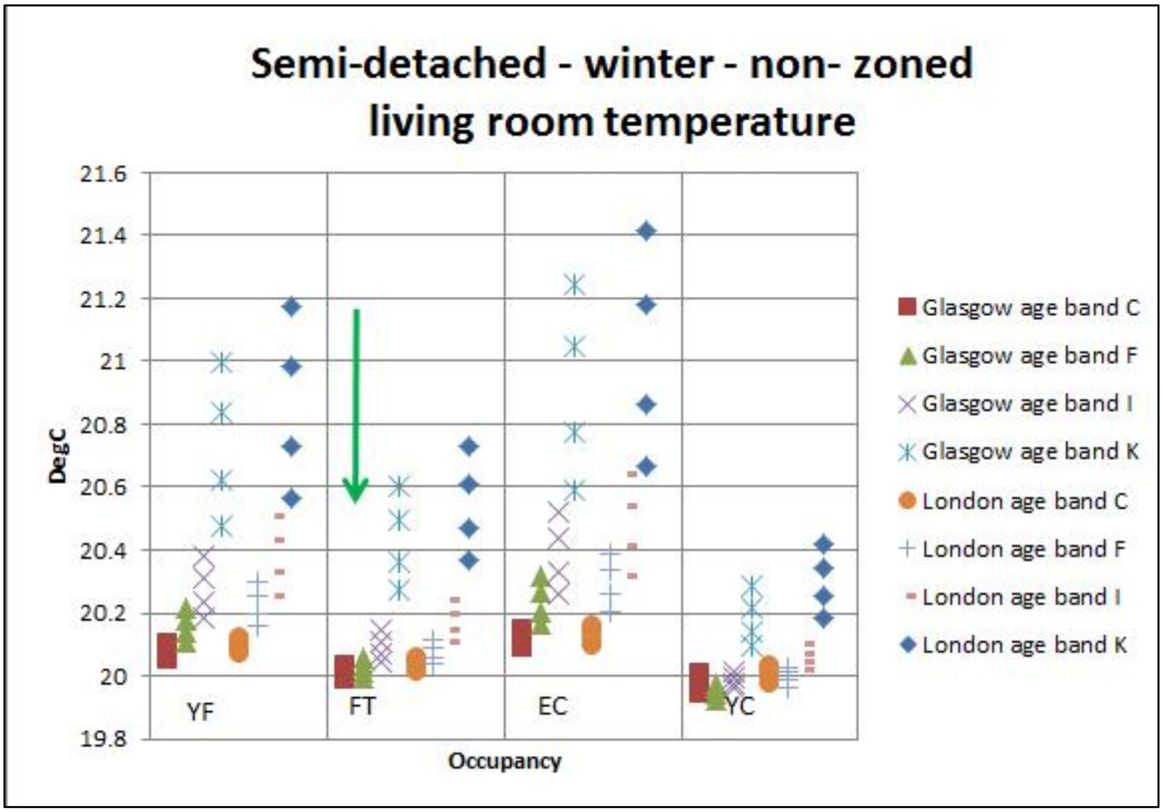

Figure 6 - Effect of occupancy on winter living room temperature (Semi-detached house, winter, non-zoned case)

The arrow indicates the direction of increasing door opening area. When doors are fully open, air can pass freely between zones, so heated zones will lose heat to unheated zones. This will tend to increase the heat demand of the heated zones and, because they will take longer to reach their setpoint temperature at the start of each occupied period, will reduce their average temperature over each occupied period. Therefore, the lowest temperatures correspond to the 100% door open cases, and the highest temperatures to the door closed case. However the range in each case is quite small with a maximum of 0.8K for the EC case. Some observations may be made:

- The temperatures in the YC (young couple) case are generally slightly lower than in the other occupancy cases, due to lower internal heat gains throughout the day and, to some extent, set point temperatures not being achieved due to shorter heating on periods.

- There is a tendency toward higher temperatures as insulation standards improve, and for the milder London climate. The highest temperatures are observed in the YF (young family) and EC (elderly couple) cases, in the milder London climate, for the best insulated K age band houses. This is expected due to the longer heating periods, and therefore shorter heating start up times. The effect of door opening percentage is greatest in these cases, due to the larger impact of inter-zone heat transfer.

Despite these variations, the overall spread of average temperature is 1.5K. Similar results were obtained for other zones, in both the semi-detached and bungalow cases, with similar overall spread of average temperatures being obtained.

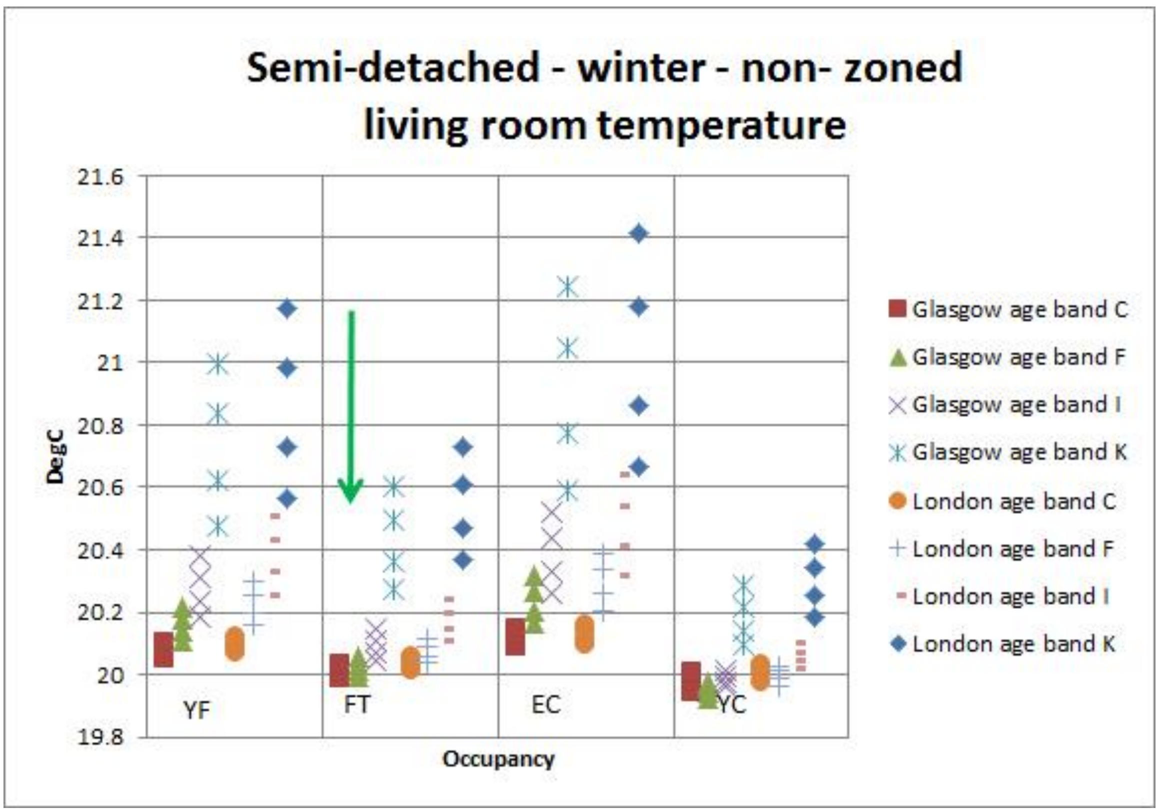

Figure 7 - effect of occupancy on change in living room temperature due to zoning (Semi-detached house, winter)

On comparing the results from the simulations with zoned controls, it is important that average temperatures during the occupied periods in each zone are maintained close to set point, to ensure a fair comparison between the non-zoned and zoned results. Figure 7 shows the effect of occupancy (YF, FT, EC and YC as described in the Model Construction section) on the average living room temperature in the semi-detached house during occupied hours for the zoned cases, minus that for the non-zoned cases. For each occupancy type, the difference in average temperature is shown as a function of climate (Glasgow or London), and house construction age band. For each case, a range of four values is plotted corresponding to four door opening percentages (0, 10, 50 and 100%). The arrow indicates the direction of increasing door opening area. The smallest temperature differences correspond to the 100% door open cases, and the largest differences to the 0% door open cases. This reflects the lower inter-zonal heat transfers when the doors are closed. These differences, and the impact of door opening percentage, are greater for the higher insulated and milder London climate cases, due to the larger influence of inter-zonal heat transfer. However the range in each case is quite small with a maximum reduction in average temperature less than 0.4K.

Similar results were obtained for other zones, in both the semi-detached and bungalow cases, with a similar overall spread of temperature differences being obtained. This raises confidence that the comparison of energy consumptions between the non-zoned and zoned simulations is fair.

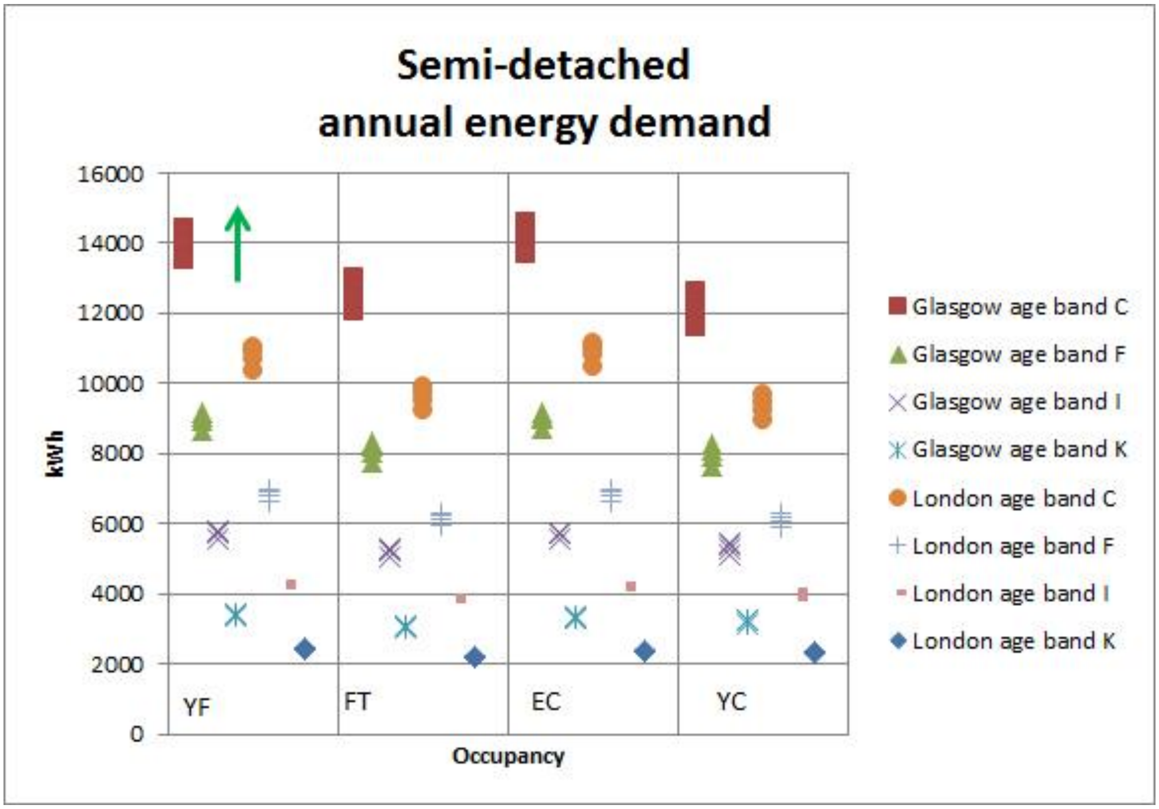

Figure 8 - Annual energy consumption for the semi-detached house, non-zoned.

The annual energy consumptions for the semi-detached house, non-zoned, are shown in Figure 8. The pattern is as expected, with consumption reducing as insulation levels improve, and less for the London climate than the Glasgow climate. The consumptions for the FT and YC occupancy cases are slightly less than the YF and EC occupancy cases due to longer periods of absence. The effect of door opening is quite small, as all zones are heated together, minimising the effect of inter-zone heat transfer. The arrow indicates the direction of increasing door opening area. Consumptions are slightly higher at the 100% door openings due to greater inter-zonal heat transfer.

The annual energy saving for the semi-detached house due to zoning is shown in Figure 9. Savings as a percentage of the non-zoned energy consumption are hardly affected by climate or age band. EC and YC occupancy cases exhibit larger savings than the YF and FT cases. The differences are due to complex interacting factors, one of which is that both EC and YC ‘couple’ occupants have shorter evening bedroom heating periods than the YF and FT ‘family’ occupants.

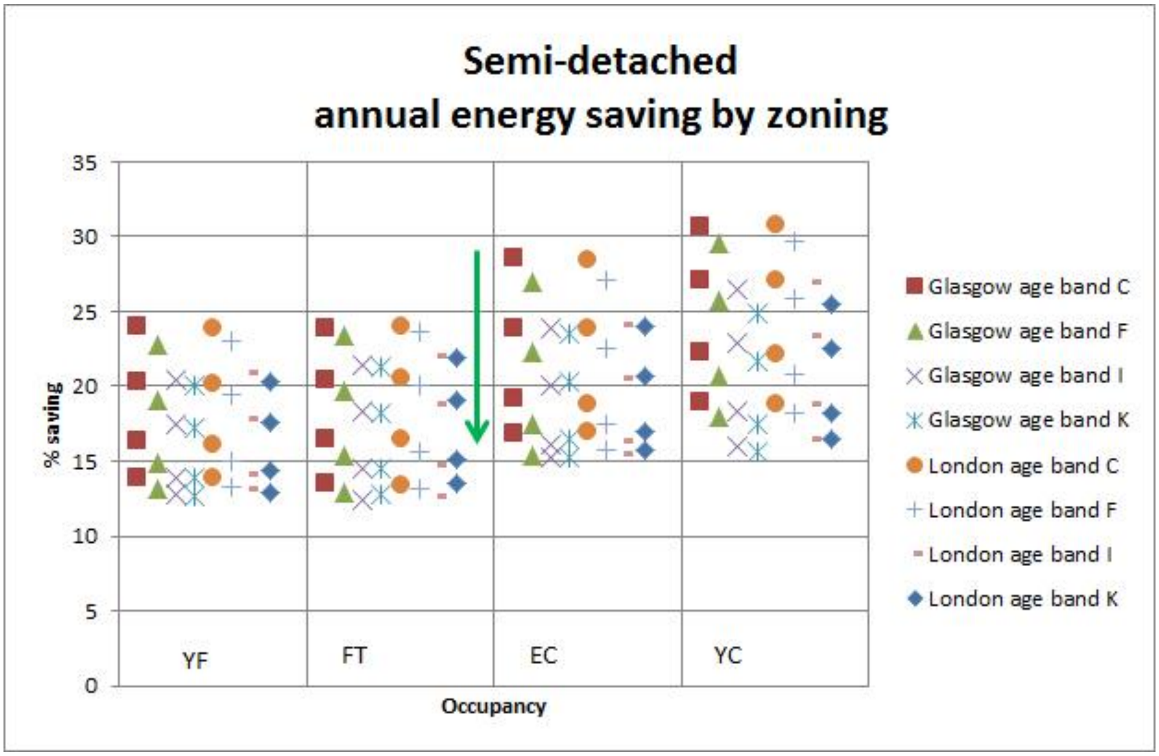

Figure 9 - energy saving in semi-detached house due to zoning

By far the biggest influence on saving is the door opening percentage (the arrow indicates the direction of increasing door opening area) with 100% door opening almost halving the saving obtainable if all doors are closed. This indicates that an effective zoning strategy relies on isolating zones as far as possible to maximise the savings benefit.

Although house age band has only a minor effect on savings potential as a percentage, there is some tendency to reduced savings in better insulated houses. Of course, the absolute savings will be lower, as the baseline non-zoned energy consumptions are lower.

Overall, the savings obtainable across all simulations range from 12% to 31%, with an average around 19%.

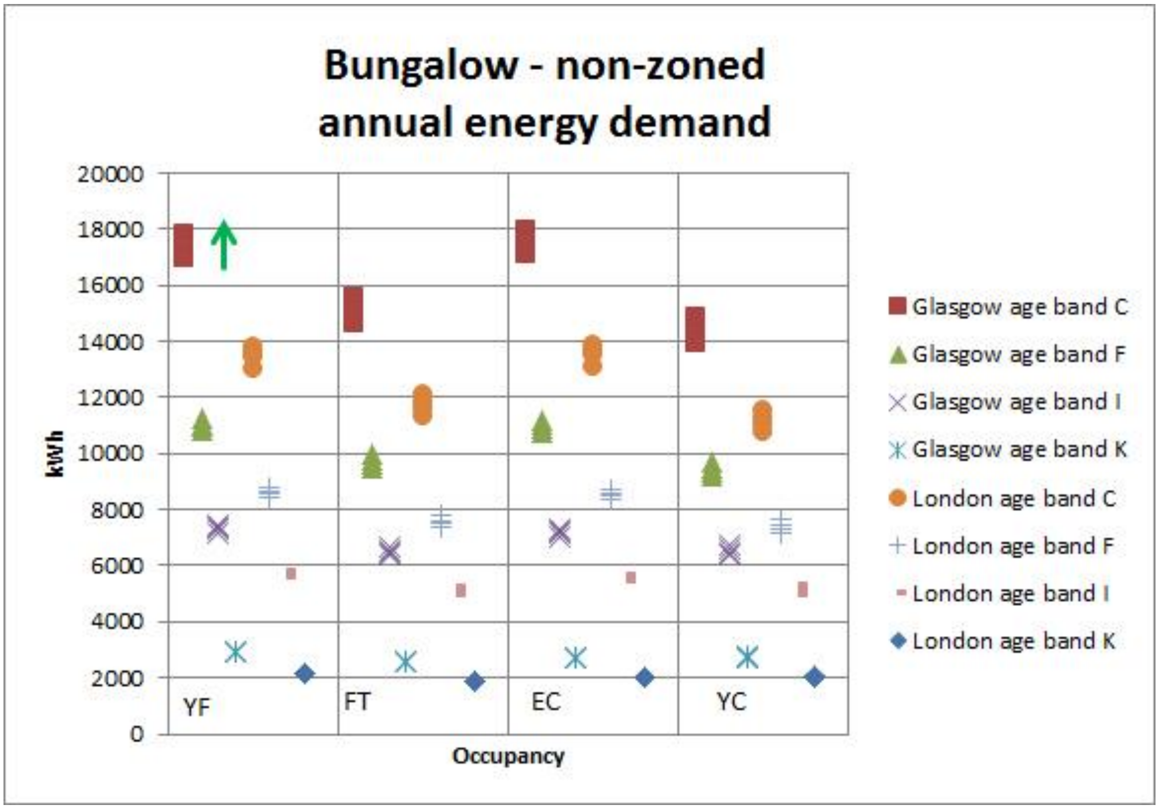

Figure 10 - Annual energy consumption for the bungalow, non-zoned

A similar pattern of energy consumptions for the bungalow as for the semi-detached case can be seen in Figure 10. Overall consumptions are slightly higher than for the semi-detached house, due to the lack of a party wall, and the less compact layout. Again, the effect of door opening percentage is minor.

The annual energy saving for the bungalow due to zoning is shown in Figure 11. As in the semi-detached case, savings as a percentage of the non-zoned energy consumption are hardly affected by climate, and EC and YC occupancy cases exhibit larger savings than the YF and FT cases.

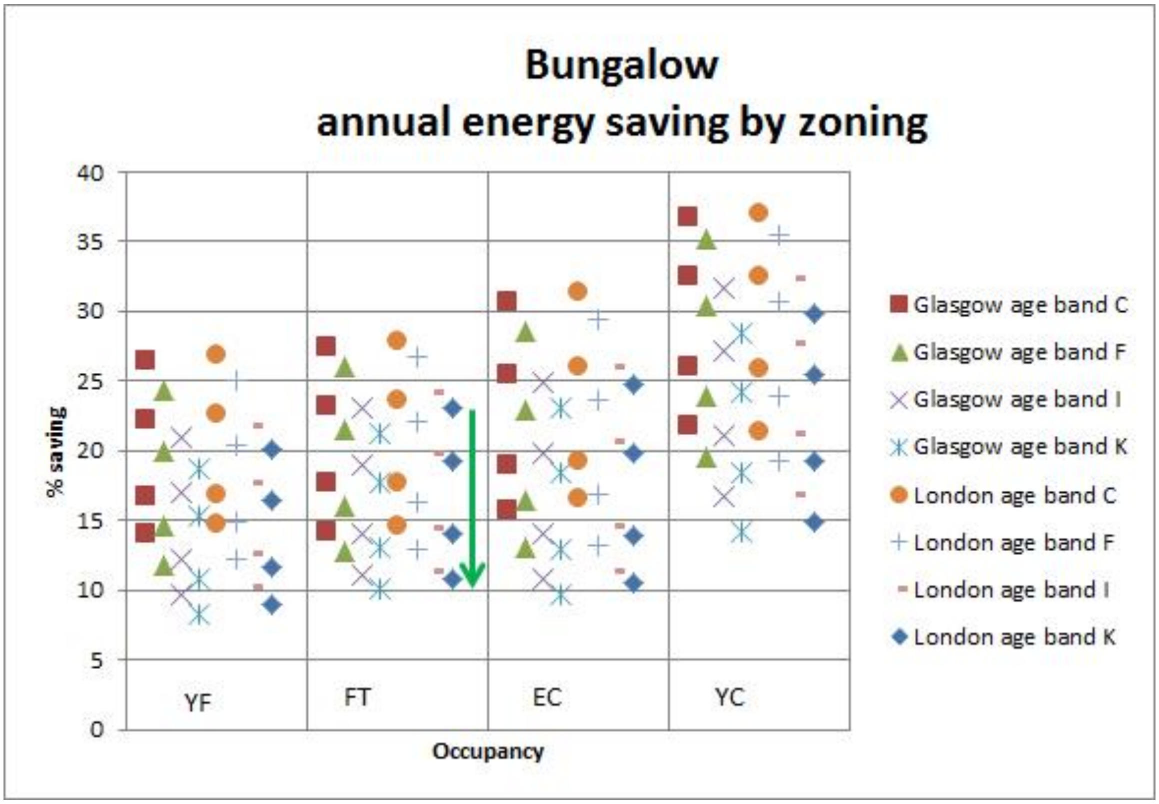

Figure 11 - energy saving in bungalow due to zoning

Again the biggest influence on saving is the door opening percentage (the arrow indicates the direction of increasing door opening area). The effect of house age on savings potential is somewhat more pronounced for the bungalow case, compared to the semi-detached case. The bungalow house type has a greater proportion of exposed fabric surface area, so the energy saving potential is greater in the older, poorly insulated properties. The savings reduce to a level similar to the semi-detached house type in the newer, better insulated properties.

Overall, the savings obtainable across all simulations range from 8% to 37%, with an average around 20%. This is a wider spread of savings than was observed in the semi-detached house.

The main difference in savings between the semi-detached and bungalow house types is due to the reduced inter-zone heat transfer from living, dining and kitchen zones to the bedroom zones in the bungalow, compared to the semi-detached type where buoyancy effects in the stairway, and upwards heat transfer through ceilings are present. However the overall increase in savings is quite small, being greatest for the EC and YC occupancy types with doors closed.

Table 3 - Summary of energy savings %

	Door opening %	Young family	Family with teens	Elderly couple	Young couple
Semi-detached	0	21.9	22.7	25.8	28.1
	10	18.6	19.4	21.8	24.5
	50	14.8	15.4	17.4	19.8
	100	13.2	13.0	15.8	17.3
Bungalow	0	23.0	25.0	27.3	33.3
	10	18.9	20.8	22.1	28.9
	50	13.8	15.4	15.9	22.5
	100	11.2	12.2	12.6	18.1

Table 3 summarises the energy savings for each door opening and for each occupancy type, these being the most significant influences. The figures are thus averages for the two climate types and four age bands.

8. Conclusions

The simulation results show that significant energy savings are possible by adopting a multi-zone control strategy, whereby temperature and time based control is applied independently in each room of a typical house, compared with a non-zoned strategy, whereby all rooms follow a single time/temperature profile. Confidence in these results was provided by validating simulation results from a calibrated model against monitored data, showing agreement in average energy saving to within 3%.

The non-zoned strategy would be implemented using a seven day (or 5/2 day) programmable timer, and single room thermostat, with thermostat or TRVs in all rooms. This is typical installation practice for new central heating systems in the UK. The zoned strategy would require independently programmable radiator controls in each room. Such control systems are now available from more than one manufacturer.

Savings potential is greatest where doors are kept closed for as much time as possible (maybe through use of gravity or spring activated door closers), and for older, less well insulated houses. If doors are kept closed, there is a risk that IAQ will be worse in the occupied zones, so ensuring adequate ventilation is essential at a zonal level, and not just a whole-house level. Savings are least where occupancy is relatively high, e.g. the young family case. Climate was not a major factor in the percentage savings obtainable in any case, for the two UK climates tested. Savings will be least in very low energy demand housing, such as Passivhaus; in such cases it is unlikely the potential saving will justify the investment.

Given the range of parameters studied here, a typical average saving of 20% seems to be possible across a range of house types, ages, and occupancy patterns. These savings are in-line with the limited previously reported studies on the benefits of zonal control. This compares favourably with other demand reduction measures such as wall insulation, or double glazing, and in many cases can be applied to an existing central heating system. It is an attractive option where property architecture and conservation considerations make other options difficult to apply. After having deployed the applicable demand reduction measures, building integrated renewables and other low carbon supply technologies may be considered. Future work should expand the range of influencing factors, and in particular include door opening patterns as an element of occupancy profiles. It should then be possible to evaluate how multi-zone control techniques might fit into the portfolio of demand reduction measures for existing housing.

The favourable energy savings and low installation costs compared to alternative energy saving technologies might encourage the development of intuitive user interfaces for the controls, to develop rigorous commissioning, and to educate users in the operation and benefits.

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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Appendix A Occupancy profiles

4 profiles with and without zoning control; zoning control is employed using 3 zones (living, kitchen/dining and bedrooms). Profiles include {A = adult, C = child}:

- YF = Young family (2A + 2C, 1A works and 1A looks after 2C)
- FT = Family with 2 teenagers (2A + 2A, 2A work and 2A teenagers study and party)
- YC = Young couple (2A, both work and party)
- EC = Elderly couple (2A, both do not work)

Case	Parameter	Day type	Zones: Living		Kitchen/dining		Bedrooms	
			Timing	Occ’cy	Timing	Occ’cy	Timing	Occ’cy
Young family	Occupancy	W’day	9-13	1A+2C	8-9	2A+2C	20-23	2C
			16-18	1A+2C	18-20	2A+2C	23-8	2A+2C
			20-23	2A				
		W’end	9-13	2A+2C	Same as weekdays			
			16-18	2A+2C				
			20-23	2A				
	Heating (no zoning)	W’day	6-13 & 16-23					
		W’end	Same as weekdays					
	Heating (zoning)	W’day	8-13 & 16-23		7-9 & 18-20		6-8 & 20-23	
		W’end	Same as weekdays					
Family with teenagers	Occupancy	W’day	16-18	2A	8-9	4A	7-8	4A
			20-23	2A	18-20	4A	20-23	1A
							23-7	4A
		W’end	9-11	4A	Same as weekdays		7-8	4A
			16-18	2A			23-7	4A
			20-23	2A				
	Heating (no zoning)	W’day	6-9 & 16-23					
		W’end	6-11 & 16-23					
	Heating (zoning)	W’day	15-23		7-9 & 18-20		6-8 & 20-23	
		W’end	8-11 & 16-23		Same as weekdays		6-8 & 22-23	
Elderly couple	Occupancy	All	9-13	2A	8-9	2A	7-8	2A
			15-18	2A	18-20	2A	23-7	2A
			20-23	2A				
	Heating (no z’ing)	All	6-13 & 15-23					
	Heating (zoning)	All	8-13 & 15-23		7-9 & 18-20		6-8 & 22-23	
Young couple	Occupancy	W’day	20-23	2A	8-9	2A	7-8	2A
					18-20	2A	23-7	2A
		W’end	9-11	2A	Same as weekdays			
			20-23	2A				
	Heating (no zoning)	W’day	6-9 & 18-23					
		W’end	6-11 & 18-23					
	Heating (zoning)	W’day	19-23		7-9 & 18-20		6-8 & 22-23	
		W’end	8-11, 20-23		Same as weekdays			

Appendix B Weather data summary

		Dry bulb temperature C			Direct normal radiation W/m^2			Wind velocity m/s		
		Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
London (Heathrow)	Jan	-1.7	6.2	13.1	0.0	26.3	311.0	0.0	4.3	15.4
	Feb	-4.6	6.3	16.2	0.	32.2	327.0	0.5	4.6	12.9
	Mar	-3.2	7.1	19.3	0.0	50.5	336.0	0.5	4.5	16.4
	Apr	0.5	9.6	18.0	0.	64.7	337.	0.	3.6	9.8
	May	5.4	13.5	26.4	0.0	78.5	337.0	0.0	3.6	11.8
	Jun	5.8	16.0	31.8	0.	99.9	335.0	0.0	3.3	8.2
	Jul	11.0	18.5	28.5	0.	90.5	334.0	0.0	3.4	10.3
	Aug	8.8	17.9	31.0	0.0	85.2	334.0	0.0	3.0	8.7
	Sep	3.9	15.1	24.3	0.0	70.7	333.0	0.0	3.0	9.8
	Oct	1.1	11.8	18.9	0.0	46.9	329.0	0.0	3.5	9.8
	Nov	0.3	8.7	16.5	0.0	26.9	315.0	0.0	3.4	9.8
	Dec	-2.9	6.2	14.1	0.0	22.3	291.0	0.0	4.0	12.3
Glasgow (Abbotsinch)	Jan	-7.7	3.0	10.5	0.0	37.1	617.0	0.0	5.3	16.4
	Feb	-10.8	2.9	11.2	0.0	66.7	634.0	0.0	4.8	14.4
	Mar	-3.2	5.9	11.5	0.0	64.6	621.0	0.0	5.2	14.4
	Apr	-3.2	6.8	15.5	0.0	93.7	610.0	0.0	4.4	15.4
	May	-2.5	10.4	23.6	0.0	122.8	617.0	0.0	4.2	12.3
	Jun	4.5	13.1	23.8	0.0	110.6	616.0	0.0	4.2	12.9
	Jul	4.6	14.5	24.8	0.0	102.8	612.0	0.0	3.7	10.8
	Aug	3.6	14.2	22.3	0.0	81.9	578.0	0.0	4.4	11.8
	Sep	0.9	12.3	20.1	0.0	101.6	608.0	0.0	4.3	15.4
	Oct	-4.6	9.1	15.7	0.0	55.7	602.0	0.0	4.5	15.4
	Nov	-4.4	6.0	15.0	0.0	51.5	599.0	0.0	4.5	18.0
	Dec	-9.1	5.4	13.0	0.0	34.0	618.0	0.0	4.7	15.4