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Control System for Energy Reduction in Vacant Environments

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ABSTRACT: The existing building stock is central to the mitigation of global CO_2 emissions [1]. The energy used in UK buildings includes avoidable waste of between 25% – 50% of the minimum required for user comfort and equipment [2, 3]. There are more refurbishment, conversion and renovation than new built projects at any time in the UK construction industry. These present rich opportunities for installing energy saving innovations. This paper assesses the energy saving potential of a 'Control System for Energy Reduction in Vacant Environments' (ConSERVE) in buildings with hot water heating radiators. The results show that the widespread application of ConSERVE can significantly reduce the UK's national energy use. The value of such a control system is therefore undoubtedly great in the context of UK's target of reducing greenhouse gas emissions by 80% by 2050.
Keywords: Energy saving, heating control, building occupancy patterns

INTRODUCTION

Buildings require effective controls to achieve the best possible energy performance. Many buildings employ manual on/off switching but evidence shows that these are ineffective, unless users are frequently reminded. Building users are good at detecting uncomfortable environments and switching on systems to correct them, but are poor at remembering to switch off systems once the environments have been corrected [4]. Users also occupy buildings in highly variable patterns, making the control of building environmental systems a very challenging task.

Demand based control of heating, ventilation and lighting is one of the most important ways to ensure that energy use matches space utilisation patterns. Automated switches based on human presence detection have addressed this issue for lighting. CO_2 sensor based air supply has done so for ventilation and air-conditioning. However, this remains a huge challenge in heating control systems. The UK building regulations require zone and timing controls for heating [5]. The typical features to meet these requirements are programmers and room thermostats. However, it is difficult to predetermine space use in many buildings, and users often forget to reset programmers to changing occupancy. Programmers on their part result in energy waste if they are incorrectly programmed by users who do not understand their function. For zoned heating, air exchange between spaces often defeats the aims of differential heating.

Most of the existing hot water heating radiators are controlled centrally based on set temperatures and time rather than occupant presence. Unoccupied bedrooms and second reception rooms in homes; and office spaces of expected workers, remain environmentally 'prepared' for occupation in many cases when the building is in operation, even where their users are away. Current retrofit solutions include replacing old radiator valves with Thermostatic Radiator Valves (TRVs) to control individual radiators. The operation of TRVs is also based on set temperature, irrespective of occupancy, and the common practice is that they are rarely adjusted once set. Although significant energy savings can be made by fitting TRVs, occupants' failure to understand their function results in many being set to maximum [6]. The solution is usually to fit internal limit stops but this still doesn't address the issue of heating unoccupied spaces. In addition to wasting energy, majority of the existing radiator controls are technologically backward. Sensors and actuators should by now enable manual, automated and/or remote control in individual spaces based on weather, space use, and/or when users expect to occupy their spaces.

The latest and most advanced TRVs, (the RA-PLUS-w by Danfoss Randall, and Type1 PWM by Thermokon), are yet to effectively minimise heating in unoccupied spaces. They still rely on users (who are typically ineffective) to adjust heating settings. However, research to improve the quality of service of Wireless Sensor and Actuator Networks (WSAN) regarding reliability, timeliness, robustness, and security is increasing at a great pace [7]. Technologies to control building environments using WSAN, and heating remotely via GSM mobile phones have recently emerged [7, 8, 9, and 10]. The latter operate with no phone charges – they respond to an incoming call without actually answering it. Products in the market include: the Velleman MK160, the SmartHome Text and the Textsmart module. The best of these can control only up to three independent zones. All these technologies control the boiler output and they do not control heating locally from wet radiator valves. ConSERVE aims to address the above limitations of existing radiator heating controls.

ENERGY WASTE IN UNOCCUPIED SPACES

Empirical evidence shows that many work and home spaces remain unoccupied for significant lengths of time. In UK, the majority of people aged between 4 and 64 (80% of UK's population [11]) go either to work or academic institutions regularly. Energy is wasted heating homes when owners are at work/academic institutions, and vice versa, and owing to users' failure to lower heating when they leave spaces. The UK's average of 5.34 rooms per household and average household size of 2.4 [11] imply that over 55% of the rooms in homes remain unoccupied at any given time. In open-plan and enclosed offices, the average occupancies have been reported as 60% and 40% respectively, and 90% and 70% after considering the time they were temporarily unoccupied [12, 13]. A different study [14] reported average occupancies in *often absent, mobile* and *sedentary* staff as 15%, 30% and 50% respectively, and 30%, 50% and 80% after considering the time spaces were temporarily unoccupied. Empirical evidence shows that unoccupied spaces result in avoidable waste of energy. In UK buildings, this is between 25% and 50% [2, 3]. Avoidable waste represents the difference between actual energy use and the base energy (the minimum required for user comfort and equipment for a building operation).

MINIMISING AVOIDABLE ENERGY WASTE

The limitations of existing radiator controls, their technological backwardness, decreasing household sizes, increasing trends of working away from the workplace, and the resultant energy waste, all point to an urgent need for more advanced heating controls. There is also an urgent need to analyse the occupant factor in radiator heating, which is not well understood. This work assesses the potential for energy saving by way of a 'Control System for Energy Reduction in Vacant Environments (ConSERVE) that is being developed to tackle the limitations of current wet radiator heating controls. Figure 1 shows a schematic of ConSERVE. The design integrates three key factors of energy efficiency (the building as a control in its own right, systems controls, and occupant interaction) in ways that have not been done in the past. The key features of ConSERVE (Figure 1) are designed to work as follows:

1. A Next generation TRV with a 4-point valve, temperature scale and receiver to automatically adjust heating output for minimum or baseline heating, and top it up to full comfort heating as follows:

   I. The lower limit of temperature for occupied spaces: 18^{o}C. This is the minimum recommended temperature [15]

   II. The lower limits of temperature for unoccupied spaces:
      - Minimum recommended temperature [15] – 10^{o}C to be set to protect building fabrics and contents.
      - Baseline temperature 2 – 13 ^{o}C to be set as the lower limit that the temperature can reach when users exit a building to return later.
      - Baseline temperature 1 – 16 ^{o}C (the minimum temperature set by the UK Health and Safety at Work Act) to be set as the lower limit that the temperature can reach when users are elsewhere in a building.

   The assumption for baselines 1 and 2 is that occupants can tolerate lower temperature when they re-enter their spaces from outside than from another heated space. 13 ^{o}C and 16 ^{o}C are not temperature levels to be maintained – they are lower limit temperature targets. When a user has left a space, the presence detector linked controls will lower the heating output to a level that can maintain these baselines respectively, but the actual temperature in the space will remain as close to the comfort level as possible. The heat retention features of the system, as explained later in point 4, will retain the heat already in spaces, so that the baselines may not be reached.

2. Controls of the next generation TRV to adjust the heating as follows:
   - Control 1: to maintain the comfort temperature when a space is occupied, and reduce heating output when a user is elsewhere in a building to a level that can maintain baseline temperature 1. It is a wireless TRV activation system based on user presence detection – a wireless actuator, linked with PIR and temperature sensors to transmit signals to a TRV receiver.
   - Control 2: to lower heating output when a user exits a building to a level that can maintain baseline temperature 2, and raise it to a level that can maintain baseline 1 when the user enters. It is a TRV activation system based on coded user detectors at building entries/exits (e.g. card readers) to communicate with TRVs to adjust radiator output in spaces owned by the detected users as they move in and out of buildings.
   - Control 3: to enable users to remotely pre-heat or lower heating to minimum recommended 10^{o}C [15] for unoccupied spaces. The Control includes a remote TRV activation system using GSM

Mobile Phones and existing infrastructure. In large building applications, a central controller is included to instruct and obtain the status of many TRVs; and communicate with boilers.

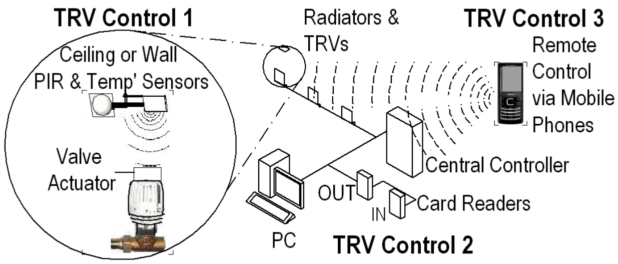

Figure 1: Schematic of ConSERVE. In small buildings, the PC the Central Controller will be replaced by smaller controllers embedded into actuators that will be attached to TRVs.

3. A user coding system to link user cards (entry/exit and SIM) and TRVs to ensure that the system does not violate user privacy – a key concern in human tracking devices [16].
4. Integrated heat containment features to minimize heat loss and delay temperature drop so that the minimum and baseline temperature levels may not be reached in spaces when users leave. This is to ensure temperature stability. These features include self-closers and seals for windows and internal doors, thermal mass and internal insulation to cut off outdoor air ingress into unoccupied spaces and heat losses to lower heated adjoining spaces.

The system is therefore designed to run without the constant attention of users to turn down/up heating, but have manual overrides to adjust to user preferences. Users tolerate wider conditions when given high levels of personal control. It has been designed to retrofit in existing radiators cost effectively with minimal environmental costs of manufacturing.

HOW MUCH ENERGY CAN ConSERVE SAVE?

ConSERVE has been designed for application in cellular spaces in many buildings (office buildings, schools, universities, retail, hotels, & hospitals), and in homes, where radiator heating is used. The following sections describe the methodology and results of a simulation done to compare its performance with that of a conventional control system in a cellular office.

Methodology The simulation used the TAS (Thermal Analysis Software) software package. TAS is a suite of software products which simulate the dynamic thermal performance of buildings and their systems. The procedure for the simulation involved the following:

1. Creation of a 3D model in TAS.
2. Specification of its characteristics of construction elements, site location, orientation, and weather conditions. Table 2 shows the conductance values of the roof, floor, walls and windows, compared with Building Regulations maximum U-values. These are all kept constant in all the simulations.
3. Calculation of the illuminance levels for each room.
4. Calculation of the required supplementary artificial lighting (and therefore lighting heat gains).
5. Calculation of occupant heat gains (sensible and latent), and sensible equipment heat gains.
6. Input of the heat gains to the Internal Conditions Data Editor in TAS.
7. Calculation of natural ventilation through permanent background vents from a first TAS run.
8. Calculation of required supplementary ventilation (based on the first TAS run results) where natural ventilation does not meet the recommended minimum fresh air. Where a result indicates over-ventilation, the level of waste is also calculated.
9. Input of the hourly mechanical ventilation levels, where required, into the TAS models for each scenario.
10. Second TAS run of the final dynamic response of the model to calculate the detailed airflow, temperature, humidity profiles and energy load breakdowns for each zone.

Figure 2 shows the layout in a 12m wide office space slice, in a building 12m deep. This depth is based on the 2h (2 x ceiling height) definition of the passive zone, for a ceiling 3m high. Although this assumes the narrow floor plates in most European offices resulting from strict regulations on natural light and outside views in work places, office depths in other part of the world, such as America, may be considerably deeper. Office layouts and floor plate shapes also vary considerably between world regions because of zoning laws and codes, and depending on whether they were built as cooperate headquarters, speculative offices, extensions or were conversions [17].

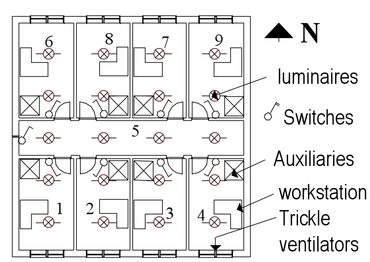

Figure 2: 144m² Cell layout of 8 offices (18m² per user) used in the simulations.

The glazing ratio is 30% and uniformly distributed on the north and south facades, with the east and west being windowless. 30% glazing ratio is the optimum for southern UK office buildings [4], the upper limit for avoidance of glare [18, 19], and lower limit for user appreciation of sunlight penetration [4]. Office partitions are placed to ensure that the 30% glazing ratio is maintained and daylight, vents, and luminaires are distributed equally in the rooms. Light reflectance levels of interior surfaces in the model are 0.3 for floors, 0.55 for walls and 0.7 for ceilings. A 300mm high fanlight is provided on each internal door – there are no external doors. The space use density is 18m^2/occupant - based on planning standards [20] and typical UK densities [21].

Table 2: Characteristics of building elements of the model compared - internal and external surface resistances are excluded in the conductance values. These are compared with the maximum U-values (in brackets) recommended in UK Building Regulations [5].

Element	Description	Conductance (W/m^2 ^{o}C).
Flat Roof	15mm acoustic panel, 200mm air cavity (downward flow), 150mm concrete, 125mm expanded polystyrene sheet & 3mm asphalt	0.266 (0.25)
Ground floor	5mm plastic tiles on 50mm screed on 125mm concrete on 75mm crushed brick aggregate on 1000mm sand	0.29 (0.25)
External wall	25mm light weight plaster, 100mm aerated autoclaved concrete block, 100mm glass fibre, 50mm air cavity (horizontal flow) 105mm brickwork.	0.256 (0.35)
Internal Wall	25mm lightweight plaster, 100mm foamed slag concrete blocks, 25mm lightweight plaster.	1.054 (-)
Windows	6mm kappa float – 12mm air cavity (horizontal flow) – 6mm clear float	2.6 (2.20 metal, 2.0 timber & PVcu)

For ventilation, windows are assumed closed and natural ventilation is through the trickle vents – one above each window and one on the west wall (Figure 2). The UK Building Regulations [16] require a minimum size of background ventilation openings of 400mm^2 per m^2 of floor area and 4000mm^2 in rooms less than 10m^2. In the simulation, air-infiltration between rooms is through 3240mm^2 gaps at the bottom of each door – assuming standard 800mm wide door shutters and that doors are closed. In occupied rooms, where background ventilation does not meet the recommended minimum fresh air requirements of 8 litres per second per occupant (assuming a no smoking provision), the hourly deficit is input and assumed to be met by supplementary mechanical means. Fan power is not taken into account in the simulations. In unoccupied rooms, ventilation is only through trickle vents.

In practice, trickle ventilators for background ventilation usually have provisions for manual control but occupants rarely close or adjust them – partly because they are typically small in size and incorporated into windows or wall decoration. This camouflages and makes them obscure and not obvious whether open or closed. Occupants would therefore unlikely open closed vents or close open ones. Automatic dampers are increasingly being installed in some new buildings and refurbishments but the assumption in this simulation is that the vents are manual and remain open throughout.

The different ventilation requirements, internal heat gains, lighting and thermal environments are adjusted hourly to match occupancy levels in each zone. Simulations are limited to a peak winter day – 21st December using the weather of BRE's Garston station. Garston was chosen partly because it is where BRE carried out research on the light switching behaviour of occupants. The results of the BRE research have been used to guide lighting loads in the analysis in this study. Occupant and equipment heat gains are 130W per occupant and 150W per computer.

Lighting calculations are based the probabilities of switching on lights as a function of time of day and minimum Daylight Factors [22]. They indicate that lights would be switched on during the peak winter morning (9:00 am) in all the rooms. The assumed installed lighting capacity is 3W/m^2 for every 100 lux required, based on the good practice capacity of 10-12 W/m^2 to achieve 400 lux [18]. Other assumptions are; that lights are manually controlled and that users control lighting in their owned spaces [22]; that if the Daylight Factors call for switching on, the lights would remain on until people leave the rooms [23, 24, 25].

The heating is set with a one-hour preconditioning period to operate between 8:00 and 18:00 hrs in all cases. In occupied spaces, it is set to size automatically the heating for three scenarios. In the ConSERVE case, it assumes the 16 ^{o}C and 13 ^{o}C baselines for two scenarios in unoccupied spaces and 18^{o}C in occupied spaces in both. These are based on the typical 50% occupancy in UK offices [12]. For the conventional control case, it assumes 18^{o}C throughout. The lower and upper limits of relative humidity are 40% and 60% [26].

RESULTS AND DISCUSSION

The results in Figure 3 are presented to show the combined energy use and put into context the three areas where energy is used (computers, lighting and heating), and that contribute to internal temperature conditions. Computer and lighting energy use is constant in all cases. The heating is however, varied based on the assumed local controls for radiators in a central heating system namely, conventional radiator valves and ConSERVE. These heating results represent the actual heat output during the time heating is on. The column labelled 18 represents the total energy use assuming a conventional control, which is set to maintain minimum temperature at 18°C from 8:00 to 18:00 hrs whether spaces are occupied or not. The column labelled 16 represents the total energy use assuming a ConSERVE installation set to maintain minimum temperature at 18°C during 50% of the time when spaces are occupied; and reduce the heat output to a level that can maintain 16°C during 50% of the time when spaces are unoccupied between 8:00 and 18:00 hrs. The column labelled 13 represents the total energy use assuming a ConSERVE installation set to maintain minimum temperature at 18°C during 50% of the time when spaces are occupied; and reduce the heat output to a level that can maintain 13°C during 50% of the time when spaces are unoccupied between 8:00 and 18:00 hrs.

As mentioned in the description of ConSERVE earlier in this paper, when the heating output is reduced, with the 16 °C and 13 °C as baseline targets, it does not mean that the actual temperature will drop to these levels. The heat containment features will prevent the temperatures from dropping. Part of the ConSERVE strategy will include investigation of the impact of heat retention strategies so that temperature drop to the minimum or baselines is delayed as much as possible when space users leave. This will reduce the reheating and the time taken to reheat when space users return.

The results show 12% and 23% heating energy savings at the two baselines respectively. These are expressed as percentages of the heating loads of the conventional heating control. How significant is this in the context of UK's National energy use and CO_2 emissions? Office buildings account for 2% of UK's total energy use [27] and 40% of this is for space heating. 12% and 23% savings represent 0.1% and 0.2% of UK's total energy use respectively. Higher savings are possible since most existing office buildings are leaky and have very inefficient fabrics. These typically supply more than the 8l/s/person of fresh air used in the simulation, and in some cases insulation cannot be retrofitted. The simulation looked only at the potential savings in a good practice building shell. In addition to leakage, most real buildings have many thermal bridges, which are not taken into account in the simulations. Higher savings are possible if ConSERVE integrates the measures of internal wall insulation, thermal mass, door/window closers and seals in existing buildings where these can be retrofitted.

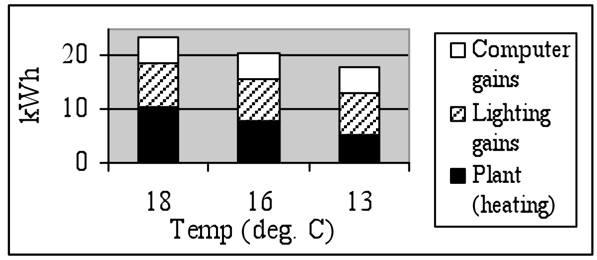

Figure 3: Energy use on 21st Dec. (8am to 6pm) assuming: 50% occupancy; Lights on in occupied rooms & off in unoccupied ones; the computers on equal the no of occupants.

How much heating energy can be saved in UK's domestic sector? Experimental evidence shows that significant energy can be saved by controlling heating in homes in the ways ConSERVE aims to do. An experiment to separate the upstairs bedroom temperature zone from the ground floor in a house, and to reduce heat losses due to the stack effect was done by having internal doors leading to the staircase closed in one case and open in the other [28]. The results showed 27.7% energy saving (70.2 MJ/day compared to 97.1 MJ/day) by accepting a lower temperature in the bedrooms. The house used in the experiment is representative of UK's national average number of rooms per household of 5.34 [11], and such thermal zoning is possible vertically and/or horizontally in many homes.

The domestic sector accounts for 27% of both UK's total energy use and CO_2 emissions [29]. Domestic space heating accounts for 58% and 46% of the 27% energy use and CO_2 emissions respectively [30]. This represents 15.7% and 12.4 % of the UK totals respectively. Based on the estimated over 55% of rooms in UK homes that remain unoccupied at any given time, and the potential saving of 27.7% in the experiment, widespread installation of ConSERVE in UK homes can potentially save up to 4.3% of UK's total energy use, and reduce up to 3.4% of the total CO_2 emissions. The potential savings from ConSERVE in the domestic sector, together with other buildings that have cellular spaces are therefore a significant proportion of UK's total energy use. A similar simulation to that described for the cellular office layout in this paper is needed to confirm the estimate for the domestic sector savings.

CONCLUSION

This paper looked at the potential energy savings through a 'Control System for Energy Reduction in Vacant Environments' (ConSERVE) in buildings with hot water heating radiators. The results show that ConSERVE can save up to 23% of energy in office buildings in peak winter. They indicate that a significant amount of energy may be saved, but that annual simulations need to be done to calculate annual savings, as well as tests in real buildings in order to confirm the results. The analysis suggests that a significant proportion of the energy used in radiator heating in peak winter could be attributed to the way in which their controls interact with occupant patterns of space use. Widespread application of ConSERVE can significantly reduce in offices and the domestic sector, and consequently UK's national energy. The value of such a control system is therefore undoubtedly great if the UK is to meet its target of reducing greenhouse gas emissions by 80% by 2050.

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