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Review

Driving factors for occupant-controlled space heating in residential buildings

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ABSTRACT

Occupant behaviour has a large impact on the energy consumption of buildings, and therefore a better understanding can assist in many building-related applications, such as facility management, building performance simulation and occupant guidance.

As occupant space-heating operation has a significant influence on the energy consumption of residential buildings in winter, an investigation of drivers for this behaviour was undertaken and the result is expressed in this paper. From the analysis, 27 drivers have been evaluated in previous behavioural studies and at present none of them can be identified confidently as having no influence.

Following the identification of these key drivers, the modelling of occupant space-heating behaviour in traditional building performance simulation was reviewed and the result indicates that most of these factors are typically ignored when modelling space-heating operation in building performance simulation.

It is concluded that future behavioural studies into the drivers discussed in this paper are needed to gain a better understanding and quantification of the impact of these factors on building energy use.

Contents

1. Introduction

Occupant behaviour in buildings has a significant impact on energy use, especially in dwellings [1–6]. In the past several decades, studies have been carried out to identify the variation of energy use in residential buildings due to differences in occupants' behaviour [7–12]; the reported magnitude of this variation varies significantly and covers a range of 4–26% [8,12]. The actual impact of occupant behaviour on energy use in a specific residential building depends on various factors, such as occupant engagement, building automation, thermal properties of the building (insulation, thermal mass) and climate conditions [2,5,8,13,14]. Quantifying this impact is challenging: both the method of measuring the influence of people on the thermal behaviour of actual buildings and the method of modelling and simulating this influence need to capture all relevant drivers. Previous studies in this area typically cover only a limited set of parameters, risking incomplete observation and simulation – for instance through a simplified and schematic

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representation of the occupants' operation of heating controls or window operations [15–22]. Such a simplified view is also problematic for any work that aims to change occupant behaviour in order to reduce building energy use: in such work, it is important to understand both the existing behaviour and the factors that cause this behaviour. These factors are referred to as 'drivers' in this paper, the same as Fabi et al. [23] who have used the same term for window opening behaviour.

This paper critically assesses the existing literature on the underlying drivers of occupant space-heating behaviour in residential buildings, which can be used to guide both monitoring and simulation studies (Section 2). The paper then focuses on building simulation, and reviews how occupant space-heating behaviour has been modelled in existing simulation studies. Two key aspects are explored:

(1) the range of values that have been used to define the heating setpoint value in building simulation; and,
(2) the dependence of the heating setpoint value on influencing factors, that is, how the value changes over time when the simulation condition changes.

2. Factors influencing occupant space-heating behaviour

Occupants typically heat their buildings to keep warm in winter. Their preferred indoor temperature, however, can differ substantially from person to person [24,25]. In this section, the underlying factors influencing occupants' space-heating behaviour are discussed. These factors are classified as:

- environmental factors: outdoor climate and indoor relative humidity;
- building and system related factors: dwelling type, dwelling age, dwelling size, room type, house insulation, type of heating system, type of temperature control, and type of heating fuel;
- occupant related factors: occupant age, occupant gender, occupant culture/race, occupant education level, social grade, household size, family income, previous dwelling type, house ownership, thermal sensation, perceived indoor air quality (IAQ) and noise, and health; and,
- other factors: time of day, time of week, occupancy, heating price, and energy use awareness.

The literatures reviewed for this section all focus on studies of drivers of occupants' space-heating behaviour in residential buildings. The papers cited have been taken from (1) SCI impact journals, such as Energy and Buildings or Building and Environment, and (2) key conferences, such as the IBPSA Building Simulation Conference or the ECEEE and ACEEE Summer Study Conferences.

In actual buildings, many of these factors will be correlated. For example, house insulation, the type of heating system and type of temperature control may relate to dwelling age. However, this paper discusses the influence of the above factors on space heating one at a time, reporting on conclusions from existing studies as to whether the factor's influence is deemed to be significant or insignificant. The possible combined influences of factors are not presented, unless these combinations have been expressed explicitly in the literature.

2.1. Environmental factors

The impact of *outdoor climate* on space heating has been evaluated in many existing studies. Newman and Day [26] suggested that night-time winter temperature settings were strongly affected by outdoor climate conditions, supported by Pimbert and Fishman [27]. Additionally, both Vine [28] and French et al. [29] found that homes in warmer climates turned the heating system off or maintained lower winter settings than those located in colder climates. Based on a questionnaire survey, Andersen et al. [13] suggested that "*the proportion of dwellings with the heating turned on was strongly related to the outdoor temperature*", and this is supported by real-measured data from 13 Danish dwellings [30]. Besides outdoor temperature, outdoor humidity and the wind speed were also found to influence the heating setpoint in dwellings [30]. Day and Hitchings [31] stated that the weather forecast affected occupants' heating behaviour greatly, based on an in-depth qualitative survey of 21 British households.

Fabi et al. [3] reported that for occupants who frequently adjusted thermostat settings (more than 50 times within a six-month period), *indoor relative humidity* drove them to turn up thermostatic radiator valve (TRV) settings significantly.

2.2. Building and system related factors

Dwelling type is a factor that has been investigated in many studies. From data collected in the US, Vine [28] found that winter thermostat settings were lower among multi-family dwellings, compared with other types of dwellings. From a survey carried out in 2356 households, Tachibana [32] also found that residents of apartments and condominiums were more likely to turn off their heating systems, compared with those living in houses. Additionally, they also had a lower proportion of morning and evening temperatures at high degrees, and higher temperatures at night. Based on data collected from 600 Swedish households, Linden et al. [33] suggested that families residing in detached houses tended to adopt lower indoor temperatures than those living in apartments, in order to save energy. Shipworth et al. [34] carried out a year-round study in 358 British houses, and found that the heating operation hour was statistically dependent on dwelling type, and that the largest difference was between detached and mid-terraced houses. Yohanis and Mondol [35] also investigated this factor in a study carried out in 25 households in Northern Ireland. They found that the lowest average temperature in winter was in terraced houses and the highest was in semi-detached houses, and they reasoned that the lower temperature in terraced houses might be caused by lower occupancies in that type of house. From a survey performed in over 500 homes in the UK, Kane et al. [36] analysed the average temperature in several types of dwellings: detached, semi-detached, end-terrace, mid-terrace and flat. They reported that flats were the warmest and detached dwellings were the coldest, with a difference of 2 °C. The DEFRA (Department for Environment, Food & Rural Affairs), UK, [37] carried out a survey regarding thermostat settings, in which people living in flats also reported higher settings than those living in detached houses.

The influence of *dwelling age* has been explored in some studies. Vine [28] suggested that dwelling age had no effect on winter thermostat settings. In a national survey carried out in the UK, however, Hunt and Gidman [38] found that older homes were colder than newer homes from 1000 houses, although the analysis was affected by the strong associations between dwelling age, occupant income and the possession of central heating. Santin et al. [8] also found a small negative correlation between local heating in the living room and the construction year. In 2005, French et al. [29] also investigated this factor in their study and found that older houses tended to be colder. However, confounding factors such as the retrofit of thermal insulation, the heating fuel and region, could also possibly contribute to this temperature difference, rather than occupants' heating patterns.

The factor of *dwelling size* has been investigated in only one study carried out by Vine [28] and no significant influence was identified.