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Using results from field surveys to predict the effect of open windows on thermal comfort and energy use in buildings

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Abstract

Windows are one of the major means by which building occupants control the indoor environment. This research uses results from field surveys to formulate a method for simulation of office buildings to include the effects of window opening behaviour on comfort and energy use. The paper focuses on: (1) what is general window opening behaviour? (2) how can we frame an ''adaptive algorithm'' to predict whether windows are open? (3) how can the algorithm be used within a simulation to allow the effects of window opening on comfort and energy use to be quantified? We have found that: (1) the proportion of windows open depends on indoor and outdoor conditions, (2) logistic regression analysis can be used to formulate an adaptive algorithm to predict the likelihood that windows are open, (3) the algorithm when embedded in simulation software provides insights not available using more usual simulation methods and allows the quantification of the effect of building design on window opening behaviour, occupant comfort and building energy use.

Keywords: Thermal comfort; Adaptation; Behaviour; Building controls; Window; Simulation; ESP-r

1. Introduction

The principle which underlies the adaptive approach to human thermal comfort indicates that ''If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort'' [1]. This principle implies that if people are uncomfortable they will take actions – including the use of building controls – which they think will improve their comfort. If the action is successful they will reduce or avoid discomfort.

In temperate climates the window is possibly the most common thermal control device in any building. If people feel hot and want to feel cooler indoors, they often open the window to cool the indoor environment: if they are too cool and the window is open they will close it. This window opening behaviour is not only useful for energy saving in summer, by reducing the need for mechanical cooling or heating, but also provides for a beneficial interaction between the indoor and the outdoor environments [2]. The results of this project contribute to the current debate over how best to use natural ventilation to achieve sustainable building design.

The use of simulation tools in building design and building energy performance certification is becoming standard practice. The impact of occupant behaviour on the operational energy use of buildings is potentially very large but it is not well represented in simulation models. The literature shows that a variety of assumptions have been made by modellers about the window-opening behaviour of occupants:

(1) A schedule of windows open is assumed, based on occupancy, with or without evidence from the field [3–8].
(2) Window opening is assumed to be controlled by temperatures, humidity, wind, rain, based on assumptions about behaviour [9–14]. Again evidence from the field is often absent.
(3) Windows are controlled to produce a given air flow rate or air exchange rate [15–17], may be more related to indoor air quality or minimum ventilation rather than thermal comfort. This approach assumes the occupant will utilize the window openings to achieve the design ventilation rates.

Such window opening assumptions do not necessarily express the occupants' actual behaviour. Thus it is necessary to use an algorithm for window opening based on field investigations in real offices. The main purpose of the research

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described is to develop and implement such an adaptive algorithm for window opening for use in building simulation.

The main aims of the research are:

- To understand window opening behaviour.
- To construct an adaptive algorithm for window opening to use in building simulation.
- To implement the algorithm in simulation software and investigate results.
- To illustrate some effects of occupant behaviour on comfort and energy use.
- To show the effect of building design on occupant behaviour and energy use.

2. Methodology

2.1. Field survey

This investigation of window opening in office buildings uses data collected in thermal comfort surveys conducted in 15 office buildings in UK between March 1996 and September 1997 [18–20]. Nine of the buildings were in the Oxford area in the central south of England (seven naturally ventilated (NV) and two air conditioned (AC)). Six of the buildings were in Aberdeen on the north-east coast of Scotland (three NV and three AC). These data are among those which have previously been used to provide a general overview of control behaviour in buildings [21].

Three types of survey were conducted:

1. Transverse surveys (Abdnox-trans) were conducted 1 day each month by researchers visiting each building with measurement instruments and with questionnaires administered verbally to each of the subjects. The questionnaires included subjective responses to the thermal environment at the time of the visit as well as information on their clothing and activity and the use of controls, including the windows. On each visit, one set of responses was recorded from each subject. Four thousand nine hundred and ninety-seven sets of responses were collected from the 890 subjects (min 1, max 13, median 5, mean 5.6).
2. A longitudinal survey (Abdnox-long) was conducted during the same period using a sub-sample of the transverse subjects. Simple Temptrak temperature dataloggers were placed in the working environment close to the subjects. They were asked to record their thermal satisfaction, their clothing and activity, and their use of building controls using a simplified questionnaire filled in four times a day (early morning, late morning, early afternoon and late afternoon). Most subjects produced four records daily for periods of up to 3 months though fewer than four records were sometimes recorded. In all 35,764 responses were collected from the 219 subjects. The minimum number of responses from a single subject was 8 and the maximum 780 (median 123, mean 163.3).
3. A background survey was also conducted. A questionnaire was sent to all the subjects in the transverse survey sometime during the survey period. This questionnaire collected information about the subjects themselves and their attitude to, and experience of, the building they occupied (453 subjects completed the questionnaire).

2.2. The ESP-r dynamic simulation model

The ESP-r dynamic simulation tool is open source software which is in global use in building design and research. ESP-r has many well developed and validated capabilities and new capabilities are continuing to be developed, validated and released [22,23]. ESP-r allows analysis of many different aspects of building performance either as stand alone investigations or as integrated studies with the different elements dynamically coupled:

- The thermal modelling capability allows investigation of dynamic thermal conditions inside a building in response to variations in climate, occupancy, equipment, ventilation rate and allows the energy requirements for heating and cooling to be quantified.
- The airflow network capability allows ventilation paths and components to be described in detail and their operation and response to climate and controls to be modelled.
- The computational fluid dynamics (CFD) capability within ESP-r allows a very detailed grid to be used for calculation within a space and allows parameters such as air freshness, draught, or local temperature to be established at individual grid points.
- The plant network capability allows plant equipment to be modelled in a range of complexities and includes renewable energy and low carbon technology components.
- The hydronic network capability can be used to analyse wet plant systems.
- The contaminant models can be used to evaluate moisture or pollutant distribution and dispersal characteristics.
- Daylight and lighting analysis is available in ESP-r through the interface to the RADIANCE ray tracing software.
- Thermal comfort model calculations such as predicted percentage of dissatisfied (PPD) and predicted mean vote (PMV) are embedded in ESP-r and can be used to generate comfort metrics and statistics from simulation results.

Many control modes are modelled within ESP-r. Most mimic standard building controls as would be executed by a building management system including proportional control, integral control, on/off control and optimum start control.

Some behavioural control models have been implemented. The Hunt model [24] for the switching on and off of office lighting is implemented in ESP-r. The stochastic Lightswitch 2002 algorithm developed by Reinhart to predict dynamic personal response and control of lights and blinds from field study data and Newsham et al.'s [25] original Lightswitch model is available [26]. Most recently Bourgois et al. developed the SHOCC module to enable sub-hourly occupancy modelling and coupling of behavioural algorithms such as Lightswitch 2002 across the many ESP-r domains [27].