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Occupant movement and the thermal modelling of buildings

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Abstract

Conventional computer models of the thermal transfer processes and energy consumption of buildings treat occupants as little more than fixed metabolic heat generators impassively experiencing the prevailing indoor environment. However, occupants do move around inside spaces and may experience several thermal environments within the same space. The computer model FENESTRA has been developed to include mobile occupants: their thermal comfort and the consequences for energy consumption. The model predicts that a mobile occupant can experience improved thermal comfort compared to an occupant fixed at the centre of the same space. Implications for both the size of cooling plant and thermostat settings for cooling are discussed. Finally, FENESTRA modelling provides testable hypotheses regarding occupant movement within spaces. If such tests were to be performed they could be used to validate and improve the FENESTRA model itself.

Introduction

The use of computer-based mathematical models for the prediction of building element temperatures and building energy consumption is well established. The tendency in model development has been towards increasing complexity of algorithms, so that physical elements and processes can be modelled with greater accuracy. However, a major source of error in prediction, occupants, have largely been ignored. If the variance in model predictions due to occupant behaviour is large, attention to occupant behaviour is likely to yield greater improvements in model accuracy than more complex modelling of physical elements and processes.

Occupants have often been modelled as no more than passive metabolic heat generators. But it is a fact that the energy consumption of identical buildings can vary significantly, and that these differences are largely caused by the occupants of the buildings: their number, their occupancy period, their activities, and the actions they take to secure their comfort during occupancy. Indeed, with regard to energy conservation, there is no point in saving energy at the expense of comfort, as the action that occupants take to secure comfort may be costly in energy use.

One comfort strategy available to the occupant is movement within the space. Modellers have always assumed, implicitly or explicitly, a fixed occupant position, usually at the room centre. But since the thermal conditions can vary spatially [1], rooms actually offer several thermal environments. Occupants often exploit this to improve comfort, by avoiding unwanted direct beam sunlight or 'migrating' toward a radiator when cold. The positioning of a favourite chair may be influenced by a time aggregate of such considerations. The thermal model FENESTRA [2] has been used here to examine the effects on comfort and energy consumption of occupant movement in a space. A rudimentary, comfort-stimulated, movement algorithm is introduced that may point the way to more complete modelling of occupied spaces in the future, and perhaps to energy-saving strategies accessible only through the modelling of such behaviour. It should be stressed, however, that the purpose of this work is not to make recommendations on how people should move within spaces. Rather, it is to introduce and predict the difference, in comfort and energy terms, between the common assumption of modellers (a fixed occupant) and reality (a potentially mobile occupant). If this predicted difference is large then a more comprehensive study, perhaps involving the observation of real behaviour, may be warranted.

Description of the model FENESTRA

FENESTRA [2] is a finite-difference model of a single, south-facing, rectangular plan, direct-gain

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room. Each wall surface is divided into a 3×3 network of nodes (see Fig. 1). All walls are two nodes thick, a surface node and a buried node, except for the south (exterior) wall, which is three nodes thick, for a total of 117 fabric nodes. There is no net heat exchange through the walls to the surrounding space except through the south wall and the floor. The room air volume is divided similarly into 27 (3×3×3) equal volume cells. Each finite time element (timestep) represents 15 minutes of real time.

The room is heated by a radiator at one of the wall node positions. There is no mechanical cooling, but a constant rate of ventilation with outdoor air is assumed. Sunpatch tracking onto walls and occupants is performed. There is also a simple routine for the prediction of air temperature gradients, so that both air and radiant temperature have spatial definition. A vertical air temperature gradient is predicted using a simple method developed by the author [2] that involves examining the location of convective gains/losses to the room air. The room air is divided into three layers vertically. The assumption is made that convective gains to the room air are in the form of warm air that rises to the upper air layer, and that convective losses to the room air are in the form of cool air that sinks to the lower air layer. Air rising from the floor surface and air sinking from the ceiling surface are assumed to be distributed evenly between the three air layers. If there is rising air originating below sinking air (a radiator beneath a window, for example) only the net gain or loss to the room air is assigned to the upper or lower air layer respectively. Then:

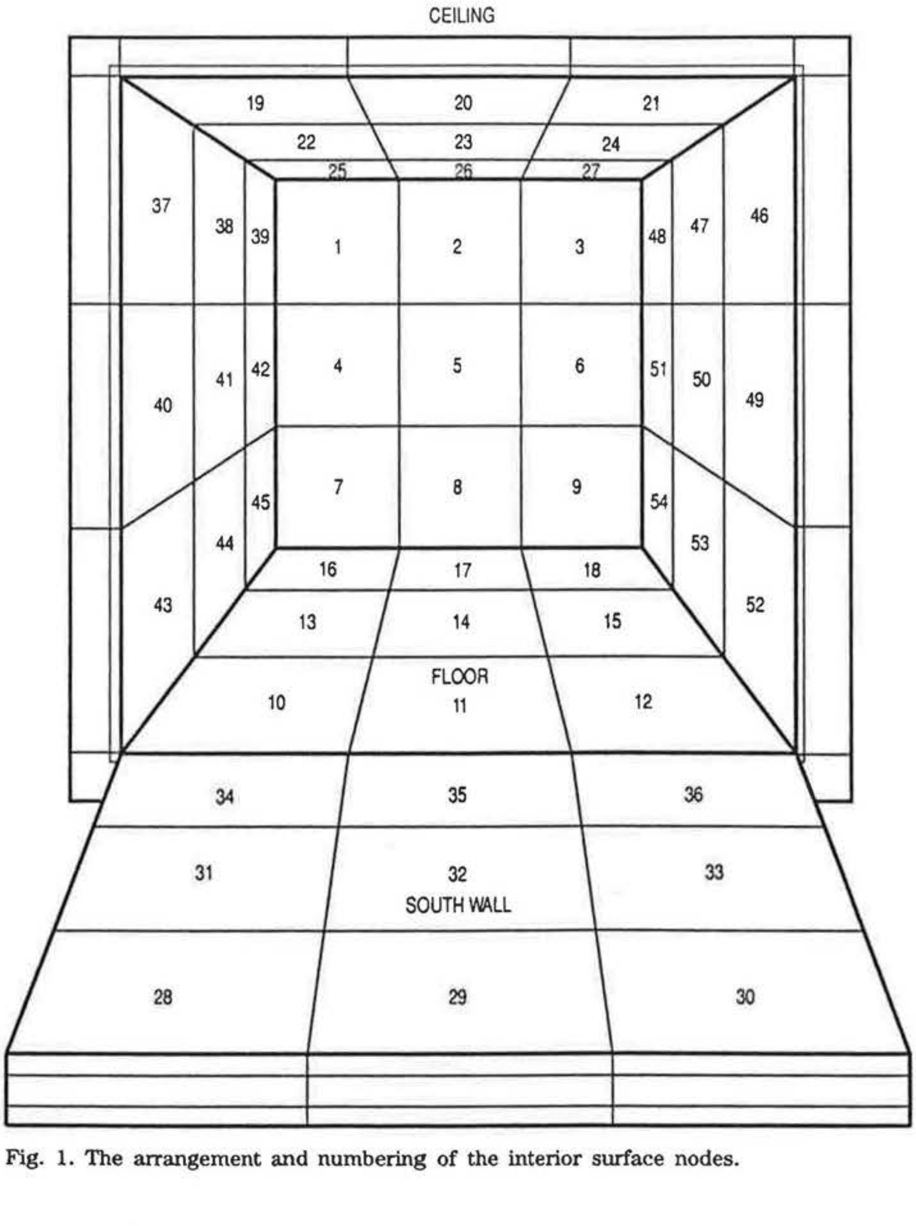

Fig. 1. The arrangement and numbering of the interior surface nodes.

$$\delta = (\Sigma_{\text{upper}} - \Sigma_{\text{lower}})/k_{\text{v}} \qquad (1)$$

where

δ = stratification temperature increment applied to the calculated mean air temperature, $T_{\text{mean air}}$ (°C)

Σ_{upper} = sum of gains to the room air accumulated in the upper air layer (J)

Σ_{lower} = sum of losses to the room air accumulated in the lower air layer (J)

k_{v} = empirically derived constant with units of capacitance (J °C^{-1}).

Then, for the three vertical air layers:

$$T_{\text{upper}} = T_{\text{mean air}} + \delta \qquad (2a)$$

$$T_{\text{middle}} = T_{\text{mean air}} \qquad (2b)$$

$$T_{\text{lower}} = T_{\text{mean air}} - \delta \qquad (2c)$$

so that the overall thermal balance is maintained.

A similar process is followed for horizontal air temperature gradients, both north–south and east–west. However, there is no simple buoyancy-driven principle to the horizontal airflow. Gains and losses to the room air, though rising and falling as above, are assumed to stay in the vicinity of their source. For horizontal gradients a different constant, k_{h}, is employed. This simplistic temperature gradient routine has been shown to work satisfactorily for panel heat sources in domestic-sized rooms with the coefficients $k_{\text{v}} = 4 \times 10^5$ J °C^{-1} and $k_{\text{h}} = 8 \times 10^5$ J °C^{-1} [2]. The physical significance of k_{v} and k_{h} has yet to be established.

FENESTRA also incorporates a simple daylighting model [3] which calculates the daylight factors (the ratio of indoor illuminance to outdoor illuminance) on a notional horizontal surface at the centre of the air cells. A uniform sky approximation is adopted for the purposes of daylight calculations, although a direct beam component to the daylight factor is included [2]. From the calculated daylight level, necessary artificial lighting and resulting lighting thermal gains are calculated.

Central to this study is the prediction of comfort within a space. Human comfort is determined by many factors, physiological, psychological and illogical. The comfort calculations made by FENESTRA are purely thermal, and simplified. The assumption is made that air speed in the space is close to zero, and that humidity is in the range 30–70%, such that for the conditions prevailing in the space during these simulations the effect of both on thermal comfort is negligible. Therefore:

$$T_{\text{h}} = 0.54T_{\text{air}} + 0.46T_{\text{mrt}} + \beta \quad [4] \qquad (3)$$

$$T_{\text{pref}} = 20.5 + 0.1T_{\text{h}} \quad [5] \qquad (4)$$

$$\text{PPD} = 2(T_{\text{h}} - T_{\text{pref}})^2 + 5dT^2 + 5 \quad [5] \qquad (5)$$

where

T_{h} = temperature 'sensed' by a human being (°C); T_{air} = local air temperature (°C); T_{mrt} = local mean radiant temperature (°C); β = increase in radiant temperature due to direct beam radiation on the occupant (°C); T_{pref} = preferred value of T_{h} (°C); PPD = predicted percentage dissatisfied, the percentage of people unhappy with the prevailing thermal conditions (%); dT = change in T_{h} from one timestep to the next, assuming that a change in temperature is uncomfortable (if only because of 'bother') (°C).

Implicit in eqn. (4) is the notion that clothing and metabolic rate are functions of temperature, i.e., the hotter it gets the less clothing one will wear, and the less vigorous one's activity will be. Therefore preferred temperature is reduced to a function of prevailing temperature (a similar relationship was observed by Peterson and W-Dafgard [6]). This simplified approach avoids the need to define a clothing and metabolic rate at each timestep, as one would have to do if one were using Fanger-type equations [7]. However, having arrived at a preferred temperature, an equation based on Fanger's formulation of PPD is used (eqn. (5)), as PPD is a convenient and clearly understood unit of comfort.

The modelled room

The room modelled in these studies had the following characteristics:

site: south-east England

horizon: 19° (sun's altitude must be greater than this angle to be above obstructions)

room dimensions: 4 m×6 m×2.4 m

construction: high mass (23 MJ °C^{-1}), solid floor

U-value south wall = 0.30 W m^{-2} °C^{-1}

U-value floor = 0.42 W m^{-2} °C^{-1}

glazing: 33% of the south wall in a central horizontal slot, double glazed

overhang: none

shades: nighttime insulating shutters

occupancy: 06:00–24:00

observer position: the most comfortable

thermostat: active during occupancy only

  sensed temperature: $T_{\text{mean air}}$

  target temperature: 18–26 °C

bandwidth: ±1 °C
radiator: on south wall at lower east corner (node 36)
boiler fuel: natural gas
design light level: 150 lux (at the centre of the room on a horizontal plane 1.2 m above the floor) when occupied
lighting: 60 W incandescent lamps (maximum of 180 W), with the assumption that their illuminance is evenly distributed around the room
ventilation rate: 0.75 ach
internal gains: 250 W (metabolic heat and occupancy-related gains, e.g., TV) when occupied.

Runs were performed over climate data from the climate dataset for Kew, UK, 1967, consisting of three days per month: an average day (judged by temperature and sunshine), an above-average day, and a below-average day. At each timestep, the PPD at each of the nine positions in the horizontal plane (see Fig. 2), 1.2 m above the floor, was calculated. The position with the lowest PPD was adopted as the occupant position for that timestep. Lighting was assumed to be unaffected by occupant position.

The heating system target temperature was varied in the range 18–26 °C. Although the limits of this range may not represent reasonable settings in most circumstances, they are used to deliberately underheat and overheat the space beyond any underheating and overheating induced by the outdoor climate (Kew data). Thus, the effectiveness of mobile occupants in reducing discomfort in climates other than that represented by the Kew data could be examined.

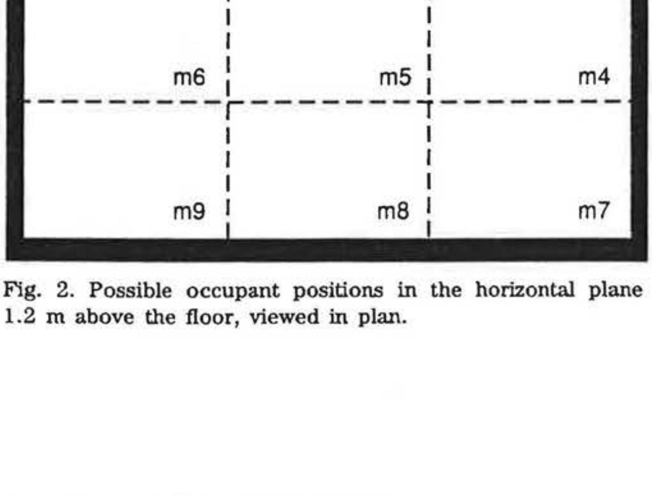

Fig. 2. Possible occupant positions in the horizontal plane 1.2 m above the floor, viewed in plan.

Results

Predicted annual energy consumption for the space is shown in Fig. 3; since the thermostat responds to mean air temperature only the energy consumption is independent of occupant movement strategy. Below a thermostat setting of 24 °C, lighting forms the greater part of the total energy consumption.

ISO standard 7730 [8] recommends that an indoor thermal environment be acceptable to at least 80% of occupants (PPD < 20%). In these terms, the comfort advantage that the mobile occupant has is clearly shown in Fig. 4. In both underheated and overheated cases the mobile occupant experiences less discomfort than the fixed occupant. The mobile occupant can avoid overheating by dodging direct radiation and sunpatches, and can avoid underheating by seeking out direct radiation, sunpatches or the panel radiator. The air temperature at which the fewest hours of thermal discomfort occur is a function of the comfort equation adopted (eqns.

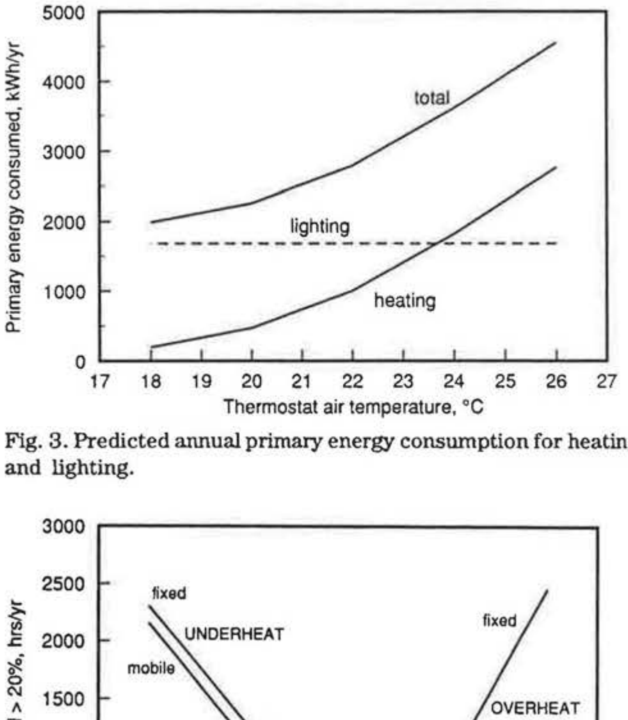

Fig. 3. Predicted annual primary energy consumption for heating and lighting.

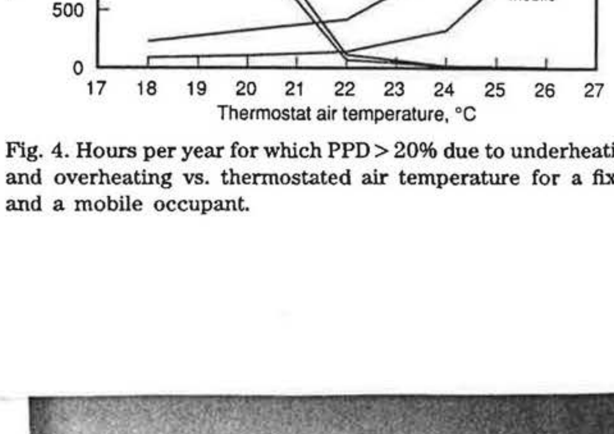

Fig. 4. Hours per year for which PPD > 20% due to underheating and overheating vs. thermostated air temperature for a fixed and a mobile occupant.

(3)–(5), and is in this case 22 °C. At this temperature, the model predicts that fixed occupants experience 420 h/yr for which PPD > 20% due to overheating ($PPD_{20}{}^{+}$) compared to 140 h/yr for mobile occupants; and 114 h/yr for which PPD > 20% due to underheating ($PPD_{20}{}^{-}$) compared to 70 h/yr for mobile occupants*.

These initial predictions support the hypothesis that the mobile occupant is more adept at avoiding overheating than underheating. This may be because the radiator is positioned on the south wall, beneath the window. This is the usual desired position as, in opposing any cold downdraught from the window surface, the radiator output reduces air temperature gradients within the space. However, this also means that the variety of thermal conditions accessible to the occupant is reduced; on a cold day one would expect the occupant to get as close as possible to the radiator, but this also means getting close to the cold window surface. In addition, change in temperature is defined in eqn. (5) as an undesirable aspect of the thermal environment; changes in temperature local to the radiator may on occasion be high due to heating system cycling.

Temperature shift

To express the benefits of the mobile occupant in more familiar terms, the notion of a 'temperature shift' (τ) can be employed. τ is the difference between the thermostated mean room air temperatures resulting in a given level of discomfort for the fixed and the mobile occupant. For example, fixed occupants experience $PPD_{20}{}^{-} = 1000$ h/yr (in the particular room modelled and for the particular climate used) at a thermostated mean room air temperature of 20.4 °C. The thermostat setting resulting in the same degree of underheating for mobile occupants is 20.2 °C (see Fig. 5); $\tau = 0.2$ °C. τ is much greater when the thermostat temperatures resulting in $PPD_{20}{}^{+} = 1000$ h/yr are calculated. For a fixed occupant the thermostated mean room air temperature must be 24.2 °C for this level of overheating, for the mobile occupant the thermostat setting must be 25.7 °C (see Fig. 6); $\tau = 1.5$ °C.

Predicted movement

Figures 7 and 8 show the positions of lowest PPD predicted by the model to be adopted by the mobile occupant on two particular days. The results for three heating regimes (thermostat setpoints) are presented. Most comfortable positions are generally occupied for lengthy periods of time, typically several hours (these featured days actually showed more movement than most). This is in part due to the definition of the comfort equations which dictate that temperature changes, including those experienced in moving from one location to another, cause some discomfort. This seems reasonable, the 'bother' of moving is an important practical obstacle to the occupant with flexibility of position. Thus, the amount of movement demanded to obtain the benefits outlined above would not be unreasonable in the real world. Incidentally, there is no single position that is most comfortable all day – merely fixing the occupant position somewhere other than the room centre is not an optimum solution.

Day 44, a cold but sunny day in February, serves as an excellent example of the mobile occupant's

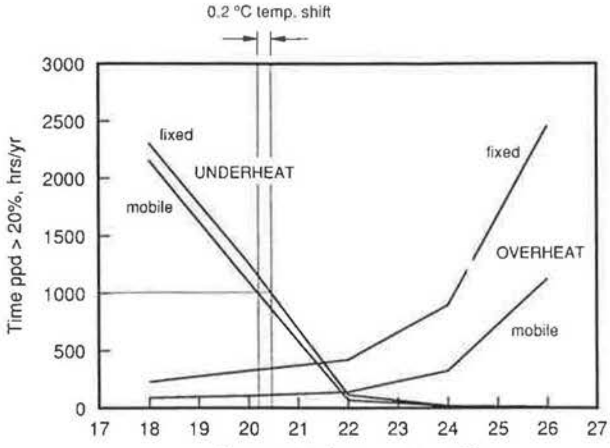

Fig. 5. Calculation of the temperature shift for 1000 h/yr for which PPD > 20% due to underheating.

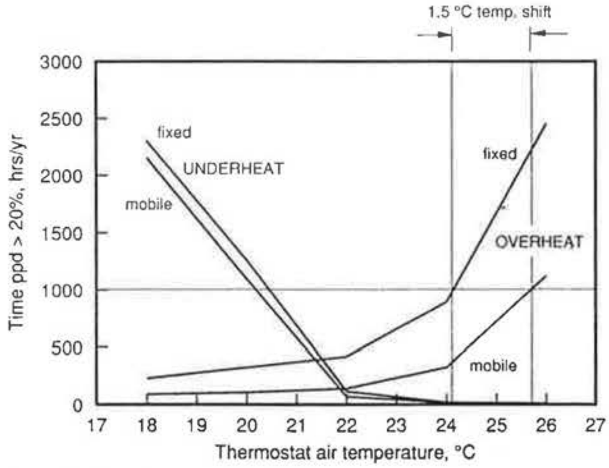

Fig. 6. Calculation of the temperature shift for 1000 h/yr for which PPD > 20% due to overheating.

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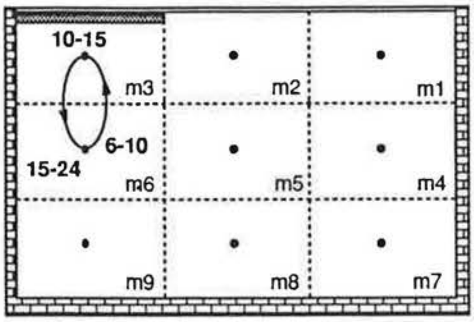
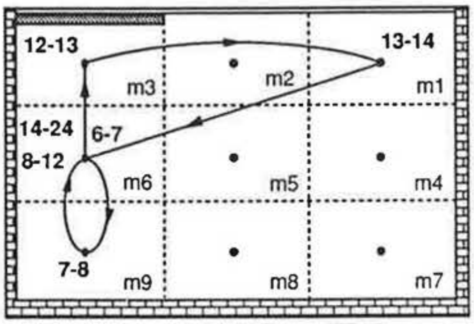
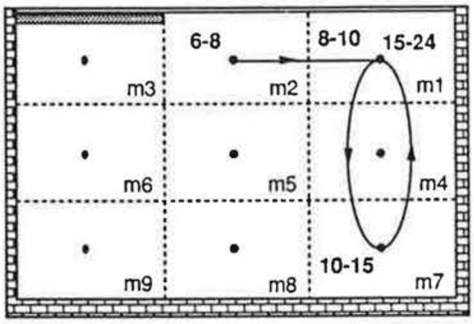
*Some underheating is experienced even at the higher thermostat settings; this is primarily because the period for which the thermostat is active is defined as being the same as the occupancy period, so that warm-up takes place during occupied hours.



thermostat = 18°C

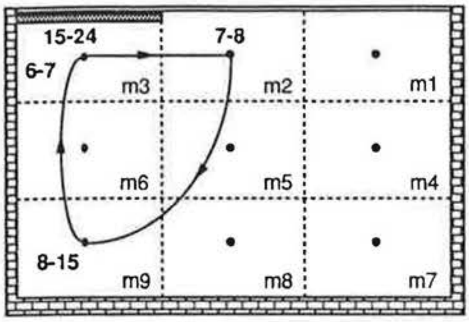


thermostat = 22°C

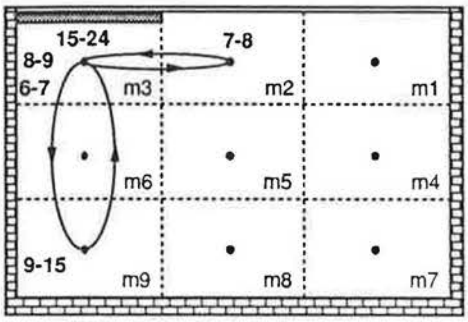


thermostat = 26°C

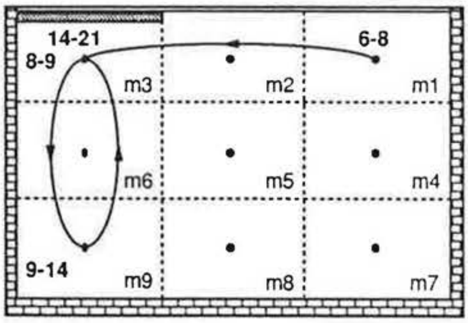
Fig. 7. Positions of the mobile occupant for three thermostat settings on day 44. The bold numbers indicate the hours for which that position was occupied.



thermostat = 18°C



thermostat = 22°C



thermostat = 26°C

Fig. 8. Positions of the mobile occupant for three thermostat settings on day 270. The bold numbers indicate the hours for which that position was occupied.

predicted reaction to thermal conditions (Fig. 7). In the underheated case (thermostat setting = 18 °C) the occupant seeks the warmest parts of the room. During the early morning and evening this is position m6, opposite the radiator but not too close to the cold window. From mid-morning to mid-afternoon the occupant moves to position m3, next to the radiator and exposed to direct sunlight. In the overheated case (thermostat setting = 26 °C) the occupant seeks the coolest parts of the room for optimum comfort, the situation is the reverse of that in the underheated room and this is reflected in the occupant movement. During the morning and evening the favoured positions are m1 and m2, close to the cold window surface. From mid-morning to mid-afternoon the occupant moves back to position m7, avoiding the sun and the radiator. For a more normal thermostat setting of 22 °C the movement of the occupant is, as might be expected, somewhere in between the two previous cases.

On day 270, a warm and sunny day in August, the room overheats no matter what the heating regime, only the degree of overheating varies (Fig. 8). The occupant behaves in a similar way for all three of the featured thermostat settings. During the early morning and evening, the favoured positions are m1, m2 and m3, close to the cool window surface. From mid-morning to mid-afternoon the occupant retires to position m9, avoiding direct sunlight. The success of the mobile occupant in achieving comfort on days 44 and 270 in comparison with the occupant fixed at the room centre is displayed in Table 1.

TABLE 1. Hours per day for which PPD > 20% for three thermostat settings on days 44 and 270 for both the fixed and mobile occupant. + indicates overheating and − indicates underheating

	Thermostat setting and associated discomfort (h/day PPD > 20%)					
	Fixed	Mobile	Fixed	Mobile	Fixed	Mobile
Day 44	17.6 −	16.0 −	1.2 −	0.5 −	3.2 +	0.0 +
Day 270	6.2 +	3.2 +	7.5 +	4.2 +	16.0 +	11.5 +

Discussion

Obviously, the extent to which an occupant has freedom to move depends on the situation they are in and their interaction with other individuals. Only the extremes have been modelled here: an occupant who is rigidly fixed in position and an occupant who is completely free and willing to move with the goal of securing optimum thermal comfort. Any real occupant of a real room will be somewhere between these two extremes. Actually encouraging movement as a strategy to improve thermal comfort is particularly desirable because it carries no energy penalty. But encouraging movement is not always realistic; in an office, for example, movement to a more thermally comfortable location could take the occupant away from phone, computer, files, etc. A next step would be to put limitations on the number or spatial location of alternate positions offered to occupants by the model. This would simulate spaces in which the occupant is not completely free to move.

Although the room modelled in this study was a 'generic' room, it has been shown that the effect of occupant movement on model predictions can be significant. Specifically, the reduction in overheated hours for mobile occupants compared to fixed occupants has potentially large implications for the mechanical cooling of buildings: mobile occupants would need less cooling. Current calculations of required cooling plant are made assuming a fixed occupant, but this study shows that real occupants with some mobility can experience a variety of thermal conditions within a space. Thus, cooler parts of the space can be occupied during periods of overheating. Therefore, more freedom of movement results in higher setpoints for cooling plant activation, thus delaying or avoiding the need for mechanical cooling and resulting in energy savings (FENESTRA does not calculate cooling energy at present so the amount of saving is not estimated here). This prediction will be tested at a later date on a room more characteristic of an office, with cooling plant modelled.

The impact of occupant behaviour on the energy consumption of a space is not simply limited to movement. For example, occupants can often adjust lighting, ventilation and shading to make themselves more comfortable. Daylighting strategies could be investigated using FENESTRA by introducing an algorithm for the manual control of artificial lighting. Similarly, shading and ventilation strategies could be investigated by introducing algorithms for the manual control of shading and ventilation (a preliminary study into the manual control of shading and ventilation was carried out [2]. Some observations of human behaviour and the manual control of artificial lighting [9, 10], shading [11–13] and ventilation [14–17] have already been made.

Ideally, it would be desirable to define, as far as possible, real behavioural algorithms from observed behaviour. Occupant movement within a space could be studied by time-lapse photography techniques, and correlated with measurable environmental conditions. Through such observations the algorithms used by FENESTRA can be refined and validated, and the accuracy/utility of modelling techniques would be improved.

Conclusion

By implementing a simple behavioural model, FENESTRA predicts mobile occupants will be more comfortable than occupants who remain fixed in the centre of a space. The number of overheated hours/year experienced by a mobile occupant can be cut in half, and the number of underheated hours/year can also be reduced. This suggests that thermal models which attempt to calculate building energy consumption on the basis of human comfort in a space may overestimate energy consumption if they do not account for occupant mobility.

The results presented here are significant enough to warrant further study of the mobile occupant's impact on building thermal modelling. It seems likely that more detailed modelling of other building-related human behaviour (lighting, ventilation, shading, etc.) will yield similarly significant results.

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Nomenclature

$T_{\text{mean air}}$	calculated mean air temperature (°C)
δ	stratification temperature increment (°C)
Σ_{upper}	sum of gains to the room air accumulated in the upper air layer (J)
Σ_{lower}	sum of losses to the room air accumulated in the lower air layer (J)
k_{v}	vertical stratification constant (J °C^{-1})
k_{h}	horizontal stratification constant (J °C^{-1})
T_{upper}	air temperature in the upper air layer (°C)
T_{middle}	air temperature in the middle air layer (°C)
T_{lower}	air temperature in the lower air layer (°C)
T_{h}	temperature 'sensed' by a human being (°C)
T_{air}	local air temperature (°C)
T_{mrt}	local mean radiant temperature (°C)
β	increase in radiant temperature due to direct beam radiation on the occupant (°C)
T_{pref}	preferred value of T_{h} (°C)
PPD	predicted percentage dissatisfied, the percentage of people unhappy with the thermal conditions (%)
dT	change in T_{h} from one timestep to the next (°C)
$\mathrm{PPD}_{20}{}^{+}$	time for which PPD > 20% due to overheating (h/yr)
$\mathrm{PPD}_{20}{}^{-}$	time for which PPD > 20% due to underheating (h/yr)
τ	temperature shift (°C)

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