Considering the impact of situation-specific motivations and constraints in the design of naturally ventilated and hybrid buildings

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Abstract

A simple logical model of the interaction between a building and its occupants is presented based on the principle that if free to do so, people will adjust their posture, clothing or available building controls (windows, blinds, doors, fans, and thermostats) with the aim of achieving or restoring comfort and reducing discomfort. These adjustments are related to building design in two ways: first the freedom to adjust depends on the availability and ease-of-use of control options; second the use of controls affects building comfort and energy performance. Hence it is essential that these interactions are considered in the design process. The model captures occupant use of controls in response to thermal stimuli (too warm, too cold etc.) and non-thermal stimuli (e.g. desire for fresh air). The situation-specific motivations and constraints on control use are represented through trigger temperatures at which control actions occur, motivations are included as negative constraints and incorporated into a single constraint value describing the specifics of each situation. The values of constraints are quantified for a range of existing buildings in Europe and Pakistan. The integration of the model within a design flow is proposed and the impact of different levels of constraints demonstrated. It is proposed that to minimise energy use and maximise comfort in naturally ventilated and hybrid buildings the designer should take the following steps: 1. Provide unconstrained low energy adaptive control options where possible, 2. Avoid problems with indoor air quality which provide motivations for excessive ventilation rates, 3. Incorporate situation-specific adaptive behaviour of occupants in design simulations, 4. Analyse the robustness of designs against variations in patterns of use and climate, and 5. Incorporate appropriate comfort standards into the operational building controls (e.g. BEMS).

Keywords

Thermal comfort; Constraints; Window; Fan; Adaptive algorithm; Behaviour; Simulation; Natural ventilation; Hybrid ventilation.

1. Introduction

How occupants exercise control over their indoor environment is a topic of current research (see e.g. Nicol and Humphreys 2004; Yun and Steemers 2007; Yun et al. 2009; Robinson and Haldi 2008; Haldi and Robinson 2010). For reliable design of naturally ventilated buildings a realistic model of human behaviour is needed, and its parameters must be representative of, and supplied by, studies of people in everyday life. This paper presents such a model and describes its relevance to the Architectural design process. The intent here is to give a more Architectural focus to material previously presented in building engineering and building simulation contexts[1].

We have previously developed several algorithms describing occupant behaviour, and implemented them in building dynamic simulation (see e.g. Rijal et al. 2007; 2008b). The procedure we have used to capture human adaptive behaviour is to construct a simple model, and then increase

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[1] For a fuller version of this paper for software engineering see Rijal et al. (2011).

its realism step by step until it usefully portrays daily life. A new development described here is the use of ‘constraints’ to represent the specific circumstances of the building. These constraints are used to quantify the accessibility, usability and desirability of available controls, and to incorporate any non thermal benefits or adverse effects that may be associated with the use of a particular control (e.g. noise, air pollution or security risk). The model is initially applied to environmental control using window opening to achieve cooling through natural ventilation, and is then extended to cover the use of ceiling fans. Further extension to night ventilation, heating systems and mechanical cooling devices is proposed.

The basic principles of using fans and windows to secure thermal comfort appear similar in different parts of the world. For example when people are uncomfortably warm and windows or fans can provide some benefit, then people will in general attempt to achieve some benefit by using the windows or fans; when people are uncomfortably cool and changing the settings of windows or fans can supply some benefit then people will in general attempt to improve comfort by changing those settings.

The temperature variation above and below the ‘comfort temperature’ is then a useful metric on which to base algorithms describing the operation of windows and fans. However, people are not always free to open windows. It may be that the outdoor air quality is poor, or that the environs of the building are noisy or dusty, or there may be security risks or privacy concerns. In such cases there is some degree of constraint acting on the opening of the window. If people open windows, it may not be until their thermal discomfort outweighs the inconveniences caused by opening them. Conversely people may have non thermal motivations to open windows (e.g. poor indoor air quality) and may open windows without experiencing warm thermal discomfort or may even tolerate cool thermal discomfort to some extent. It is convenient to represent such non-thermal motivation as a ‘negative’ constraint.

From the perspective of thermal modelling, it is necessary to quantify such constraints if we are to predict whether the building will afford a comfortable environment for its occupants and how much energy will be consumed to maintain this environment. It is not to be expected that there will be a fixed level of constraint. The magnitude of a constraint will be situation specific and depend on the buildings surroundings and also the specific design and location of the operating mechanisms of the controls.

In this paper we describe the comfort based model incorporating constraints and then quantify the values of constraints for the buildings for which we have survey data. Building by building analysis is presented that identifies and quantifies the constraints on window and fan use for the surveyed buildings – that is to say: for each building, by how much must the room temperature differ from the comfort temperature before each control is used? The procedure for quantification of constraints is explained as the calculations are presented. The resulting list shows the extent of the variation in constraints found, and illustrates very different behaviours in different buildings.

The incorporation of the new model including the situation specific constraints into building simulation code is demonstrated. The application of the model in a building performance analysis or in a building design context is also discussed.

It is proposed that to minimise energy use and maximise comfort in naturally ventilated or hybrid buildings the designer should take the following steps: 1. Provide unconstrained low energy adaptive control options where possible to minimise energy used in mechanical heating and cooling, 2. Avoid possible problems which provide motivations for excessive ventilation rates and associated energy use e.g. with indoor air quality, 3. Take account of situation-specific constraints and the associated comfort and behaviour of occupants in design simulations, 4. Analyse the robustness of designs against probable variations in patterns of use and climate and ensure that the building is robust or that limitations in use are communicated to building occupiers, and 5. Incorporate appropriate comfort standards into the operational building controls (e.g. BEMS) so that the extent of periods of free running operation are maximised.

Research into the behaviours is proceeding in parallel with the development of methods for incorporating these behaviours in building simulation. What we present here is intended to provide some necessary steps towards the goal of comprehending and quantifying human comfort and behaviour in building performance analysis and hopefully useful insights intended to assist in successful design and operation of comfortable low energy buildings.

2. The logical basis of the occupant behavioural model

2.1 The consistent occupant

People avoid discomfort if they can, and among the actions they take are opening and closing windows. The assumptions for the simplest case are as follows: the occupant's thermal-comfort perception is consistent; the occupant is free to open or close the window; the window is easy to operate; opening the window cools the room; there is no non-thermal reason to open or close the window.

(Fig. 1 Near here)

A consistent person would always become uncomfortably warm at the same room-temperature (t_{warm}), and always uncomfortably cool at the same (lower) room-temperature (t_{cool}) (see Fig. 1). We call these the 'trigger-temperatures', for at these temperatures the occupant would take action to restore comfort. Between the two trigger-temperatures is the comfort-zone, and the temperature at its centre may be taken to be the optimum room-temperature – we shall call it the 'comfort-temperature' (t_{comf}).

If the room-temperature is above the warm trigger-temperature t_{warm} the consistent occupant will always be uncomfortably warm and so the window will always be open. If the room temperature is below the cool trigger-temperature t_{cool} the occupant will always be uncomfortably cool and the window always closed. Between the two trigger-temperatures the person will be comfortable, and the window might be either open or closed; for if it were open there would be no need to close it, while if it were closed there would be no need to open it.

2.2 Introducing human variability

We next build into the model human variability. Consider an office block occupied by numerous people, each in a cellular office with an openable window. Suppose it is cold, and no windows are open. If the indoor temperature gradually rises, the proportion of occupants becoming too warm would increase. These people would open their window. This is represented by the ascending curve on the right of Fig. 2. It is the proportion of people who are warmer than they would like to be, and so have opened the window. The curve represents the conditional probability that the window would be opened, had it been closed. Now suppose it is hot and all the windows are open. If the indoor temperature then gradually cools, the proportion of windows open at first remains unchanged, and then, as people begin to feel uncomfortably cool, it will fall steadily from unity to zero. This is the descending curve on the left. It is the conditional probability that the window, being open, would remain so.

(Fig. 2 Near here)

The temperature-displacement between the curves is the width of the comfort-zone for the median occupant, and the centre of the zone at the 0.5 probability level is the median occupant's comfort-temperature. The points where the curves cross the 0.5 probability level are the trigger-temperatures for the median occupant.

What happens if the room-temperature varies in a less regular manner? Let the room-temperature gradually rise from a cold start until the proportion of windows open has risen (on the right-hand curve) till it was, say, 0.5 (Fig. 3). If the room-temperature were then to fall, the proportion of the windows open would remain unchanged, for those who had already opened them would not need to close them, and those who had not yet opened them would have no need to do so. However, when the falling temperature reached the value for the 0.5 level on the left-hand curve, the proportion would then fall according to that curve. This argument applies to any chosen proportion of windows open, so the proportion open has a strong tendency to stay the same when the direction of temperature-change reverses, giving a 'horizontal grain' to the observations falling within the loop. Rising and falling room-temperatures of differing extents over many days will result in spot observations of the proportion of windows open eventually 'filling in' the entire zone between the two curves[2].

(Fig. 3 Near here)

2.3 The single occupant: random variation

Consider a single occupant who does not respond consistently to the thermal environment. The comfort-temperature varies from time to time, and so the trigger-temperature correspondingly varies. A figure similar to Fig. 3 may therefore be drawn for a single occupant. The vertical axis would then be the *probability* that the window would be open.

2.4 Extending the model to include other control actions

It is important to notice that the trigger-temperatures, corresponding as they do to the onset of thermal discomfort, apply not only to windows but also to *any control action that could be freely used*, such as blinds, thermostats, fans or clothing.

It should be noticed that some of these actions – removing a garment or switching on a fan – change the comfort-temperature. Consider the median occupant who has a fan. It will be switched on when the warm trigger-temperature is reached. But because the fan increases the air speed in the room, the comfort-temperature is raised by two or three degrees, and so are both trigger-temperatures (Fig. 4). If the room were then to cool down, the fan would be turned off when the person became too cool. This would occur at the *new* 'too cool' trigger-temperature, two or three degrees higher than the original one. Identical considerations apply to the removal of a layer of clothing.

(Fig. 4 Near here)

2.5 Use of controls in the presence of constraints

If the various controls were equally effective and easy to use, they would all be equally likely to be used. In practice which control the occupant uses depends on its ease of use, its effectiveness, and the likelihood of undesirable consequences. For example, opening a window is less likely if it is difficult, ineffective, causes papers to be disturbed, or allows in rain, noise, dust or pollution.

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[2] The model is analogous to the hysteresis loop of a magnetic material, and to the method of deriving thermal comfort data from the clothing behaviour of schoolchildren (Humphreys 1973) and to Hunt's model for the switching of lights in offices (Hunt 1979).

A universally applicable ‘hierarchy’ of use of the various controls is not to be expected, since the likelihood of any particular control being used would depend on the design of the control, on the outdoor environment and also on social circumstances such as dress codes.

Dress codes may impose constraints on the occupants’ adaptation to their thermal environment, and tend to increase the probabilities of discomfort. The *circumstance* of having a dress-code for the workplace introduces a restriction or *constraint* on the occupants’ choice of clothing (see Humphreys and Nicol 1998 for a more extensive discussion). During research into school-children’s summertime comfort a school was found where the girls disliked their summer-uniform dress. As a result they tended to wear the warmer winter dress, and they tolerated some three degrees of heat-stress before they adopted their summer uniform. Thus the constraint on their behaviour (due to fashion) could be translated into a temperature-difference of some three degrees (Humphreys 1973).

It should be noticed that cost can be a powerful constraint. If heating is costly, people may tolerate some cold discomfort before considering turning on their heating.

(Fig. 5 Near here)

Constraints need not be symmetrical in their action. If a window were difficult to open but easy to close, there would be a constraint on opening but not on closing. If the constraint on opening a window arose from traffic noise, there would be a motivation to close the window before it had become necessary for avoiding cold discomfort. A constraint may also vary with time of day – traffic noise and fumes might be a problem only during rush hours.

If each control were associated with a different degree of constraint, each would have a response-curve displaced by a different amount from the comfort-predicted trigger-temperature (Fig. 5). The displacements could be either positive or negative and vary from very small to indefinitely large. At or above a particular trigger-temperature each of the controls could therefore have a different probability of being used. More than one control action could occur - if an office were very hot when people arrived at work in the morning, opening the window and turning on the fan could both be highly probable actions.

For the comfort of the occupant, there should be enough effective controls that are free from constraint. Thus if window opening were constrained by the location of the building low constraint effective controls would need to be provided.

Energy could be conserved by applying constraints to control-actions that resulted in high energy consumption, provided there were other effective controls that were free from constraint.

Constraints could become a very flexible way of encouraging some actions and discouraging others. For example some accessible secure window-openings could be designed to have a lower constraint than other windows, and so encourage their use. The use of constraints could be extended to depend on parameters such as air quality, occupancy, or degree of over-heating on previous days, which could be useful in the context of window opening on arrival or window-opening for night-time cooling etc. Constraints therefore could be used in modelling to represent behaviour based on non-thermal factors other than thermal comfort.

2.6 Systematic variation of comfort-temperature

We have already incorporated into the model random variations of the comfort-temperature, and noticed that some controls alter the median comfort-temperature. The median comfort-temperature is the ‘anchor’ of the model, and the control-response arises from the departure of the room-temperature from this central anchor-point. So if the median comfort-temperature undergoes a systematic change, the effect is to shift the whole figure to the right or to the left according to the size and direction of this temperature change. In order to apply the model to thermal simulation it is therefore necessary to estimate the current comfort-temperature.

The probable comfort-temperature may be estimated from the prevailing outdoor temperature together with knowledge of the mode of operation of the building (heated, cooled, free-running) (see Humphreys 1978; de Dear and Brager 1998, Humphreys et al. 2010). ASHRAE Standard 55-2004 (Fig. 5.3 in the Standard) relates the indoor comfort temperature to the monthly mean of the outdoor temperature. The CIBSE Guide provides lines relating the indoor comfort temperature to an exponentially-weighted running-mean of the outdoor temperature (CIBSE 2006). Similar lines are found in European Standard EN 15251:2007 (CEN 2007). The seasonal change in comfort temperature in these standards incorporates average seasonal variations in clothing and in air speed. Alternative comfort temperature estimation using thermal physiological model such as the PMV/PPD system has been found to give comfort temperatures that deviate from those observed in naturally conditioned buildings.

3. Developing the adaptive algorithm from field observations

3.1. Field data-bases

We have available three main sets of data: the UK data, the European data (SCATs: Smart Controls and Thermal Comfort) and the Pakistan data. We use these to obtain parameters and to quantify relationships required by the model.

The UK data were collected in Oxford and Aberdeen and the database has some 36,000 records from 15 buildings. The records include a comfort evaluation on the ASHRAE scale, a record of the use of fans and windows, a list of the clothing worn, and a note of the level of activity. There was a corresponding record of the room temperature, obtained from a data-logger at the work-station. Respondents provided information up to four times during the working day. The data are ‘longitudinal’ – respondents provided repeated estimates over a period of time, varying from a few days to some months according to their willingness to continue. In all we have records from 219 respondents. A fuller description can be found in Raja et al. (2001) and Rijal et al. (2007).

The SCATs data were collected over a year-long period in a similar manner, in five European countries (France, Greece, Portugal, Sweden, UK). For this study we are using the data from the ‘longitudinal’ aspect of the project. This has over 28,000 records from respondents in 26 buildings. In all we have records from 127 respondents. A fuller description can be found in McCartney and Nicol (2002) and Rijal et al. (2009).

The Pakistan data were collected in five cities (Islamabad, Karachi, Multan, Quetta, Saidu-Sherif) each in a different climatic zone of Pakistan. The research design was transverse. Each building was visited once a month for a year, and each month all available respondents gave replies to a questionnaire (Bedford scale), and thermal measurements were made at their work-stations. There are 7,105 records from 33 buildings, and 846 respondents in total. A fuller description can be found in Nicol et al. (1999) and Rijal et al. (2008b).

3.2 Construction of the algorithm from field data analysis

3.2.1 The comfort temperature

The adaptive comfort temperature is related to the outdoor temperature (McCartney and Nicol 2002). The following equations enable the temperature most likely to be thermally neutral in the building to be estimated from the recent history of the daily mean outdoor temperature. For the

UK and Europe the following equations are adopted in EU standard EN15251, similar but not identical standards have been adopted by ASHRAE.

$$T_{comf}=0.33T_{rm}+18.8\ (T_{rm}>10^{o}\mathrm{C}) \qquad (1)$$

$$T_{comf}=0.09T_{rm}+22.6\ (T_{rm}\leq 10^{o}\mathrm{C}) \qquad (2)$$

The derivation of these equations for Standard EN15251 is set out fully in Nicol and Humphreys (2010). T_{rm} is the exponentally weighted running mean outdoor temperature for the day (CIBSE 2006). T_{comf}, the comfort temperature, was estimated by Griffiths' method, assuming a regression coefficient 0.5 votes/K of indoor operative temperature (Griffiths 1990; Nicol et al. 1994; Rijal et al. 2008b; Humphreys et al. 2010). Equation 1 is for the 'free-running' mode – no heating or cooling in operation. Equation 2 applies when the heating is in operation.

The EU standard in common with others introduces a modification to the comfort temperatures where air movement is raised for example by the use of fans. The EU standard increases the upper comfort limits by around 3K when the air speed is increased from less than 0.1 m/s to 1 m/s.

In the Pakistan database there were sufficient data to allow thermally neutral temperatures to be established for both the fan-on and the fan-off conditions. The EU and Pakistan data agree in attributing an effect of up to about 3K to the use of fans. In the Pakistan analysis, the increase in neutral temperature due to fans is seen to be $0.07{*}T_{rm}$ (K) and we have used this value in our model.

The comfort temperatures we use in the model for Europe are plotted in Fig. 6, for both the fan off and fan on conditions. It is based on equations 1 and 2, together with the fan relationship from the Pakistan analysis ($0.07{*}T_{rm}$). The discontinuity at running mean temperature of 10°C represents the transition between the heating (equation 2) and the non heating (equation 1) season (EU survey data suggests that heating is on for $T_{rm} \leq 10$°C and that occupants' neutral temperature increases in response to the heated indoor environment).

(Fig. 6 Near here)

3.2.2 Probability of window opening and fan use in relation to the comfort temperature

To investigate the manner of variation of the probability during occupied periods that the window will be open or the fan on it was helpful to group the data to obtain these 'binned' data-points the data were sorted by building and then by the temperature departure from the comfort temperature (Δt). These probabilities were plotted as scatter diagrams (Fig. 7). As expected from the underlying model (Humphreys et al. 2008), the horizontal scatter of the resulting points shows the presence of a substantial 'deadband' between the actions of opening a window and of closing it. This dynamic human behaviour, as noted above, gives 'horizontal grain' to the data. We established a curve representing the centres (in terms of Δt) of the bands of observations. (For details of the procedure see Rijal et al. 2008a; b). The resulting curves are superimposed on the scatter-plots.

(Fig. 7 Near here)

Next we wished to know the width of the bands of observations, and chose to adopt the convention that the range of a set of data may be taken as three times its standard deviation. The dotted lines on the figure thus show the conventional margins of the bands of data. For the windows the right hand margin can be shown to represent the probability that the window setting will change from closed to open, while the left marginal curve applies to closure from the open position etc.

Inspection of the centre-lines on Fig. 7 shows that they are quite similar in shape, and theoretical considerations had suggested that they should be parallel (Humphreys et al. 2008), thus, the regression gradient for window opening and fan use is taken to be 0.8 for Δt (Rijal et al. 2011).

The deadbands for operation of windows (*WD*) and fans (*FD*) appear to vary between the different datasets as could be expected if constraints vary among the buildings. In the current work we will use a value of 4K for WD and for FD to represent the typical trigger temperatures in the absence of any non-thermal constraint or motivation. From logistic regression analysis the following equations are derived to represent occupant adaptive control actions:

Windows opening (closed to open)
$\text{logit}\ (P_w)=0.8\ (T_g-T_{comf}-C_{wo})$ (3)

Windows closing (open to closed)
$\text{logit}\ (P_w)=0.8\ (T_g-T_{comf}+C_{wc})$ (4)

Fans on (off to on)
$\text{logit}\ (P_f)=0.8\ (T_g-T_{comf}-C_{fo})$ (5)

Fans off (on to off)
$\text{logit}\ (P_f)=0.8\ (T_g-T_{comf}+C_{fc})$ (6)

Where C_{wo} and C_{wc} are the constraints for windows open and closed, C_{fo} and C_{fc} are the constraints for fan on and off. These constraints are defined here as offsets from the neutral or comfort temperature (T_{comf}); a constraint of 0 represents a situation where at T_{comf} there is 50% probability of the occupant taking the action. The constraints are defined in these equations to be always positive, the higher the constraint value the further from T_{comf} the action will tend to be taken. How we reckon the sign of a constraint is a matter of convention. We have adopted the convention that a positive constraint indicates that the action is for some reason difficult or undesirable, for example the windows may not be opened until the room temperature is higher than expected, or not closed until the room temperature has fallen to below the comfort temperature. This pair of constraints would occur if, for example, a window mechanism were difficult to operate. An example of a negative constraint would be some non-thermal incentive to open the window – perhaps a desire to improve the indoor air quality. The operation of these equations is illustrated in Figs. 8 and 9 for the window closed to open case.

Fig. 8 illustrates the effect on window opening probabilities of seasonal adaptive variations in comfort and running mean temperatures (T_{comf} depends on T_{rm}, i.e. equation 1, people are comfortable or feel neutral in higher indoor temperatures when the running mean outdoor temperatures are higher) and also the impact of air velocity through fan use (in higher air speeds people are comfortable and feel neutral at higher indoor temperatures). The constraint value of 2 degrees ($C_{wo} = 2 = WD/2$) applied in Fig. 8 corresponds with there being no barrier to thermal comfort driven window opening and no motivation to open the window before the thermal comfort trigger point.

(Fig. 8 Near here)

Fig. 9 illustrates the potential effect of different constraints associated with particular situations. The comfort-only window opening probability is where the constraint is equal to the thermal comfort trigger point value i.e. $C_{wo} = 2$. Where there is some difficulty or adverse effect associated with opening the window (noise, pollution, lack of privacy) then the constraint would be larger, and this is illustrated by $C_{wo} = 4$. Conversely motivation to have the window opened at lower temperatures than the comfort trigger temperature would be illustrated by either the $C_{wo} = 0$ or $C_{wo} =$

-2 cases; the motivation for earlier opening could be for ‘fresh air’ or because there is a pleasant sheltered green space outside etc.

(Fig. 9 Near here)

Figs. 10 and 11 show the complete window open and closed hysteresis loop enclosed by combining P_{wo} and P_{wc} for various constraint situations: where there are only thermal constraints (C_{wo} = 2, C_{wc} = 2); where there is a noise problem with opening the window (C_{wo} = 4, C_{wc} = -1) (Fig. 10), where the window control is difficult (C_{wo} = 4, C_{wc} = 4) (Fig. 11), and where there is a desire to have the window open for indoor air quality reasons (C_{wo} = -1, C_{wc} = 4) (Fig. 12). We will go on to discuss how to estimate these constraint values in later sections.

(Fig. 10 Near here)
(Fig. 11 Near here)
(Fig. 12 Near here)

4. Quantification of constraints for individual buildings from survey data

Realistic knowledge of window-opening and fans use behaviour is needed to predict the thermal comfort and energy use in buildings. If controls such as windows and fans were effective and easy to use, thermal discomfort could be largely avoided in some circumstances. In practice there may be constraints that hinder or motivations that drive the use of such controls. In any thermal simulation these constraints need numerical values. We explore the nature and extent of some of the observed values of constraints operating on the use of windows and fans, making numerical estimates of their magnitudes from extensive field databases.

To illustrate this process, consider Fig. 7 (a). The dotted curve for the action of opening the window cuts the 0.5 probability level at a temperature some 1.5K above the comfort temperature, while the corresponding closure occurs some 3K below the comfort temperature. We may say there is a constraint of about 1.5K on opening the window and a constraint of some 3K on closing it (C_{wo} = 1.5, C_{wc} = 3). From the thermal comfort point of view, people normally tolerate departures of some 2K (i.e.*WD/2*) from the comfort temperature before desiring to take remedial action. So the picture emerges that on average people opened their windows a little before their thermal discomfort would have suggested they would have done so, and closed them a little after their thermal discomfort would have suggested they would. That is to say, across the UK and EU data there appears often to be some non thermal motivation to keep the windows open. The trend in the Pakistan database is different such that window opening is seen as somewhat less desirable.

Table 1 shows the constraints we have extracted for each of the individual buildings in our data sets by carrying out a building by building analysis. We have reckoned all constraints from the relevant comfort temperature. Table 2 gives a frequency analysis of the data.

(Table 1 Near here)
(Table 2 Near here)

Inspection of Table 1 and Table 2 shows considerable variation in the constraints from building to building, as would be expected. The constraints relate to the various factors discussed earlier (e.g. ease or difficulty of window opening and closing, fan generated noise, air pollution etc.), and further field investigation is required to improve our understanding of physical constraints in particular buildings and circumstances.

The Europe and UK data shows a frequent occurrence of window opening well before it would have been needed to avoid thermal discomfort, and of windows remaining open beyond the point where they would be predicted to be closed owing to thermal discomfort. There are examples such as UK buildings 7-GT, 11-GH and 14-SH which show window operation as predicted by unconstrained thermal comfort driven behaviours (with constraints approximately 2 for both window opening and closing as illustrated in Fig. 10). Others, however, show a strong non-thermal comfort motivation for windows to be open (UK 4-BH, 9-VW, Europe F1, G4, U3, U7, similar behaviour illustrated in Fig. 13), or a non-thermal motivation for windows to be closed (P3).

The Europe and UK data has many cases where the turn-on point for fans is at a much higher temperature than that predicted by unconstrained thermal comfort considerations, and where the turn-off point is before the point of cool thermal discomfort (UK: 1-MF, 2-AL, 7-GT, 8-RP, 11-GH, Europe: F1, P3) these cases indicate some non-thermal motivation to avoid use of fans (One reason could be that some fans do not work effectively or are noisy). In all of the UK buildings surveyed except one (4-BH) the fan turn-on point is considerably higher than predicted by unconstrained thermal comfort motivation alone indicating some other constraint on fan use or possibly a preference for using other available controls first (e.g. windows). Buildings F5 and G4 in Europe are exceptions in that fans are used around or slightly before the unconstrained thermal comfort trigger temperature (C_{wo} = 2) and the fans then appear to remain on, as indicated by the fan off operation having a high constraint value.

For the Pakistan buildings surveyed the dataset shows a tendency towards window opening much later and closing sooner than would be predicted by unconstrained thermal comfort considerations, indicating reluctance to open windows in the majority of the surveyed buildings. As with the EU and UK surveys, further research is required to establish reasons for such behaviour. One possible explanation is that the higher outdoor temperatures often experienced in Pakistan make window opening less effective in cooling the room, and in extreme cases will heat it rather than cool it. Also the buildings in Pakistan were in urban settings where noise and air pollution from vehicle exhaust and dust was a common experience. Night cooling of buildings and thermal mass could also be factors. In the surveyed Pakistan buildings there appears a reluctance to use fans but to a lesser extent than in the Europe and UK buildings.

The presence in the table of some large values for the constraints, both for fans and for windows, indicates that the action is unlikely to be taken in that building unless discomfort is more severe. We recall that a constraint of 2K is normal and unlikely to result in discomfort, while constraints of around 5K would indicate a significant problem with the use of that control, while a constraint of around 8K would render the control of little use for controlling the thermal environment.

5. Incorporating comfort and behaviour in building performance simulation

5.1 Background

Our fundamental conviction is that thermal simulation of buildings requires a realistic representation of occupant behaviour – behaviour that is sensitive to the occupants' comfort and to the adaptive opportunities available in the particular situation. This necessitates the study of people in real buildings; in our opinion it is not sufficient to assume schedules of behaviour that lack a sensitivity to the indoor conditions, to occupant behaviour, or to the particular building and its specific location.

Our algorithmic modelling of control-behaviour has been evolving over a period of years. A new feature of the model developed in this paper is its ability to handle the use of several occupant controls simultaneously, by introducing to the model the concept of differing constraints acting upon their probable use. The concept of constraint is a flexible addition, useful for extending the scope of the simulation algorithms. The merit of a logical model such as the one developed here, as compared with a simple empirical model, is that refinements can be added without disturbing its form. We believe the model realistically portrays the underlying behavioural dynamic of occupant control, while allowing refinement as further research is done.

The model described here is intended to be transparent and easy to translate into algorithmic form for use in the dynamic thermal simulation of a room or building. It provides the conditional probabilities of use for each of several controls. The modeller can use these and so estimate the effect of realistic user-control on energy use, indoor temperature and comfort.

5.2 Implementation of the algorithm in simulation

The current algorithm for use in simulation builds on previous work that used the open source dynamic simulation software ESP-r (Clarke 2001), but the intent is that algorithms are applicable also to other simulation software.

A brief history: First the CEN15251 adaptive thermal comfort criteria were established, then the Humphreys algorithm for use of windows implemented. Simulated building performance incorporating the Humphreys model was then compared with other approaches to modelling window use (Rijal et. al 2007). A simulation output for a UK office on a summer day is shown in Fig. 13; here the Humphreys algorithm triggers window opening at 1pm leading to increased infiltration and reduced subsequent temperatures compared to the case with the window always closed shown in Fig. 14.

Next, an algorithm developed from Pakistan data was implemented in ESP-r incorporating use of windows, doors, ceiling fans, night ventilation, heating and local air conditioning (Rijal et al. 2008b). This Pakistan algorithm included the shifting of thermal comfort temperature based on fan use.

Both the Humphreys and Pakistan algorithms trigger control responses based only on thermal comfort stimuli. The algorithm elaborated in this paper includes possible non-thermal constraint and motivations (negative constraints) that may modify these responses. This latest algorithm has also been translated into the logical steps needed for implementation in dynamic simulation (Rijal et al. 2011). The situations in Figs. 13 and 14 correspond to constraint values of 2 °C and 8 °C respectively. A 2 °C difference in operative temperature is the result of the different constraints on window use.

The simulation software computes environmental conditions and energy flows on each simulation time-step (Fig. 15). Inputs include the current setting of controls (windows, fans, heating set-points, cooling set-points etc.); outputs include setting the controls for the next simulation time-step (Fig. 16). The behaviour algorithm is developed to run on an hourly time-step. The underlying simulation time-step need not be the same and can be shorter if required.

Historically, non building-specific settings have been applied to represent user behaviour e.g. fixed temperature thresholds applied to window opening and closing, or a seasonal air change rate applied to represent average window opening behaviour. In contrast, the approach taken here attempts to account for the building specifics, climate, thermal comfort, air quality and occupants interactions with available building controls.

The approach allows for different probabilities for the start of occupancy period, during occupation and the end of the occupied period. This paper has focussed only on the use of windows and fans during occupied periods but a similar approach incorporating constraints could be taken for the use of heating (local 'personal' heating or zone thermostat control) and mechanical cooling (local units or zone thermostat control) and for the use of night cooling[3].

The behavioural algorithms are probabilistic. The equations define the probability that the control action will be taken, and then the probability is compared to a random number to determine if the control action is indeed taken at that time-step. The probabilistic nature of the algorithms allows a range of behaviours to be represented, and by running the simulation multiple times a distribution of possible building performance outcomes is generated, which may be used to represent the variation in occupant behaviour (Tuohy et al. 2009).

(Fig. 13 Near here)
(Fig. 14 Near here)
(Fig. 15 Near here)
(Fig. 16 Near here)

5.3 Setting the constraint values

As discussed earlier, physical and other reasons behind the constraint values extracted from the available survey data are not yet known, and it will take further investigation to establish the motivations and de-motivations in each case. Once these were known it would become possible to construct a method to predict the constraint values that applied to any given situation and incorporate these into design simulations.

Constraints which relate to accessibility and ease of use of controls would appear to be possible to establish using a checklist approach, as these relate to physical parameters. Checklists providing guidance to specifiers and designers for the implementation of useful controls have been put forward by both the UK's Building Controls Industry (BCIA) (Bordass, Leaman and Bunn, 2007) and the UK's Buildings Research Establishment (BRE) (Hadi and Halfhide, 2009). Where all criteria on these checklists are met then there would in theory be no constraint applied to window opening for these factors, if the implementation does not meet any of the checklist criteria then there would be a significant barrier to window operation etc. Weighting factors relating these checklists to constraint values for use in simulation remain to be determined. It is envisaged that constraints would be set separately for each sub-group of the environmental control type (e.g. small secure windows with accessible and easy to use controls would have no barriers to retard opening and therefore would have low constraints, while large windows requiring a pole to operate them and with difficult to use control mechanism would have a larger constraint).

Constraints relating to the negative consequences of a control action (e.g. is it noisy or smelly if you open the window? does rain come in if you open the window? is there a security problem with opening the window? is the fan noisy? is the fan effective?) would also appear to be possible to establish again through a checklist approach. A checklist covering these factors and with appropriate weightings for constraints would need to be created.

Constraints relating to non-thermal motivations for operation of the environmental controls could also be established through a checklist approach e.g. is the building designed and operated to be a low polluting building, a very low polluting building, or a standard building? (Definitions of low and very low polluting buildings are included in some CEN standards e.g. EN15251). Is there sufficient ventilation with the windows closed, etc? Again a checklist covering these factors remains to be determined.

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[3] It is worth noting that the Pakistan algorithm took a more simplistic approach and assumed that where available heating would be on at $T_{rm} \leq 10$ °C, mechanical cooling on at $T_{rm} > 28$ °C and night ventilation cooling utilised at $T_{rm} > 28$ °C.

6. Application of current comfort and behavioural algorithms and constraints method

Although further development of the behavioural algorithms and their application is ongoing, the existing work has elements that can be applied at present to provide insights and benefits not generally available.

In design the provision of unconstrained adaptive control options by following the existing checklists (Bordass et al. 2007, Hadi and Halfide, 2009) and the proposed future checklists will increase occupant satisfaction and allow occupants control of their environment; and allow the adaptive thermal comfort criteria to be applied during free running periods with associated energy savings potential. Similarly incorporation of current guidance (and proposed future checklists) on avoidance of internal pollutant sources and provision of adequate background ventilation in the design will minimise non-thermal motivations for increased ventilation through window opening (and the associated increase in energy use for heating and cooling in these periods).

Having maximised the effectiveness, availability and accessibility of controls and considered and minimised both constraints due to external environmental conditions and motivations due to internal non-thermal stimuli then a realistic set of situation specific constraint values can be applied to each available control option in building design simulation through use of the adaptive algorithms elaborated here. Where there are constraints due to outside conditions such as traffic or security then these can be represented in the design as high constraint values or design measures can be taken to mitigate the constraints (e.g. ducted ventilation openings, secure window openings etc.), the latter being the preferable course of action to maximise occupant satisfaction and ensure applicability of the adaptive comfort criteria.

The algorithms elaborated here are stochastic and variation in output represents the range of occupant behaviour with respect to the use of available environmental controls. It is strongly recommended that this variation in occupant control use is combined with likely variations in climate and patterns of building use (occupancy schedules, occupancy density and internal gains etc.) in order to more fully explore the robustness of a building to possible future use (Tuohy et al. 2009, Tuohy 2009) and allow robustness to be considered as a useful design criteria. This approach is used in other industries to pick the best design option or most robust solution.

Where the above processes have been followed then the free running period of operation can be defined based on the adaptive comfort criteria, which in principle allows a longer free running period than non adaptive comfort criteria. To realise this extended free running period and associated energy savings it is important that the appropriate comfort standards are correctly comprehended and implemented in the building control systems (e.g. BEMS).

The opportunity to adapt implies an absence of excessive constraints. If applying the algorithms, including the constraints, shows that occupants would be frequently and extensively away from their comfort temperature, the building would be judged unsuccessful. The application of the algorithms thus potentially provides a useful aid for designers in the pre-construction evaluation of a building. The constraint checklists could also be useful as part of a diagnostic process for naturally ventilated buildings which are underperforming.

The adaptive thermal comfort standards have been developed based on extensive field surveys of naturally ventilated buildings; using the operative temperature (T_{op}) of the adaptive standard in the specification of indoor conditions aligns the simulation of thermal conditions with this extensive field data and gives realistic quantification of energy demands and indoor temperatures during the heating or cooling season etc. This approach is in contrast with common practice which is to use a fixed seasonal indoor temperature.

The application of the adaptive thermal comfort criteria in building control has been demonstrated in simulation to have the potential for significant energy savings (up to 50%) when compared with control to commonly specified fixed temperature set-points; the saving can become much greater for projected warmer future climates (Tuohy et al. 2010). This use of models to quantify the differences in comfort and energy use between adaptive and non-adaptive approaches to building design and operation allows investment decisions relating to new build or refurbishment to be better informed.

While the non-thermal drivers for window opening have not yet been fully characterised for use in simulation, it is possible to use the unconstrained thermal comfort ($C = 2$) behaviour models to simulate behaviour in response to thermal environmental conditions e.g. overheating. Use of the Humphreys adaptive window opening algorithm has previously been demonstrated to be more sensitive to building design than non building specific fixed ventilation rates or temperature thresholds; showing building designs which result in more stable thermal environments to result in lower energy use (Rijal et al. 2007).

As work progresses on answering the research and development questions in this field, we envisage the comfort and behavioural models becoming increasingly important in building simulation and design. The survey data has shown that people are adaptive and can be comfortable and productive in a wider range of temperatures in traditional naturally ventilated buildings than are usual in mechanically conditioned spaces. Comfort in naturally ventilated buildings appears to depend on reasonably unconstrained access to and use of controls such as windows and fans. The aim here is to allow this adaptive comfort behaviour, and the quantification of constraints, to be integrated into building simulation so that the performance of naturally ventilated adaptive buildings can be properly assessed. Results so far indicate that there are important insights to be gained through this approach and that the potential for energy savings exists. For naturally ventilated and hybrid buildings the understanding of constraints is key.

7. Concluding notes

1. We have explained the derivation of a logical behavioural model.
2. The analysis shows that window opening and fan use behaviour is consistent across our databases.
3. Opening or closing windows or switching fans on or off are actions that can be subject to various constraints. We have suggested a way of handling such constraints, and have quantified the constraints operating in our sample of buildings.
4. We emphasise that this study has some uncertainties – the data were not designed to be put to the use that we have made of them. Further field studies should be dedicated to quantifying constraints and relating them to situation specific circumstances.
5. We illustrate how the concepts can be implemented in building design and building performance simulations and give examples of benefits that can be achieved. Specific tasks to be incorporated in design of low energy naturally ventilated or hybrid buildings proposed are:
    - Provision of unconstrained adaptive control options.
    - Avoidance of excessive ventilation through provision of good indoor air quality.
    - Incorporating situation-specific adaptive behaviour in design simulations.
    - Analysis of robustness of designs against variations in patterns of use and climate.
    - The incorporation of appropriate comfort standard into building controls.
6. We believe that models of this kind are in principle applicable to any type of building, but it may be that their principal application will be to hybrid buildings – that is, buildings that can be heated in winter as necessary, cooled in summer as necessary, and for as much of the season as possible are in the ‘free-running’ mode, using no energy dedicated to heating or cooling.

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Table 1 Constraints for each building
Table 2 Summary of estimated constraints for the combined data

Fig. 1 Window opening and closing behaviour of a perfectly consistent person
Fig. 2 Window opening and closing behaviour with human variability
Fig. 3 Showing the proportion of windows open when the direction of temperature change reverses. Note the 'horizontal grain' within the loop.
Fig. 4 The effect of a fan. The dotted lines apply when the fan is on. Switching on the fan raises the comfort-temperature, and hence shifts the entire figure a few degrees to the right. The figure also applies to removing a layer of clothing.
Fig. 5 Effect of constraints on the use of controls to avoid warmth discomfort
Note: The solid lines are for zero constraint. The dotted lines are for controls having varying degrees of constraint to their application, and therefore differing probabilities of being chosen at any particular room-temperature. For simplicity only the actions to avoid excessive warmth are shown.
Fig. 6 Comfort temperature used in the model for Europe, based on equations 1 and 2 and a fan effect of 0.07* T_{rm}
Fig. 7 The central curves indicating window opening and fan use, together with the estimated margins of the band, set at ±1.5 K standard deviations of the scatter about the central curves.
Fig. 8 Probability curve for a window being opened (when previously it had been closed) in relation to indoor globe temperature for various outdoor running mean (and hence comfort) temperatures and where fans are turned on, assuming a constant constraint of 2K.
Fig. 9 Probability curve for a window being opened (when previously it had been closed) in relation to indoor globe temperature for several values of constraint on opening, the outdoor running mean temperature being constant.
Fig. 10 Hysteresis loop for window opening and closing for thermal constraints only ($C_{wo} = 2$, $C_{wc} = 2$) and where there is a noise problem with opening the window ($C_{wo} = 4$, $C_{wc} = -1$).
Fig. 11 Hysteresis loop for window opening and closing for thermal constraints only ($C_{wo} = 2$, $C_{wc} = 2$) and where the window control is difficult ($C_{wo} = 4$, $C_{wc} = 4$).
Fig. 12 Hysteresis loop for window opening and closing for thermal constraints only ($C_{wo} = 2$, $C_{wc} = 2$) and where there is a desire to have the window open for indoor air quality reasons ($C_{wo} = -1$, $C_{wc} = 4$).
Fig. 13 Temperatures and energy flows for a summer day with the Humphreys adaptive algorithm. The lines represent the outdoor air temperature, the indoor operative temperature (open symbols) and the energy flows from the convective cooling by the incoming air, the heat gains from occupants, equipment and lights and the incoming direct solar heating absorbed in the surfaces of the office (Rijal et. al 2007).
Fig. 14 Temperatures and energy flows for the same summer's day as for Fig. 14 but with the windows remaining closed (Rijal et. al 2007).
Fig. 15 Flow chart of the simulation
Fig. 16 Key steps in the simulation process.

Table 1

		Constraints (K)			
Data	Building	Windows		Fans*	
		closed	open	off†	on
UK	1-MF	**2.7**	1.3	0.5	**6.1**
	2-AL	**3.0**	1.0	0.9	**5.7**
	4-BH	**3.5**	0.5	**4.0**	**2.6**
	6-CL	**2.4**	1.6	1.4	**5.2**
	7-GT	**2.2**	1.8	0.6	**6.0**
	8-RP	1.2	**2.8**	0.0	**6.6**
	9-VW	**4.0**	0.0	1.3	**5.3**
	11-GH	**2.2**	1.8	-0.2	**6.8**
	13-SN	**2.8**	1.2	1.9	**4.7**
	14-SH	1.8	**2.2**	**3.1**	**3.5**
Europe	F1	**4.2**	0.4	1.3	**6.3**
	F5	1.9	**2.7**	**5.9**	1.7
	G4	**5.5**	-0.9	**6.1**	1.5
	P2	1.5	**3.1**	**3.0**	**4.6**
	P3	-0.6	**5.2**	-0.4	**8.0**
	P5	**2.8**	1.8	**4.0**	**3.6**
	U3	**4.8**	-0.2	**2.4**	**5.2**
	U7	**4.8**	-0.2	**3.9**	**3.7**
	Min	**-0.6**	**-0.9**	**-0.4**	**1.5**
	Max	**5.5**	**5.2**	**6.1**	**8.0**
	Mean	**2.8**	1.5	**2.2**	**4.8**
Pakistan	1.10	**4.2**	1.4	**5.7**	-0.1
	1.20	0.7	**4.9**	1.5	**4.1**
	1.30	1.9	**3.7**	**3.3**	**2.3**
	1.40	1.3	**4.3**	1.5	**4.1**
	1.50	0.9	**4.7**	**3.2**	**2.4**
	2.20	0.7	**4.9**	0.9	**4.7**
	2.40	**3.4**	**2.2**	1.8	**3.8**
	2.45	1.4	**4.2**	-	-
	2.50	**4.9**	0.7	**2.4**	**3.2**
	2.60	**2.2**	**3.4**	1.6	**4.0**
	3.10	-	-	**2.1**	**3.5**
	3.20	-	-	1.8	**3.8**
	3.30	0.7	**4.9**	**3.0**	**2.6**
	3.40	1.4	**4.2**	**3.6**	2.0
	3.50	0.1	**5.5**	0.8	**4.8**
	3.60	1.8	**3.8**	**3.0**	**2.6**
	3.70	2.0	**3.6**	1.5	**4.1**
	4.10	0.6	**5.0**	**3.0**	**2.6**
	4.20	-1.9	**7.5**	-2.1	**7.7**
	4.40	-	-	-1.5	**7.1**
	4.50	0.6	**5.0**	0.7	**4.9**
	4.60	1.5	**4.1**	0.9	**4.7**
	5.10	**3.0**	**2.6**	**5.7**	-0.1
	5.20	**2.4**	**3.2**	-0.4	**6.0**
	5.30	**3.1**	**2.5**	**3.4**	**2.2**
	5.40	**4.7**	0.9	**4.6**	1.0
	5.50	2.0	**3.6**	**5.1**	0.5
	5.60	**2.6**	**3.0**	1.1	**4.5**
	5.70	**2.5**	**3.1**	**4.0**	1.6
	5.80	**4.1**	1.5	-	-
	Min	**-1.9**	**0.7**	**-2.1**	**-0.1**
	Max	**4.9**	**7.5**	**5.7**	**7.7**
	Mean	2.0	**3.6**	**2.2**	**3.4**

Overall mean	**2.3**	**2.8**	**2.2**	**3.9**

*: In Pakistan, T_{comf} were calculated by fan off equation, †: 2 K is added to adjust the comfort temperature, -: none, Bold: Those whose absolute value exceeded 2K.

Table 2

Data	Constraints (K)	Windows		Fans	
		open	closed	on	off
Europe & UK	< 0.5	11111	1	-	111
	0.5 to 1.5	1111	1	-	111111
	1.5 to 2.5	11111	111111	11	11
	2.5 to 3.5	111	1111	1	11
	3.5 to 4.5	-	111	111	111
	> 4.5	1	111	111111111111	11
Pakistan	< 0.5	-	11	11	111
	0.5 to 1.5	111	1111111111	11	11111
	1.5 to 2.5	11	111111	11111	11111111
	2.5 to 3.5	11111	11111	1111	111111
	3.5 to 4.5	111111111	11	1111111	11
	> 4.5	11111111	11	11111111	1111

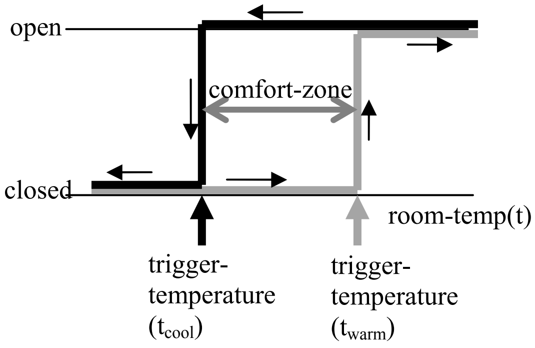


Fig. 1

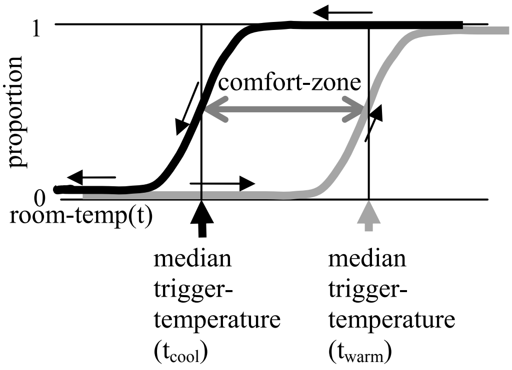


Fig. 2

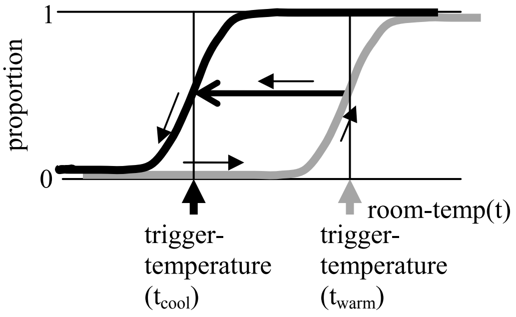


Fig. 3

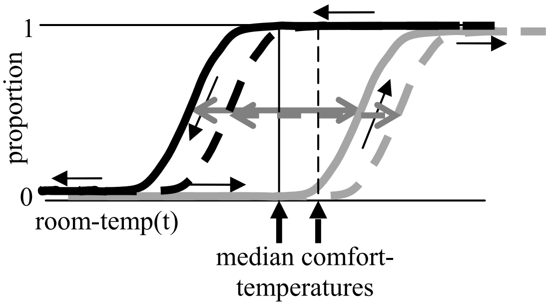


Fig. 4

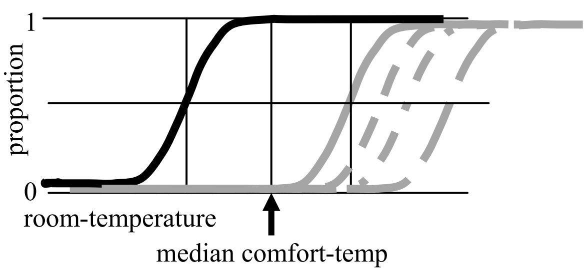

1
proportion
0
room-temperature
median comfort-temp

Fig. 5

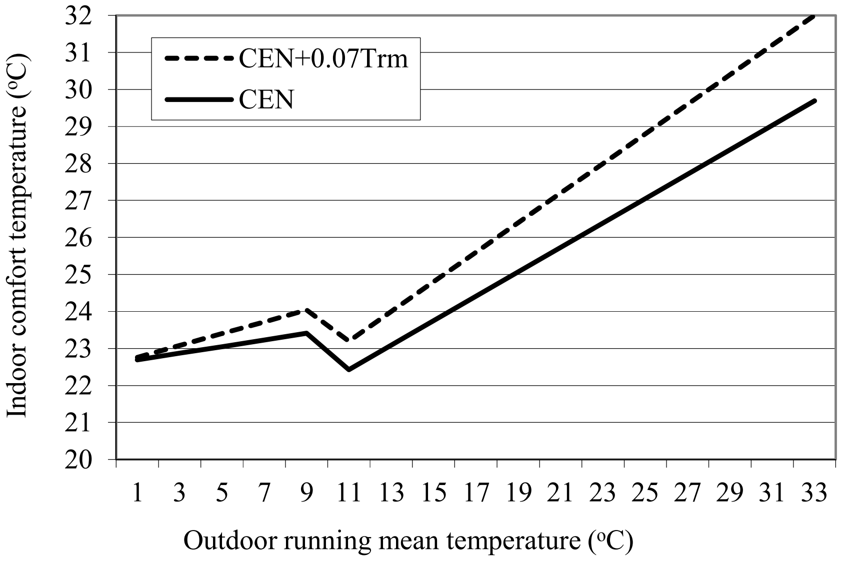

32
31
30
29
28
27
26
25
24
23
22
21
20
Indoor comfort temperature (oC)
CEN+0.07Trm
CEN
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
Outdoor running mean temperature (oC)

Fig. 6

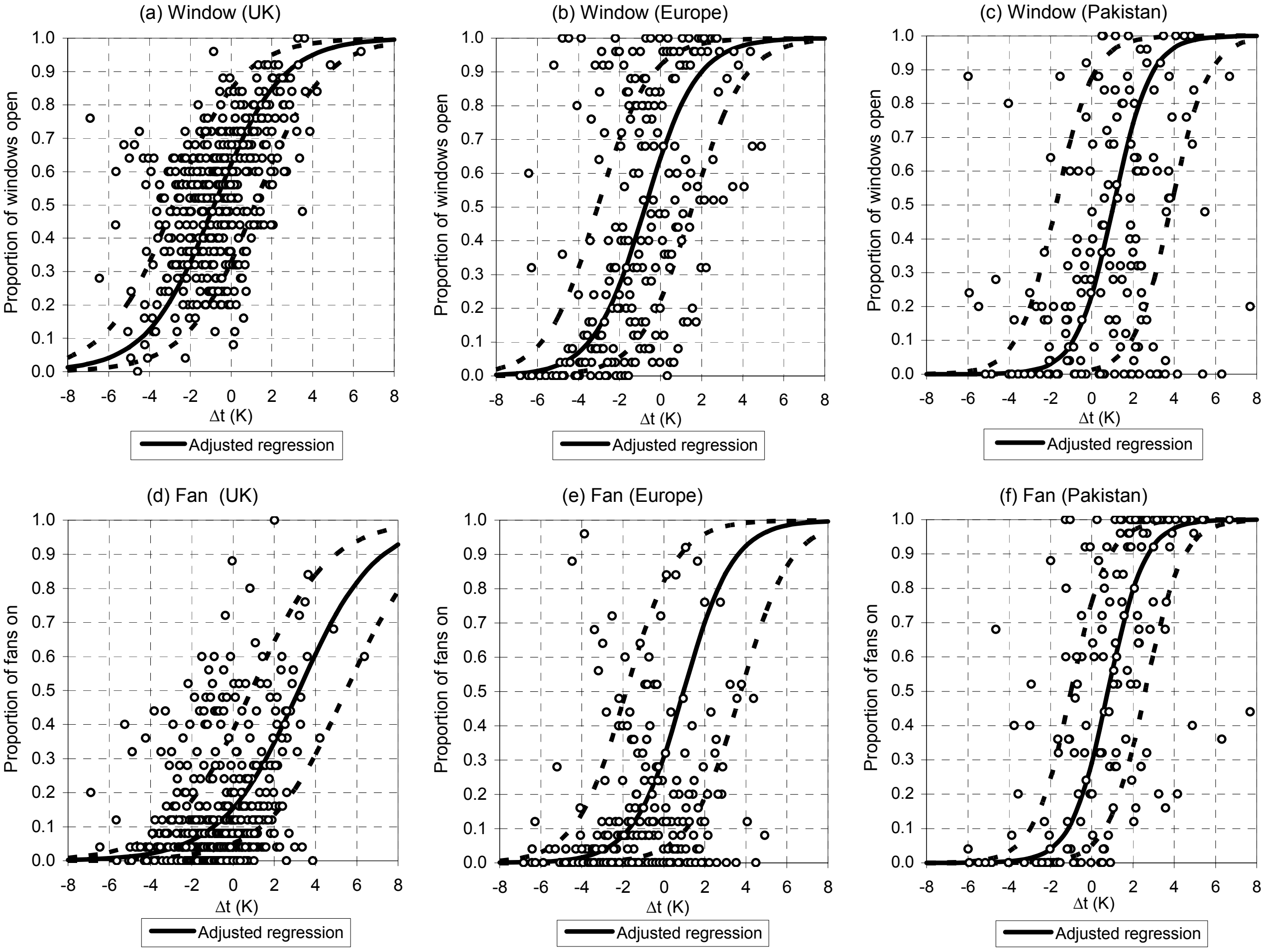
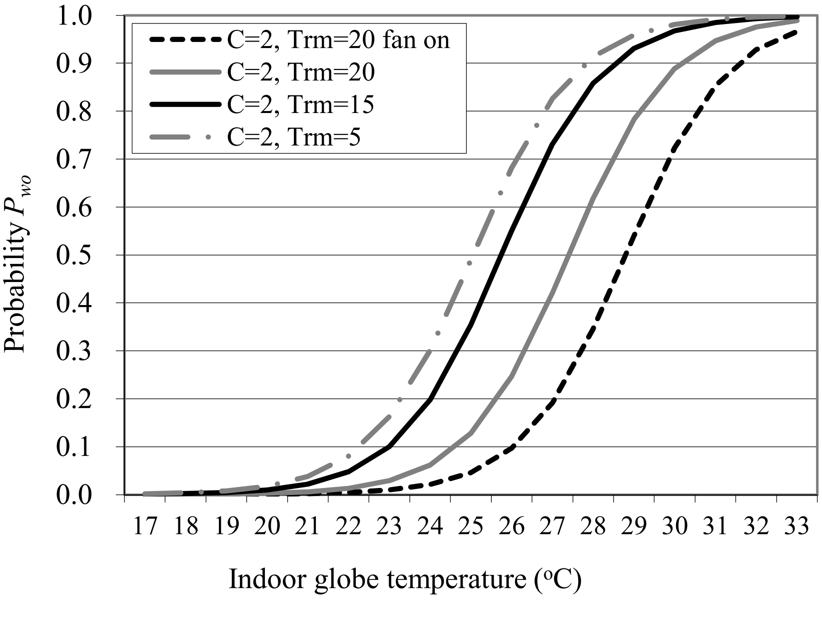

(a) Window (UK)
(b) Window (Europe)
(c) Window (Pakistan)
(d) Fan (UK)
(e) Fan (Europe)
(f) Fan (Pakistan)
Proportion of windows open
Proportion of fans on
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-8
-6
-4
-2
0
2
4
6
8
Δt (K)
Adjusted regression

Fig. 7


C=2, Trm=20 fan on
C=2, Trm=20
C=2, Trm=15
C=2, Trm=5
Probability P_{wo}
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
17
18
19
20
21
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32
33
Indoor globe temperature (°C)

Fig. 8

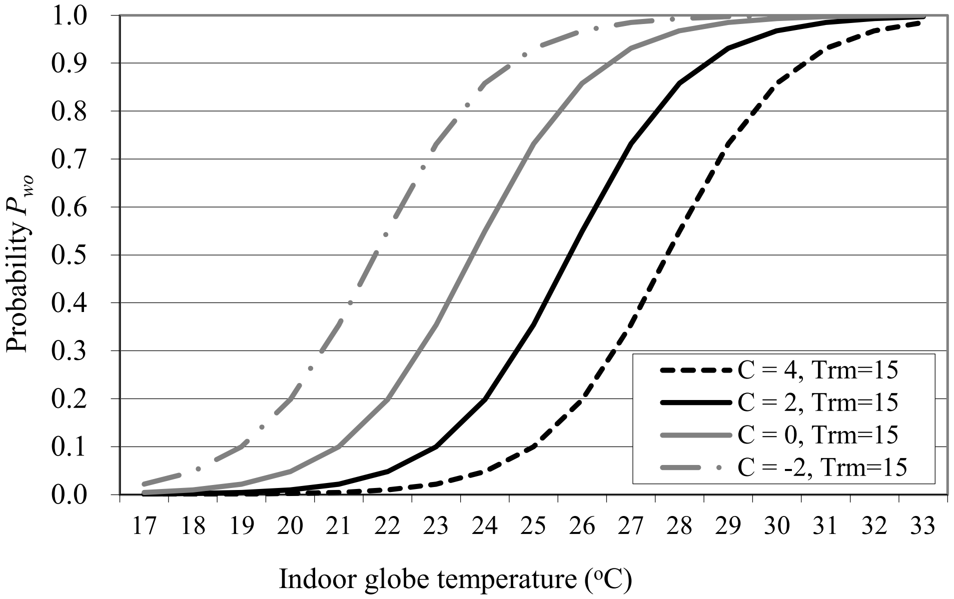
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Probability P_{wo}
C = 4, Trm=15
C = 2, Trm=15
C = 0, Trm=15
C = -2, Trm=15
17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33
Indoor globe temperature (°C)

Fig. 9

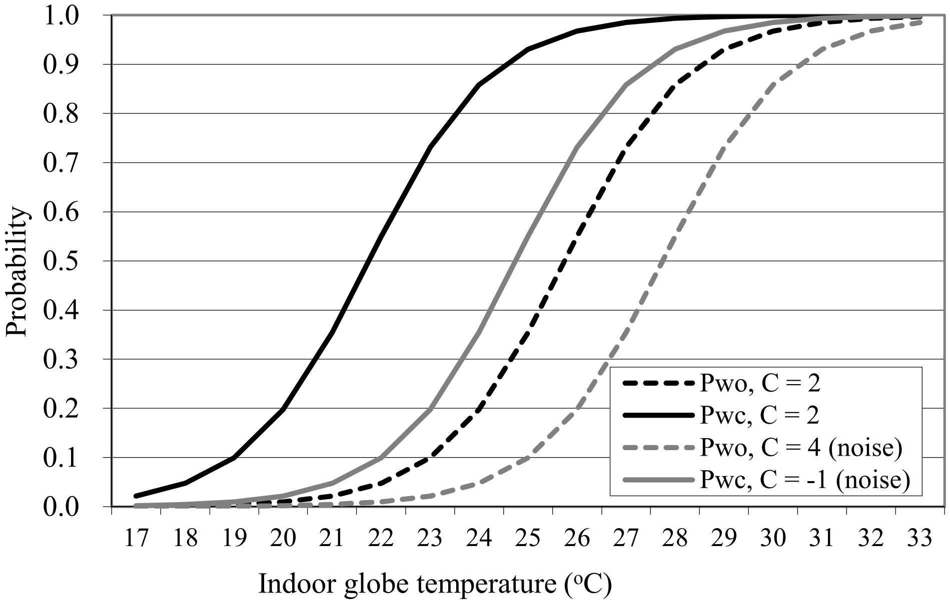
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Probability
Pwo, C = 2
Pwc, C = 2
Pwo, C = 4 (noise)
Pwc, C = -1 (noise)
17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33
Indoor globe temperature (°C)

Fig. 10

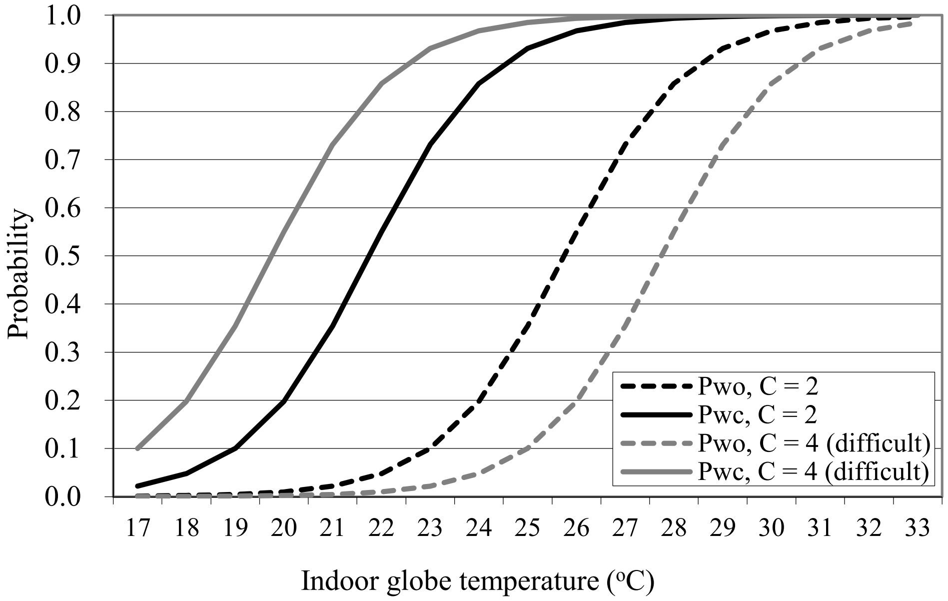
Probability
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
Indoor globe temperature (oC)
Pwo, C = 2
Pwc, C = 2
Pwo, C = 4 (difficult)
Pwc, C = 4 (difficult)

Fig. 11

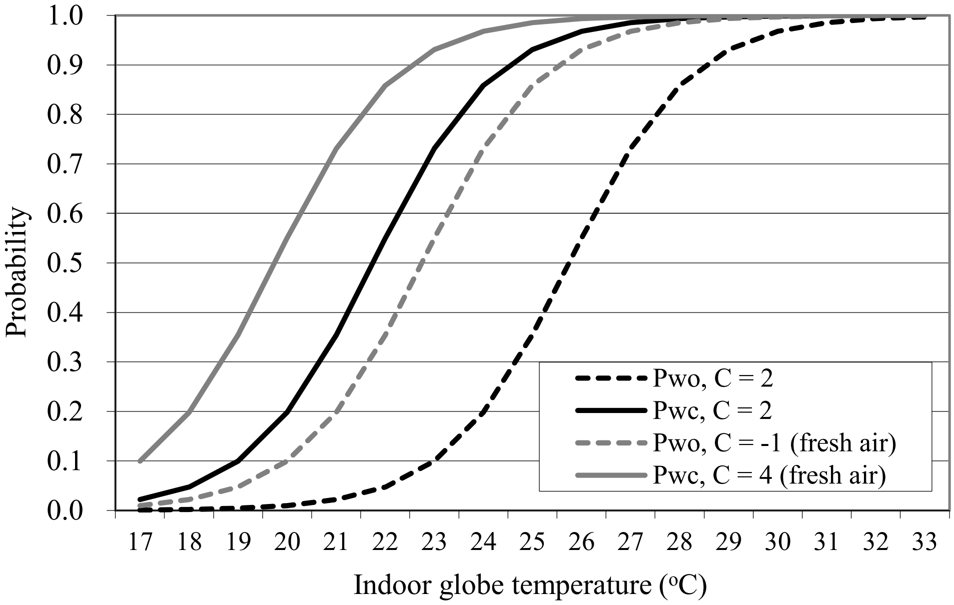
Probability
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
Indoor globe temperature (oC)
Pwo, C = 2
Pwc, C = 2
Pwo, C = -1 (fresh air)
Pwc, C = 4 (fresh air)

Fig. 12

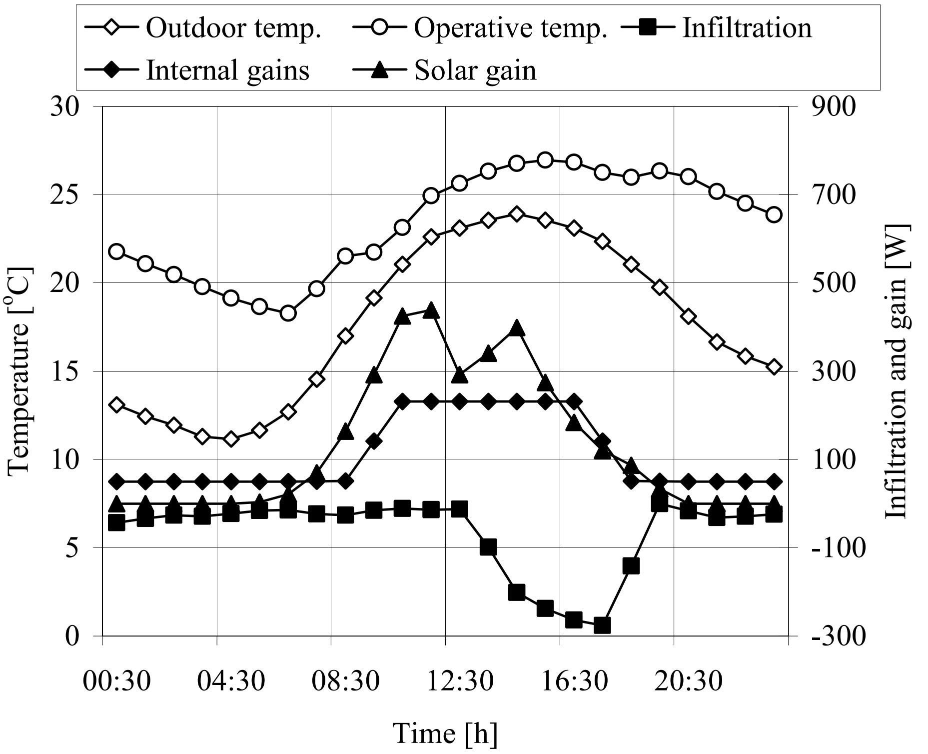
Outdoor temp.
Operative temp.
Infiltration
Internal gains
Solar gain
Temperature [°C]
Infiltration and gain [W]
Time [h]
0
5
10
15
20
25
30
-300
-100
100
300
500
700
900
00:30
04:30
08:30
12:30
16:30
20:30

Fig. 13

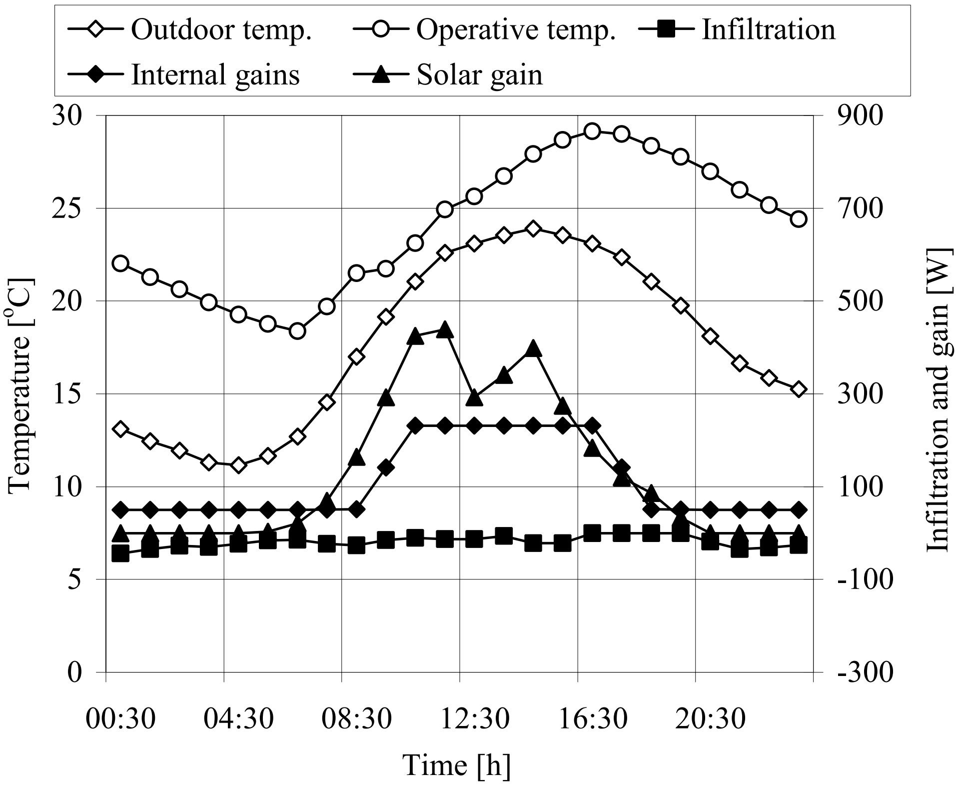
Outdoor temp.
Operative temp.
Infiltration
Internal gains
Solar gain
Temperature [°C]
Infiltration and gain [W]
Time [h]
0
5
10
15
20
25
30
-300
-100
100
300
500
700
900
00:30
04:30
08:30
12:30
16:30
20:30

Fig. 14

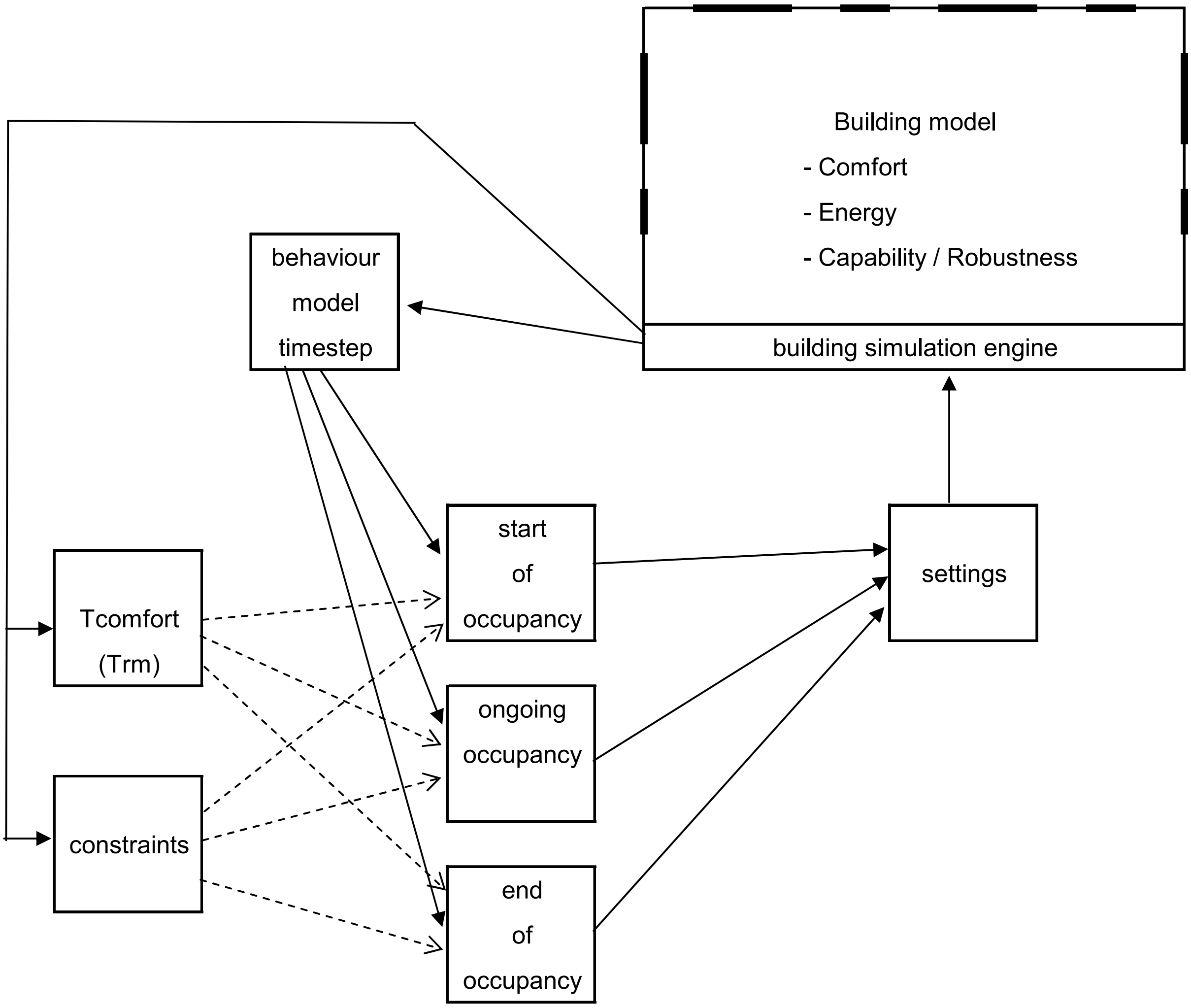

Fig. 15

1. Define thermal zones and airflow component networks.
2. Select 'adaptive control' from control menu.
3. Select zone to be sensed (T_{op}) and component(s) to be controlled.
4. Input constraints associated with use of control.
   (windows, fans, doors, local heating, local cooling)
5. Run simulation code which, for each control timestep:
   - calculates T_{rm} and T_{comf}
   - calculates Probability of control use from T_{op} T_{comf} C etc.
   - determines control settings through random number compare.

Fig. 16