A New Methodological Approach for Estimating Energy Savings due to Air Movement in Mixed-Mode Buildings

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Abstract

In recent years, there has been a proliferation of air-conditioning in both residential and commercial buildings in India. Mixed-mode buildings are buildings in which a combination of air-conditioning and natural ventilation is used to provide comfortable indoor environments. These buildings are likely to be less energy consuming than fully air-conditioned buildings, and further energy savings can be achieved by using air movement to increase the cooling setpoint temperature without jeopardizing the occupants' thermal comfort. The aim of this research was to develop and test on a typical Indian apartment a methodology to quantify these energy savings using dynamic thermal simulations. The core of this method is the definition of the cooling setpoint, which varies monthly according to the ASHRAE 55-2013 adaptive model. The results show that the annual energy demand for space cooling can be reduced by as much as up to 70 percent by using air motion devices. Moreover, the indoor thermal conditions during the occupied periods predicted by the model are closer to the values measured in field studies in India.

1. Introduction

In recent years, there has been a proliferation of air-conditioning in both residential and commercial buildings, and, due to the warming climate and the growing disposable income in several densely populated developing countries, energy demand for space cooling is dramatically increasing. The additional electricity demand generated by new in-room air conditioners purchased between 2010 and 2020 is projected to grow to more than 600 billion kilowatt-hours globally by 2020, and four countries, namely China, India, Brazil, Japan, together with the EU, are expected to represent 90 per cent of this market in 2014 (Shah et al., 2013).

Mixed-mode buildings are buildings in which a combination of air-conditioning and natural ventilation is used to provide comfortable indoor environments (Brager, 2006). There are three possible types of mixed-mode buildings based on operation strategy: concurrent, changeover, and zoned. In the first case, mechanical and natural ventilation are simultaneously used in the same space; with the second case, only one ventilation type is used in the entire building for a certain amount of time such as one day or one month; in the third case, 'zoned' means that both modalities are used at the same time, but in different parts of the building.

Mixed-mode buildings are likely to be less energy consuming than fully air-conditioned buildings, but predicting their performance is a more complex task. An approach has been proposed (Spindler and Norford, 2009a and 2009b), but its authors stated that this model cannot be used in domestic buildings because the occupants have direct control over the system. Moreover, research showed that the choice of the comfort criteria significantly affects the analysis of mixed-mode buildings (Borgeson and Brager, 2011), but the international standards (ISO 7730-2005, EN 15251-2007 and ASHRAE 55-2013) offer too little support for this choice.

Further energy savings can be achieved by using air movement devices, such as ceiling fans. Previous research (Schiavon and Melikov, 2008) estimated these savings in fully air-conditioned buildings, varying the cooling setpoint temperature based on category (EN 15251-2007) and air speed. In that study, and also in a more recent one (Hoyt et al, 2015), the cooling setpoint temperature did not vary

across the year, and both studies considered office buildings.
However, research on Indian apartments (Indraganti, 2010) highlighted that the use of air conditioners highly correlates with both outdoor and indoor temperatures. Moreover, previous work on the Indian commercial building sector (Manu et al., 2011) recognized the potential impact of using a floating setpoint temperature based on external environmental indicators such as air temperature and behavioural and psychological adaptations by the occupants in energy consumption estimates.
These studies and also recent work (Manu et al., 2016) on the Indian Model of Adaptive Comfort (IMAC) support the idea that the adaptive modelling approach is to some extent applicable also to mixed mode residential buildings.
Thus, the aim of this research was to develop and test a new methodology based on the adaptive theory to quantify the energy savings achievable in mixed-mode buildings due to air movement.

2. Methods

In this study, computer simulations have been used to test the new methodology, and the analysis focused on the energy demand for space cooling and the indoor environmental conditions predicted using this methodology. The core of this methodological approach is the way by which the cooling setpoint is defined. The proposed method was applied to an apartment in Ahmedabad, India, which is a typical example of a mixed-mode building with ceiling fans.

2.1 Cooling Setpoint Definition

IMAC was specifically developed from Indian data, but its equations implicitly incorporate the effect of air speed. Thus, it is not possible to use this model to estimate the energy savings due to the use of fans. The ASHRAE adaptive model was therefore used in this study.
According to ASHRAE 55-2013 (point 5.4.1), the adaptive model is applicable when all the following conditions are met:

a) There is no mechanical cooling system installed. No heating system is in operation
b) Metabolic rates range from 1.0 to 1.3 met
c) Occupants are free to adapt their clothing to the indoor and/or outdoor thermal conditions within a range at least as wide as 0.5-1.0 clo
d) The prevailing mean outdoor temperature is greater than 10 °C and less than 33.5 °C

Considering the Ahmedabad climate and the Indian typical domestic environment, all conditions are met, with the partial exception of the first condition for the case of a mixed-mode building. However, based on recent previous works (Indraganti, 2010; Manu et al., 2016), in this study we assumed the ASHRAE adaptive model is applicable also if air conditioning is available.
Moreover, the acceptable operative temperature limit in occupant-controlled spaces can be increased by 1.2 °C, 1.8 °C, and 2.2 °C due air speed equal to 0.6 m/s, 0.9 m/s, and 1.2 m/s, respectively (ASHRAE 55-2013, table 5.4.2.4). In warm and hot conditions, an elevated air speed can improve the thermal sensation of the occupants, rather than being the cause of an undesired draught.
In this research, a dynamic thermal model was created for a chosen mixed-mode building in which there are also fans. In the initial simulation, the cooling setpoint for temperature was varied monthly according to the ASHRAE 55-2013 adaptive model, considering the 90 per cent acceptability upper limits. In the subsequent three simulations, these

Table 1 – Dynamic cooling setpoint

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
T_m	20.0	22.0	27.0	31.0	33.0	32.0	29.0	28.0	29.0	28.0	25.0	20.0
T_{comf}	24.0	24.6	26.2	27.4	28.0	27.7	26.8	26.5	26.8	26.5	25.6	24.0
$T_{max\ (90\ \%)}$	26.5	27.1	28.7	29.9	30.5	30.2	29.3	29.0	29.3	29.0	28.1	26.5
$T_{maxAirSpeed\ (1.2\ m/s)}$	28.7	29.3	30.9	32.1	32.7	32.4	31.5	31.2	31.5	31.2	30.3	28.7
$T_{maxAirSpeed\ (0.9\ m/s)}$	28.3	28.9	30.5	31.7	32.3	32.0	31.1	30.8	31.1	30.8	29.9	28.3
$T_{maxAirSpeed\ (0.6\ m/s)}$	27.7	28.3	29.9	31.1	31.7	31.4	30.5	30.2	30.5	30.2	29.3	27.7

monthly setpoints were increased according to ASHRAE 55-2013 for air speeds up to 1.2 m/s.

The Ahmedabad weather file used in this study to calculate the monthly cooling setpoint (see Table 1) was created by ISHRAE in TMY2 format for use with building energy performance simulation programs (EnergyPlus weatherdata, 2016). T_{comf} comfort temperature, that is neutral operative temperature at which the lowest total percentage of people are expected to be either too hot or too cold (Borgeson and Brager, 2011), and $T_{max(90\ \%)}$ 90 per cent temperature upper limit, are calculated based on T_m monthly arithmetic mean of the daily average outdoor dry bulb temperatures:

$$T_{comf} = 17.88\ °C + 0.31 \times T_m \qquad (1)$$

$$T_{max(90\ \%)} = T_{comf} + 2.5\ °C \qquad (2)$$

2.2 Dynamic Cooling Setpoint Implementation

Once the four sets of monthly cooling setpoints were calculated (see Table 1), they were implemented in DesignBuilder/EnergyPlus using an advanced feature called Energy Management System (EMS), available in DesignBuilder from the recently realised version 5 (EMS, 2016b).

In EMS, a simple programming language called EnergyPlus Runtime Language (Erl) is used to describe the control algorithms. EnergyPlus interprets and executes the Erl program as the model is being run (EMS, 2016a).

In this study, an Erl script has been written to specify a different cooling setpoint per month using an IF and ELSEIF structure. Erl currently supports up to 199 ELSEIF statements, which means that by using Erl the cooling setpoint could not be changed every day of the year as would be required by the IMAC or EN15251 adaptive model. This is the technical reason why the ASHRAE adaptive model was chosen in this study rather than IMAC.

Four scripts have been developed, one for each simulation. These were used only to specify the setpoint value, while the ON/OFF control strategy has been defined in DesignBuilder.

2.3 The Case Study Building

The dynamic cooling setpoint method was tested on a typical Indian apartment, this being one of the apartments in an on-going international project on thermal comfort and air movement in residential buildings (Loveday et al., 2016). The project involves Loughborough University and De Montfort University in the UK, CEPT University in India, and University of California Berkeley in the USA.

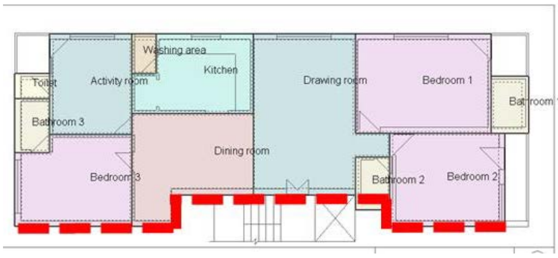

Fig. 1 – Floor plant (the red dashed line indicates an adiabatic party-wall)

Table 2 – Characteristics of construction elements

Element	Layers	U-value [W/m2K]
Internal partitions	12mm cement plaster 115mm brick 12mm cement plaster	1.98
External walls	From inside: 12mm cement plaster 230mm brick 18mm cement plaster	1.59
Ceiling and floor	From the top: 10mm vitrified tile 50mm cement – sand mix 150mm reinforced cement concrete slab 12mm cement plaster	2.17

This apartment (see Fig. 1) has a floor surface area of 145 m^2, internal height 3.2 m, and is surrounded by other apartments above, below, and to the side. Thus, ceiling, floor and party-wall have been assumed to be adiabatic. Typical construction elements of the Ahmedabad region were used (see Table 2). Due to the hot climate, there are no insulation layers, all windows have single glazing, and there is no heating system installed. The balconies were added in DesignBuilder to simulate shading effect, and the internal doors were assumed to be open 50 per cent of the time.

Physical partitions were used to create a zone for each room of the apartment, and an additional virtual partition was placed between the dining room and the drawing room. Although this is a unique open space, the former is used for having meals, while the latter is a living room. Therefore, their use is significantly different.

Since the aim of this work was to model a typical house, the occupancy schedule and relative internal heat gains were chosen from the available standard templates based on the type of each room.

Within DesignBuilder, the chosen method for natural ventilation is "calculated", which uses the EnergyPlus airflow network (AIRNET) method to calculate the ventilation rates using wind and buoyancy-driven pressure, opening size and operation, and crack sizes. This option slows the simulation down, but it is preferable if a reasonable estimate of the natural ventilation rates and infiltration rates in the building are not available (EnergyPlus documentation, 2016). The "medium" crack template was used. The "mixed-mode" option was selected, and, for any given cooling setpoint temperature, the air conditioning system was ON if:

a) The space was occupied
b) The indoor air temperature was above set point temperature
c) The outdoor air temperature was above indoor air temperature

Moreover, the air-conditioning was installed only in two rooms, namely "bedroom 1" and "bedroom 2". In an on-going field study, the authors observed that in Indian apartments there is often air conditioning only in a few rooms, not everywhere in the house. Within DesignBuilder, the modelled system is a typical residential mini-split system, with a coefficient of performance of 4.5. This type of air conditioners dominates air conditioner sales in most parts of the world including Asia and Europe (Shah et al., 2013).

In order to compare E_{nofan} energy demand for space cooling of the first simulation and the values of the subsequent three $E_{withfan}$, the energy used by the fan must also be taken into account. Considering that a higher setpoint could have been chosen due to the use of a fan, n total number of hours in which this was ON in the subsequent three simulations must be equal to the total number of cooling hours in the first simulation. The fan energy consumption E_{fan} is obtained by multiplying n for the average power of the fan, which for a typical Indian ceiling fan is 50 W (BEE, 2016):

$$E_{fan} = n \times 50W / 1000 \quad (3)$$

Since the air conditioning is available in two rooms, in a real scenario two fans may be operating at the same time, doubling E_{fan}. Therefore, this second possible scenario was also considered.

This value is then added to E_{AC} energy used by the air conditioning system:

$$E_{withfan} = E_{AC} + E_{fan} \quad (4)$$

The energy savings achievable using ceiling fans are therefore:

$$E_{savings} = E_{nofan} - E_{withfan} \quad (5)$$

Both T_A air temperature and T_O operative temperature setpoints were simulated to assess savings benefits using both approaches.

Table 3 – Energy saving without including energy used by the fan

Simulation	Cooling hours h]	Energy for space cooling [kWh]	Energy for space cooling [kWh/m²]	Savings without including the fan energy consumption [kWh]	Savings without including the fan energy consumption [%]
Control type: T_A					
no fan	1482	1381	9.52	0	0
with fan - 0.6 m/s	873	691	4.76	690	50
with fan - 0.9 m/s	654	469	3.23	912	66
with fan - 1.2 m/s	526	359	2.47	1022	74
Control type: T_O					
no fan	2527	2827	19.49	0	0
with fan - 0.6 m/s	1843	1655	11.41	1172	41
with fan - 0.9 m/s	1524	1235	8.52	1592	56
with fan - 1.2 m/s	1327	1011	6.98	1815	64

Table 4 – Energy saving including the energy used by the fan

Simulation	n [h]	Fan average power [W]	E_{fan} [kWh]	$E_{savings}$ kWh]	$E_{savings}$ [%]	Fan only hours [h]
Control type: T_A						
no fan	0	0	0	0	0	0
with fan - 0.6 m/s	1482	50	74	616	45	609
with fan - 0.9 m/s	1482	50	74	838	61	828
with fan - 1.2 m/s	1482	50	74	948	69	956
Control type: T_O						
no fan	0	0	0	0	0	0
with fan - 0.6 m/s	2527	50	126	1046	34	684
with fan - 0.9 m/s	2527	50	126	1466	52	1003
with fan - 1.2 m/s	2527	50	126	1689	60	1200

3. Results and Discussion

This section initially focuses on the effect that the choice between T_A and T_O as control parameter has on the energy predictions. It then analyses the demand for space cooling, and the energy savings that can be achieved in a typical Indian residential mixed-mode building using ceiling fans when a dynamic cooling set point is used.

3.1 Effect of Using Air Temperature or Operative Temperature

There is a noticeable difference in the energy consumption depending on whether T_A or T_O was chosen as the control parameter. In the initial case where no fan was used, the total number of cooling hours (see Table 3) is 1482 when T_A is used, but it reaches 2527 with the other control type, which is a 70 per cent increase due only to a change in this setting within the simulation program. As the fan speed goes up to 0.6 m/s, 0.9 m/s, and 1.2 m/s, this percentage grows to 111 per cent, and 133 per cent and 152 per cent, respectively. The respective energy consumption expressed in kWh is relatively low when using both T_A or T_O, but should these predictions be used to scale up the energy saving estimates to a regional scale, then these differences would make a bigger impact.

In general, T_O is a function of T_A and T_{MR} mean radiant temperature. For low air speed, smaller than 0.2 m/s, T_O is the arithmetic mean of T_A and T_{MR}. Then, as the air speed increases, the relative weight of T_{MR} decreases (Niu and Burnett, 1998).

International standards on thermal comfort usually refer to T_O when a certain temperature limit is given, and this is the case also for the ASHRAE adaptive model on which the cooling setpoints used in this study are based (ASHRAE 55-2013). Indeed, T_O gives a better indication of the temperature that a person feels in a certain environment.

On the other hand, real-world room air-conditioners are controlled by a simple thermostat, which is likely to be sensing the air temperature nearby its location, but far less influenced by the radiant component. In a real scenario, this means that a user would simply decrease the setpoint if uncomfortably warm. However, if the model uses T_A as a control, this behaviour is not captured.

It is important to highlight that in the two conditioned bedrooms, T_A and T_O are almost identical when no air conditioning is used. As the air conditioning is turned on, T_A decreases faster, with the difference ($T_O - T_A$) being within 1.6°C in over 85 per cent of the hours in which the air conditioning is used.

Previous research on Indian offices (Jain et al., 2011) also noticed that the energy demand for space cooling obtained using T_A is significantly lower than when T_O is used in EnergyPlus simulations. The difference was found to go up to 29 per cent, which at first sight might look a lot smaller that the figures mentioned earlier in this paper. However, in that case the chosen setpoint temperature was 24 °C, which means that the cooling load in kWh was very high using either T_A or T_O. Therefore the relative dif-

ference was smaller. Similarly, in this study, the percentage difference grows as the setpoint is increased due to the higher air speed.
Therefore, whenever in a given space T_A and T_{MR} are different, the energy load for space cooling is more realistic if calculated using T_O when the users have total direct control over the setpoint, and using T_A when they do not. When air conditioning is used in bedrooms overnight, it is likely to be in between these two extreme conditions.
For all these reasons, in this study both control types have been used and the respective results reported.

3.2 Energy Savings

Despite the choice between T_O and T_A, a significant reduction in energy consumption is achievable if ceiling fans are used to increase the setpoint temperature (see Table 4). The figures go up to 69 and 60 per cent or 948 and 1689 kWh using T_A and T_O as a control temperature, respectively.
The simultaneous use of a second ceiling fan only slightly reduces the energy savings (see Table 5). For both T_O and T_A based estimates, the energy savings would be negligible only if 9 ceiling fans were to be operating at the same time, which is not a realistic scenario. This significant margin has also another positive consequence. In an average Indian apartment, there are small fluctuations in the electricity supply, and also different speed settings lead to slightly different power usage. Both variations depend on the specific house and fan, but having such a big margin ensures that ceiling fans are clearly an effective way to improve thermal comfort while saving energy.
These energy predictions are calculated using the new approach based on the dynamic cooling setpoint that varies each month. If the methods used in previous research on office buildings (Schiavon and Melikov, 2008) had been applied, then the setpoints would have been constant throughout the year. Considering category II (EN 15251-2007), in which case 10 per cent of people are considered to be dissatisfied, the temperature thresholds would have been 26.0 °C, 27.7 °C, and 28.5 °C for 0.2 m/s or less, 0.5 m/s, and 0.8 m/s, respectively. These values are lower than those used in this study (see Table 1), both for the cases without and with air movement, and therefore the annual energy consumption calculated with these setpoints would be higher. However, research showed that the comfort band in Indian residential buildings can be extended up 32.5°C (Indraganti, 2010), which is much closer to the highest setpoint used in this work, that is 32.7 °C in May with air speed equal to 1.2 m/s, than the values used in previous research. Moreover, the same study highlighted how complex the domestic environment is, that users are heavily influenced by the outdoor conditions, and that the different adaptive solutions such as ceiling fans and air conditioners are widely used and combined. Therefore, energy savings predictions calculated with the proposed methodology are lower than those calculated with traditional methods for fully air-conditioned buildings, but they are likely to be more realistic for the situation of Indian residential mixed-mode buildings.

Table 5 – Energy saving including the energy used by two fans

Simulation	$E_{savings}$ [kWh]	$E_{savings}$ [%]
Control type: T_A		
no fan	0	0
with fan - 0.6 m/s	542	39
with fan - 0.9 m/s	764	55
with fan - 1.2 m/s	874	63
Control type: T_O		
no fan		
with fan - 0.6 m/s	919	33
with fan - 0.9 m/s	1339	47
with fan - 1.2 m/s	1563	55

4. Conclusions

The research presented in this paper aims to develop and test a new methodological approach for estimating the energy savings achievable due to air movement in mixed model buildings.
The key findings are:

- The dynamic cooling setpoint led to more realistic simulation scenarios since it captures the existing connection between the users of mixed-mode buildings and the outdoor temperature
- The energy demand for space cooling can be reduced by as much as 70 percent by using ceiling

fans, without jeopardising the occupants' thermal comfort.

- The simultaneous use of two fans slightly reduces the energy savings.
- Using the operative or air temperature as control parameters in EnergyPlus significantly affects the results. Since the air temperature decreases faster when the air conditioning is turned on, estimates based on it may be excessively low.

4.1 Limitations and Future Work

The currently available field-based research on mixed-mode buildings supports the idea that the users of these buildings are affected by the outdoor conditions, and therefore a method based on the adaptive model is likely to be closer to real-world scenarios.

However, these studies also show two other important things. Firstly, when air conditioning is available, even if only in certain rooms or at a certain time, then the occupants of a building tend to be a little less tolerant than people in fully naturally ventilated buildings. The second point is that in mixed-mode buildings the use of air-conditioners depends on a range of factors that are not related to the outdoor temperature, such as noise, pollution, and disposable income, and the situation is even more complex in domestic buildings.

Thus, more studies based on real field data are needed to properly address mixed-mode buildings. The economies of developing countries such as India are growing fast, and represent the main market for air conditioners, and mixed-mode buildings are extremely common. Therefore over- or underestimating their energy requirements for space cooling would heavily affect the global figures for energy demand.

It will then be possible to say whether the most suitable method for estimating energy savings due to air movement in mixed-mode buildings is the one proposed in this paper and based on ASHRAE adaptive model, one based on IMAC, or a different one that has not been developed yet.

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