A new methodological approach for estimating energy savings due to air movement in mixed mode buildings

This item was submitted to Loughborough University's Institutional Repository by the/an author.

Citation: BABICH, F. ...et al., 2017. A new methodological approach for estimating energy savings due to air movement in mixed mode buildings. Presented at the 3rd Building Simulation Applications (BSA 2017). Bolzano, (Italy), Feb 8-10th.

Additional Information:

- This is a conference paper.

Metadata Record: https://dspace.lboro.ac.uk/2134/24344

Version: Accepted for publication

Publisher: IBPSA

Rights: This work is made available according to the conditions of the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International (CC BY-NC-ND 4.0) licence. Full details of this licence are available at: https://creativecommons.org/licenses/by-nc-nd/4.0/

Please cite the published version.
A new methodological approach for estimating energy savings due to air movement in mixed mode buildings

Francesco Babich - Loughborough University, Loughborough, UK - f.babich@lboro.ac.uk
Malcolm Cook - Loughborough University, Loughborough, UK - malcolm.cook@lboro.ac.uk
Dennis Loveday - Loughborough University, Loughborough, UK - d.l.loveday@lboro.ac.uk
Rajan Rawal - CEPT University, Ahmedabad, India - rajanrawal@cept.ac.in
Yash Shukla - CEPT University, Ahmedabad, India - yash.shukla@cept.ac.in

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 set-point temperature without jeopardizing 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 set-point, 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 set-point 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 set-point 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 set-point 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 in which the cooling set-point is defined. The proposed method has been applied to an apartment in Ahmedabad, India, which is a typical example of a mixed mode building with ceiling fans.

2.1 Cooling set-point definition

IMAC was specifically developed from Indian data, but its equations implicitly incorporate the effect of air speed. Thus, using this model for estimating the energy savings due to the use of fans is not possible. 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 cause of an undesired draught.

In this research, for a chosen mixed mode building

<table>
<thead>
<tr>
<th>Table 1 – Dynamic cooling set-point</th>
</tr>
</thead>
<tbody>
<tr>
<td>JAN</td>
</tr>
<tr>
<td>------------------------------------</td>
</tr>
<tr>
<td>T_{in}</td>
</tr>
<tr>
<td>T_{cond}</td>
</tr>
<tr>
<td>T_{max} (90%)</td>
</tr>
<tr>
<td>T_{maxAirSpeed (1.2m/s)}</td>
</tr>
<tr>
<td>T_{maxAirSpeed (0.9m/s)}</td>
</tr>
<tr>
<td>T_{maxAirSpeed (0.6m/s)}</td>
</tr>
</tbody>
</table>
A new methodological approach for estimating energy savings due to air movement in mixed mode buildings

in which there are also fans, a dynamic thermal model was created. In the initial simulation, the cooling set-point 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 monthly set-points were increased according to ASHRAE 55-2013 for air speeds up to 1.2m/s.

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

\[
T_{\text{conf}} = 17.88^\circ C + 0.31 \times T_m \\
T_{\text{max}}(90\%) = T_{\text{conf}} + 2.5^\circ C
\]

2.2 Dynamic cooling set-point implementation

Once the four sets of monthly cooling set-point were calculated (see Tab. 1), these have been implemented in DesignBuilder/EnergyPlus using an advanced feature called Energy Management System (EMS), which is available in DesignBuilder from 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 set-point per month using an IF and ELSEIF structure. Erl currently supports up to 199 ELSEIF statements, which means that by using Erl the cooling set-point 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 set-point value, while the ON/OFF control strategy has been defined in DesignBuilder.

2.3 The case study building

The dynamic cooling set-point method has been 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.

This apartment (see Fig. 1) has a floor surface area of 145 m², 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 have been used (see Tab. 2). Due to the hot climate, there are no insulation layers, all windows have single glazing,

![Floor plan](image)

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

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

Table 2 – Characteristics of construction elements
and there is no heating system installed. The balconies have been added in DesignBuilder to simulate shading effect, and the internal doors have been assumed to be opened 50 per cent of the time.

Physical partitions have been used to create a zone for each room of the apartment, and an additional virtual partition has been 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 have been 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 is not available (EnergyPlus documentation, 2016). The “medium” crack template was used.

The “mixed-mode” option has also been selected, and, for any given cooling set-point 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 have 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, whose coefficient of performance is 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 $E_{\text{no-fan}}$ energy demand for space cooling of the first simulation and the values of the subsequent three $E_{\text{with-fan}}$, the energy used by the fan must also be taken into account. Considering that a higher set-point 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 $E_{\text{fan}}$ is obtained by multiplying n for the average power of the fan, which for a typical Indian ceiling fan is 50W (BEE, 2016):

$$E_{\text{fan}} = n \times 50W / 1000$$

(3)

Since the air conditioning is available in two rooms, in a real scenario two fans may be operating

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Cooling hours [h]</th>
<th>Energy for space cooling [kWh]</th>
<th>Energy for space cooling [kWh/m²]</th>
<th>Savings without including the fan energy consumption [kWh]</th>
<th>Savings without including the fan energy consumption [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control type: Tₐ no fan</td>
<td>1482</td>
<td>1381</td>
<td>9.52</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>with Fan - 0.6 m/s</td>
<td>873</td>
<td>691</td>
<td>4.76</td>
<td>690</td>
<td>50</td>
</tr>
<tr>
<td>with Fan - 0.9 m/s</td>
<td>654</td>
<td>469</td>
<td>3.23</td>
<td>912</td>
<td>66</td>
</tr>
<tr>
<td>with Fan - 1.2 m/s</td>
<td>526</td>
<td>359</td>
<td>2.47</td>
<td>1022</td>
<td>74</td>
</tr>
<tr>
<td>Control type: Tₒ no fan</td>
<td>2527</td>
<td>2827</td>
<td>19.49</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>with Fan - 0.6 m/s</td>
<td>1843</td>
<td>1655</td>
<td>11.41</td>
<td>1172</td>
<td>41</td>
</tr>
<tr>
<td>with Fan - 0.9 m/s</td>
<td>1524</td>
<td>1235</td>
<td>8.52</td>
<td>1592</td>
<td>56</td>
</tr>
<tr>
<td>with Fan - 1.2 m/s</td>
<td>1327</td>
<td>1011</td>
<td>6.98</td>
<td>1815</td>
<td>64</td>
</tr>
</tbody>
</table>
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 set-points have been simulated to assess savings benefits using both approaches.

### 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 Tab. 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 are relative low 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 set-points used in this study are based (ASHRAE 55-2013). Indeed, $T_o$ gives a better indication of the temperature that a person is feeling in a certain environment.

On the other hand, real-word 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 set-point 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 set-point 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 difference was smaller. Similarly, in this study, the percentage difference grows as the set-point 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 set-point, 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 set-point temperature (see Tab. 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 Tab. 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 a normal 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.

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Savings [kWh]</th>
<th>Savings [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control type: (T_o) no fan</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>with Fan - 0.6 m/s</td>
<td>542</td>
<td>39</td>
</tr>
<tr>
<td>with Fan - 0.9 m/s</td>
<td>764</td>
<td>55</td>
</tr>
<tr>
<td>with Fan - 1.2 m/s</td>
<td>874</td>
<td>63</td>
</tr>
<tr>
<td>Control type: (T_a) no fan</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>with Fan - 0.6 m/s</td>
<td>919</td>
<td>33</td>
</tr>
<tr>
<td>with Fan - 0.9 m/s</td>
<td>1339</td>
<td>47</td>
</tr>
<tr>
<td>with Fan - 1.2 m/s</td>
<td>1563</td>
<td>55</td>
</tr>
</tbody>
</table>

These energy predictions are calculated using the new approach which is based on the dynamic cooling set-point that varies each month. If the methods used in previous research on office buildings (Schiavon and Melikov, 2008) had been applied, then the set-points 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 Tab. 1), both for the cases without and with air movement, and therefore the annual energy consumption calculated with these set-points 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 set-point 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.

4. Conclusions

The research presented in this paper aimed 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 set-point 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 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 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 in 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 requirement 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.

5. Acknowledgement

This research was financially supported by the Engineering and Physical Sciences Research Council (EPSRC) via the London-Loughborough Centre for Doctoral Research in Energy Demand (LoLo), and by the British Council under the Global Innovation Initiative, the latter involving an international research collaboration between UC Berkeley (USA), CEPT University (India), Loughborough University and De Montfort University (UK). The authors express their gratitude for this support.

References


EMS. 2016b. Last access: 05.10.2016. https://designbuilder.co.uk/helpv5.0/Content/Energy_Management_System_-_EMS.htm


