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A Control Sequence for Prioritising Ceiling Fan Operation Over Air Conditioners Using Machine Learning to Determine Thermal Comfort

Siva Barathi
Indian Institute for Human Settlements, Bangalore, India

Thounaojam Amanda
Indian Institute for Human Settlements, Bangalore, India
(Corresponding Author: amandat@iihs.ac.in)

Prasad Vaidya
Indian Institute for Human Settlements, Bangalore, India

A Gopikrishna
Indian Institute for Human Settlements, Bangalore, India

Dalavai Uthej
Indian Institute for Human Settlements, Bangalore, India

Vipin Tandon
Manipal School of Architecture and Planning, Manipal, India

Highlights

- Machine learning for predicting OT as a scalable approach for adaptive comfort controls.
- Using the corrective power index for cooling to adjust the upper limit of the thermal comfort band based on air speed achieved by ceiling fans.
- Thermal comfort study of comfort votes and energy consumption, compared to a 24ºC constant setpoint.
- Cooling energy savings of more than 97% with higher comfort votes for the demonstrated control sequence.

Abstract

This study aims to use the corrective power of personal comfort systems of -1K to -6K [2] and prioritise ceiling fan operation over AC to reduce energy consumption and implement controls based on Operative temperature (OT). We use a machine learning algorithm that takes indoor air temperature and outdoor values for air temperature, wind speed, and relative humidity as inputs and predicts the indoor OT of a space. The predicted OT is used to determine thermal comfort according to the India Model for Adaptive Comfort (IMAC). We have developed a control sequence that automates ceiling fan speed operation and air-conditioning (AC) set-points. The control sequence is tested in two different rooms; one, a passively designed building with an insulated envelope, and another, a typical uninsulated building, tested against a base case of 24°C set-point suggested by the Bureau of Energy Efficiency (BEE), India, with no ceiling fans operating. The testing shows that the control sequence that prioritises ceiling fan operation has higher comfort votes than the BEE base case, and the control sequence provided more than 80% cooling energy savings compared to the BEE base case.

Keywords: Adaptive thermal comfort, operative temperature, corrective power Index, machine learning, ceiling fans

Introduction

Per capita annual energy consumption for space cooling in India is only 69 kWh compared to the global average of 272 kWh [1]. However, rising temperatures and income levels will increase India's cooling energy requirement, and the India Cooling Action Plan [2] calls for synergistic actions across sectors to provide sustainable cooling that is affordable. Most of the new buildings are air-conditioned, and much of the existing building stock is being retrofitted with AC systems. This has resulted in a wide array of mixed mode buildings and begs a closer look at mixed mode operation.

The existing controls are mostly based on air temperature because the operative temperature is difficult to measure in real-time, while it is a better indicator of indoor thermal conditions [3]. Also, the automation of ceiling fan controls is not explored well since most of the research performed already focuses on providing fan controls to occupants in cases of air speeds higher than 0.8 m/s [4].

This study aims to implement controls based on operative temperature (OT) used in the adaptive comfort model (IMAC) of the National Building Code (NBC) of India. We use the corrective power of personal comfort systems (PCS) of -1K to

-6K [5] and prioritise ceiling fan operation over AC to reduce energy consumption and implement controls based on Operative temperature (OT).

We use a machine learning (ML) algorithm that takes indoor air temperature and outdoor values for air temperature, wind speed, and relative humidity as inputs and predicts the indoor OT of a space. The predicted OT is used to determine thermal comfort according to the IMAC. For this study, the control sequence is tested in two different rooms; one, a passively designed building with an insulated envelope, and another, a typical uninsulated building, tested for these 3 conditions:

- Base case of 24°C (AC set-point suggested by the Bureau of Energy Efficiency, India) with no ceiling fans operating.
- IMAC AC set point at the neutral temperature of the comfort band, without fans.
- Ceiling fan prioritised control sequence

The aim of this research is to develop, implement, and test a control sequence that prioritizes the use of ceiling fans over air-conditioners, integrating products available in the market to provide energy efficient and comfortable cooling while maintaining the thermal comfort of the occupants.

The significant contributions of this work are to demonstrate that OT predicted in real-time with ML can be used in a control sequence that automates the prioritisation of ceiling fans and that in tropical conditions such as those prevailing in India, occupants report higher levels of comfort with ceiling-fan induced air movement and higher temperature set points. The findings of this study point to a method of space cooling that takes full advantage of the IMAC and can be an affordable and sustainable cooling approach.

Additional research can determine the extent to which this method is scalable to other building typologies and climates.

Literature review

Static models of thermal comfort helped in the formulation of thermal comfort standards that were applied universally, but they rely solely on-air conditioning to maintain the thermal comfort of occupants [6]. A location-specific adaptive comfort model, which includes the building's ventilation type, was developed by Manu et al., which will help in not only help in maintaining the thermal comfort of occupants but also help in reducing energy consumption [6], [7]. It allows buildings to operate within a broader range of indoor operative temperatures.

The elevated air speed comfort zone method in the ASHRAE Standard 55 standards allows us to define limits for comfort for indoor operative temperature for defined air speed in the space when other parameters like met value and clo value are held constant. In the 2017 version of the ASHRAE Standard 55, the upper limit of airspeed was increased to 1.6 m/s [8]. Occupants in warmer countries prefer warmer temperatures since they have adapted to high temperatures, especially in naturally ventilated buildings where the outdoor temperature has a significant influence on the indoor comfort parameters [9]. A study by Candido & de Dear [10] also states that occupants who feel hot prefer more air movement. Y. Zhai et al. [11] concluded that the provision of air movement is more important than temperature control in such warm environments.

Ceiling fans are an efficient adaptive comfort strategy to induce air movement, improve comfort, and have a corrective power index (CP) of -1K to -7K when the air speed is as high as 1 m/s, and the ambient temperature is as high as 33°C [12]. Corrective power is defined by ASHRAE 55 as the ability of a PCS to correct the thermal sensation of a person toward the comfort zone. It is expressed as the difference in operative temperatures between two instances where equal thermal sensation is achieved, one with PCS and one without PCS [4]. In a thermal comfort study conducted in California with a hot and dry climate across 10 buildings with air conditioners, ceiling fans provided comfort at 26.7°C with air movement rather than having only air conditioning at 22.2°C [13],[14]. In another study conducted in the tropics, ceiling fans provided comfort up to 27°C, but if given a preference, the occupants chose to have minimal air conditioning along with the ceiling fans as a preference to attain comfort [15]. A study by Bongers et al. [16] in Australia states that the use of ceiling fans can increase the temperature limit when the air conditioning needs to be switched on. The study reports annual energy savings up to 76%. A thermal comfort tool by the Center for Built Environment [17] shows that the upper limit of the comfort model shifts further upwards in response to increased airspeed in space. De et al. [3] used the tool to obtain the upward shift for several conditions and developed an equation to apply the effect of air speed on the IMAC band.

Methodology

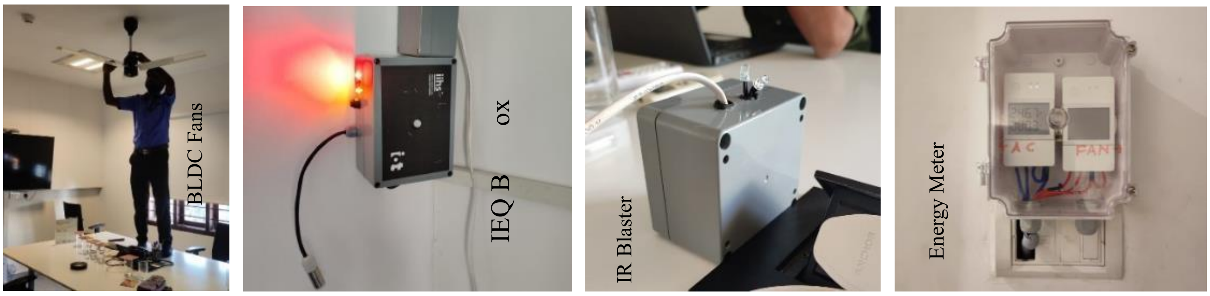
Validation of ML model

The ML model for predicting OT was developed by [3] De et al. for a workstation room in a passively designed building with significant envelope insulation. This model was tested by comparing its predictions for OT with 1-week long hourly data from measurements of the globe temperature, air temperature, and airspeed in the two conference rooms where the control sequence was to be implemented. These measured data were used to calculate the mean radiant temperature and the OT based on ISO 7726-1998. These calculated OT values were then compared with those predicted by the ML model. Mean bias error (MBE) and Root mean squared error (RMSE) were calculated. The RMSE = 4% and MBE = 3%, the accuracy was found to be 96.77 %. With these results, the ML model was then used to predict OT for use in the control sequence.

Equipment installation and setup in spaces

Two conference room spaces in Bangalore were selected for the study. One was in a passively designed insulated office building, and the other was in a typical business as usual, uninsulated office building. Both rooms had split AC units and were operated in mixed mode. Atomberg brushless direct current (BLDC) smart fans were installed in both rooms.

Indoor environmental quality (IEQ) boxes were installed in both rooms to collect air temperature relative humidity data. The boxes also had sensors for CO_2, $PM_{2.5}$, and PM_{10}, but this data was not used in the study. Outdoor weather parameters are collected with a weather station on the building. Energy meters were installed to collect energy consumption data for the AC and the ceiling fans. Infrared (IR) blasters were installed to control the ceiling fans and the AC units. See Figure 1.



(a) (b) (c) (d)

Figure 1. Images of the hardware installed in each room: (a) BLDC ceiling fan, (b) IEQ box, (c)IR blaster, and (d) energy meters

Developing the control sequence

We use the IMAC for determining the thermal comfort band. Based on the National Building Code 2016, Volume 2, the 90% acceptability range for mixed-mode buildings band is calculated as

$$IMAC\_upper = ((0.28 \times \text{outdoor temperature}) + 17.87) + 3.46 \quad (1)$$

$$IMAC\_lower = ((0.28 \times \text{outdoor temperature}) + 17.87) - 3.46 \quad (2)$$

Where IMAC_upper and IMAC_lower are the upper and lower limits, respectively, of the thermal comfort band.

The IMAC_upper is used as the threshold for determining comfort.

The OT prediction ML model runs every minute using the data from the IEQ box and the weather station. The predicted OT is compared with the upper limit of the thermal comfort band.

To determine the upward shift of the upper limit of the band when air speed is introduced as a variable in space, we use the equation determined by De et al. (2022) [3].

$$y = -1.39x^2 + 4.92x - 1.38 \quad (3)$$

where y is the shift in the upper limit of the band and x is the air velocity.

The BLDC fans have 5 speed settings. For each setting, the air speed experienced by the users in the space is calculated as an average for the air speeds experienced by all the users. The air speed experienced by each user is calculated as the average air speed measured at heights of 0.6 m and 1.1 m from the floor level [18]. This approach was used to precalculate the airspeed achieved for each fan speed. The shift of the extended upper limit (extended_IMAC_upper) of the comfort band is calculated using the airspeed achieved at each setting and equation 3.

If the predicted OT is lower than IMAC_upper, the control sequence keeps the ceiling fan and AC off.

If the predicted OT is higher than IMAC_upper but lower than the extended_IMAC_upper, the control sequence turns on the ceiling fan to the appropriate air speed but keeps the AC off.

If the predicted OT is higher than the extended_IMAC_upper for the highest fan speed setting, the fan is switched on at the highest speed to use its full potential, and the AC is switched on with the highest set-point possible. This setpoint is calculated in the following steps:

1. By using the OT formula from ISO 7726-1998 to calculate the MRT in the space using the predicted OT value.
2. Then the air temperature in the space is calculated using the same formula since MRT and the desired OT values are known.
3. The calculated air temperature is sent as set-point temperature to the AC.

Thermal comfort study and energy monitoring

A total of 70 respondents participated in the study, with 34 males and 36 females. The respondents were not compensated for taking part in the study. They signed a consent form for taking part in the study and were part of one session. Each session spanned across 2 hours and 15 minutes. The first 30 minutes were orientation, filling of forms, and acclimatisation. The forms included data related to their age, gender, height, and weight, history of their space cooling adaptations and preferences, recent physical activity, and documentation of the clothing that they were wearing.

The respondents were exposed to 3 different types of conditions for 30 minutes each, with 5-minute break outside the test room between the 3 conditions. The conditions were: *condition 1* - room maintained at a constant 24ºC setpoint without ceiling fans; *condition 2* - room maintained at IMAC band neutral temperature without ceiling fans; and *condition 3* - room comfort maintained using the proposed control sequence.

The thermal comfort study was carried out from 14th March 2023 to 17th March 2023 in the BAU building for a total of 8 sessions with 40 participants, and on the 14th, 27th, and 28th of March in the passive building for a total of 5 sessions with 30 participants. Respondents filled out Google Forms, and their responses were collated in Google Sheets.

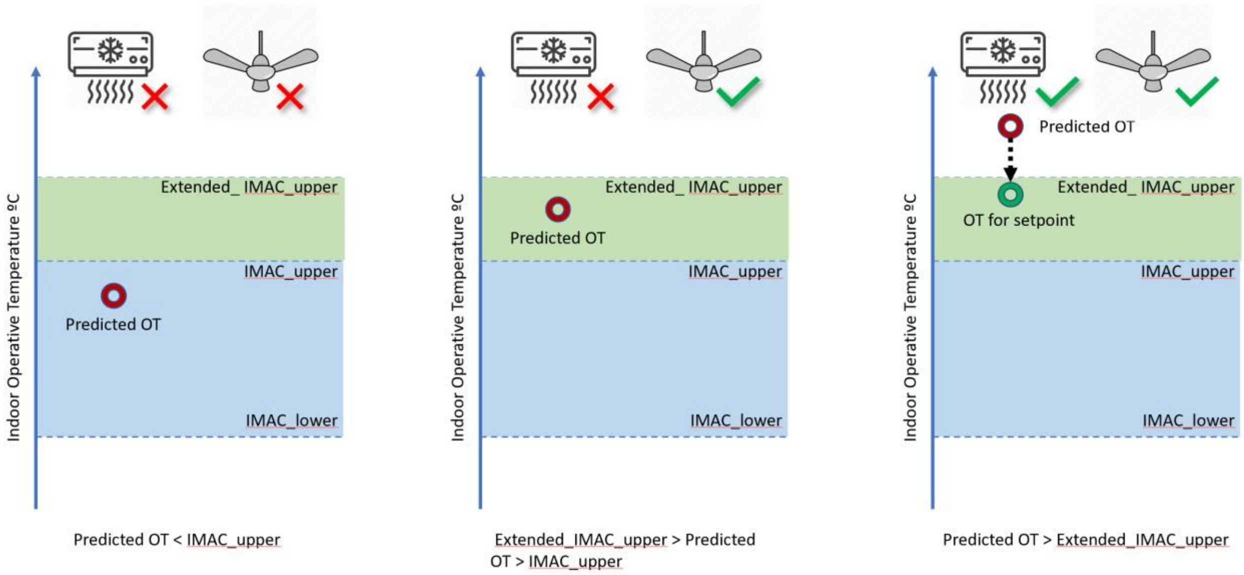


Figure 2: Three scenarios for the control sequence

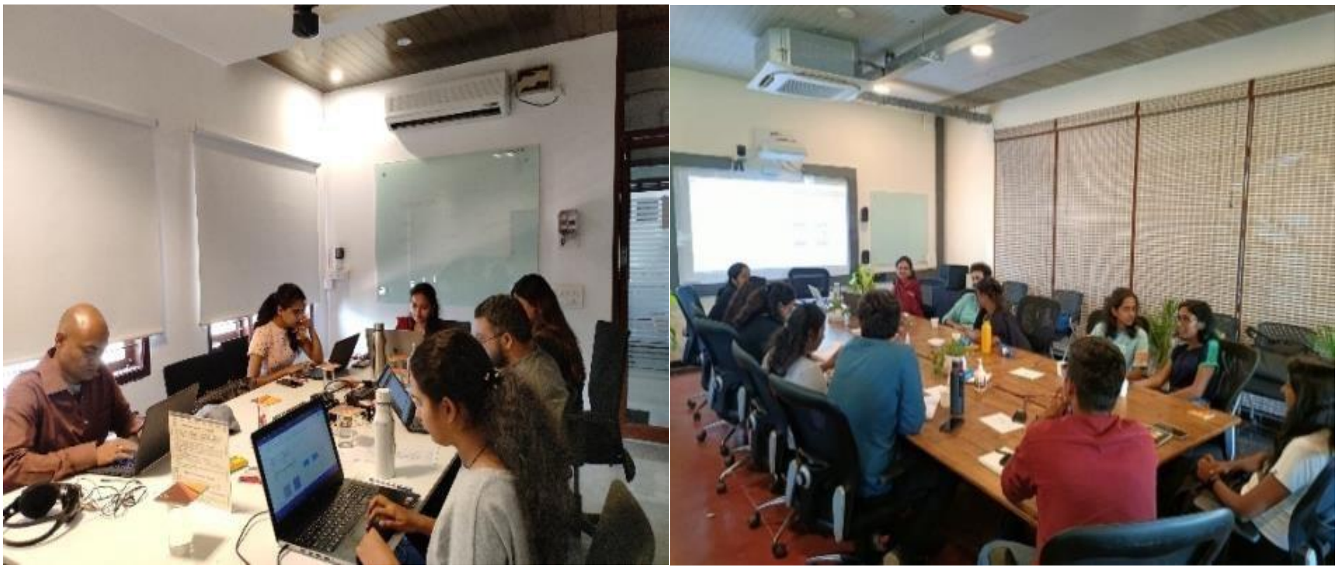


Figure 3: Thermal comfort study in progress

Energy used by the air conditioners and ceiling fans in kWh was recorded by the meters.

Figure 4: Space conditioning data from the survey

Results

Data summary

The outdoor temperature varied between 29ºC and 35ºC during the study. Around 60% of the respondents were in the age group of 20 to 39 years, and the gender ratio was almost equal. (51% male, 49% female). Most of the respondents were involved in sedentary activities before taking part in the survey. Figure 4 shows the space conditioning habits and preferences of the respondents. Almost 98% of the respondents answered that they use ceiling fans for space conditioning in their residence, followed by operable windows and usage of curtains/blinds. But in their workplaces, ceiling fans were used by 68% of the participants, and operable windows and air conditioners were used by about 49% of the participants. The preference for space conditioning methods shows ceiling fans are preferred by 49% and operable windows by 35%, respectively. ACs were preferred by only 15% of the respondents.

During the study period, the IMAC neutral temperature setpoint was calculated at 24ºC. This resulted in identical setpoints for *condition 1* and *condition 2*, and the results for thermal comfort and energy for those 2 conditions are very similar. Therefore, the thermal comfort and energy analysis results below only show *Condition 1* and *Condition 3*

Thermal comfort analysis

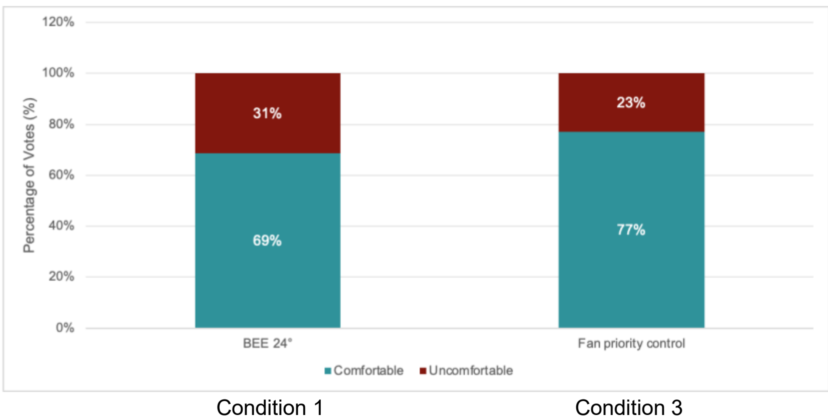


Figure 5: Thermal comfort votes for the 3 conditions tested

About 77% of the respondents reported being comfortable in *condition 3* - fan prioritized control sequence condition compared to about 69% in the other two conditions of the study (see Figure 5). While the study demonstrates that the fan-prioritised control sequence was preferred by the respondents, the statistical significance of these results needs to be determined.

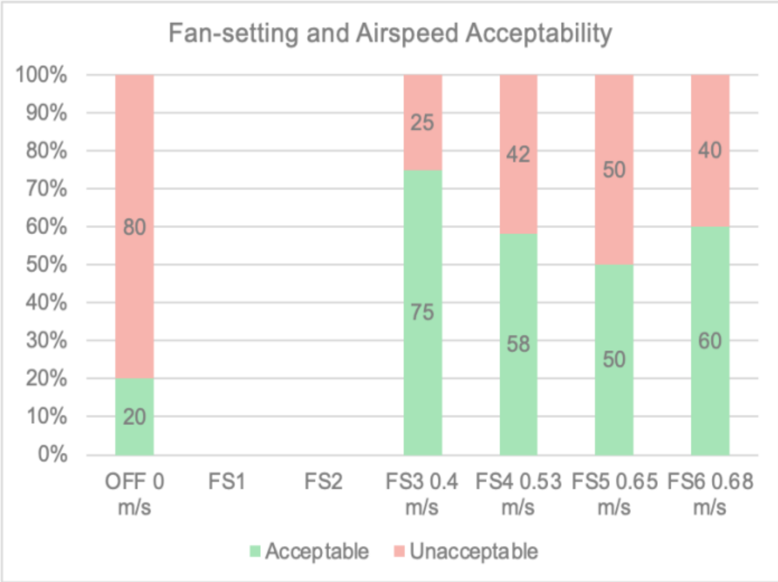


Figure 6: Acceptability of fan speeds

The respondents were also asked whether the airspeeds they experienced were acceptable to them. When the ceiling fan was off, 80% found this unacceptable. Since the fans did not come on at settings of 1 and 2 (FS1 and FS2) during the study, the data on these are not available. The airspeed of 0.4 m/s was acceptable to 75% of the respondents. The acceptability decreases when the air speed is 0.53 m/s and 0.65 m/s but seems to slightly increase again when the speed increases to 0.68 m/s (see Figure 6).

Energy analysis

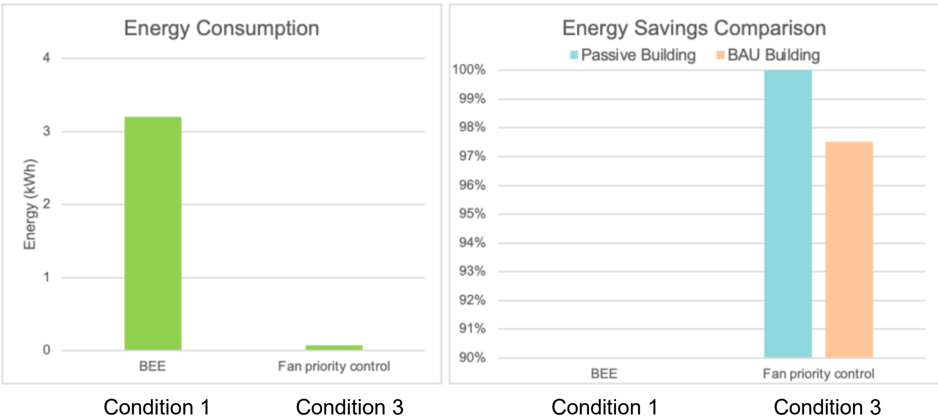


Figure 7: Energy Analysis Results, energy consumption (total during the study period in both buildings), savings for the fan-priority control compared to BAU for each building.

The energy consumption for each condition was calculated as the difference in energy meter readings at the start and the end of the condition. It is to be noted that the BEE 24°C baseline amounted to 3.32 kWh across all sessions while the fan prioritized control sequence consumed up to 0.07 kWh, resulting in a cooling energy savings of 97.9 % (see Figure 7, graph on the left). Please note that the outdoor dry bulb temperature was in the range of 35 °C to 29°C during the study period.

In the typical BAU building, the cooling energy savings were 97.9%, and in the passively designed building, the savings were 100% (see Figure 7, the graph on the right). The savings were 100% in the passive building because the OT was generally in the comfort band, and in the rare cases when it was outside the comfort band, it was lower than the extended_IMAC_upper. Thus, only the ceiling fan was switched on a few times, and the AC was never switched on. Due to the high efficiency of the ceiling fans and the least count of the energy meters, no energy consumption was recorded in the passive building. In the BAU building, while the OT was often greater than the IMAC_upper, it was generally lower than the extended_IMAC_upper, resulting in ceiling fans being switched on quite often. During the entire duration of the study in the BAU building, the AC was switched on for a duration of 5 minutes in condition 3, with the setpoint maintained at 30ºC. Thus, the energy savings for this 5-minute period (compared to the BEE 24ºC condition) was 82%. This shows that significant energy savings are possible with a ceiling-fan prioritised control sequence. This needs to be tested when higher outdoor temperatures are prevalent, where the air conditioner will kick in more often.

Conclusion

This paper shows the use of a machine learning model for predicting operative temperature as a scalable approach to providing comfort based on the adaptive model of the National Building Code of India. The approach that was developed earlier was validated in 2 test rooms for this study.

The control sequence developed in this study uses the CBE approach, where the corrective power index (CP) of ceiling fans was developed as an equation by De et al. [3]. It prioritises the use of ceiling fans in an automated control sequence, and this is tested in two conference rooms, one in a passive and one in a typical BAU building. This approach raises the upper limit of the thermal comfort band based on air speed achieved by the ceiling fan and also raises the AC set points when the ceiling fans are in operation.

The results show that 77% of the respondents found the space comfortable with the fan prioritised control sequence, as opposed to only 69% for the BEE proposed constant setpoint of 24ºC. The fan-prioritised control sequence also resulted in cooling energy savings of 98% during the study period, when outdoor temperatures varied between 29ºC to 35ºC.

The significant cooling energy savings and the fact that ceiling fans were adequate to provide comfort without ACs for several instances in the study period show that the ceiling fan prioritised controls or just ceiling fans for cooling can be a pathway to affordable and sustainable cooling.

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