Development of simulation-based strategy for mixed-mode operation of buildings

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Abstract

This study examines optimal operation strategies for mixed-mode buildings located in 8 tropical Indian cities. In order to evaluate the potential for mixed-mode operation, a small, single storey building with provision for natural ventilation (NV) is considered. The building performance is simulated using OpenStudio-EnergyPlus. EnergyPlus Typical Meteorological Year (TMY) data is used for generating the results. Depending upon the predicted inside conditions, decisions are taken whether to operate the building in non-air conditioned mode or air conditioned mode. PMV-PPD based thermal comfort model is used when the building is operated in air conditioned mode, while suitable adaptive thermal comfort model is used when the building is operated in non-air conditioned mode. An algorithm for optimal mixed-mode operation is developed, utilizing simulation data to guide window usage and HVAC systems. The algorithm enables users to input location, date, and time to determine whether to keep windows open or closed and whether to use mechanical cooling or heating systems. Results show that mixed-mode operation has a huge potential for saving energy without sacrificing thermal comfort.

Keywords - Mixed-mode buildings, Thermal comfort, Algorithm, OpenStudio-EnergyPlus, Indian tropical climate.

1. Introduction

With the growing concern about climate change and ever increasing energy consumption, there is a need to develop energy-efficient strategies in all sectors. Worldwide, buildings consume a significant amount of primary energy. A large fraction of the building energy is used for maintaining thermal comfort. Hence there is a need for smart building operation strategies that can reduce building energy usage and carbon footprint without sacrificing thermal comfort. The operation strategies depend both on the nature of the building and the climatic zone in which the building is located. Mixed-mode (MM) operation ensures thermal comfort throughout the year by making use of outdoor air whenever possible through ventilation, and the mechanical air conditioning system when required. Thus, MM operation holds great promise in reducing building energy consumption. However, there are not many studies on the potential of mixed-mode buildings for Indian conditions. The present study is focussed on improving building energy efficiency through MM operation, while considering the unique climatic conditions of tropical Indian cities. The major objectives are to determine the optimal pattern of opening area for ventilation in order to maximize the number of annual hours when indoor conditions are comfortable without operating the mechanical air conditioning system, and to operate the heating, ventilation and air conditioning (HVAC) system when it is not possible to maintain the required thermal comfort through ventilation alone. Using the building simulation tools the energy consumption trends of a building operating in only HVAC mode is compared against the natural ventilation mode condition for the same climate. The hourly indoor zone conditions are classified based on the simulation results for different city climates so as to develop a mixed-mode strategy that uses HVAC systems when indoor conditions are uncomfortable. Finally an algorithm is developed for optimal mixed-mode building operation, which can be used to make informed decisions about building operations.

1.1 Thermal comfort and comfort models

ASHRAE defines thermal comfort as "that condition of mind which expresses satisfaction with the thermal environment." To assess the level of satisfaction based on subjective evaluation, different comfort models have been developed by researchers over the years.

Fanger's Predicted Mean Vote (PMV) model [4], is a well-known and widely used method for evaluating thermal comfort in buildings. The model is based on the principle that humans have certain physiological responses to thermal stimuli, which can be measured and used to assess thermal comfort. The model considers six factors that influence thermal comfort: air temperature (t_a), mean radiant temperature (t_r), air velocity(V) , humidity ratio (W_a), clothing insulation (I_{cl}) , and metabolic rate (M). Based on energy balance, the thermal comfort equation is written in the form given by Eq.1.

$$f(t_a, t_r, W_a, V, M, I_{cl}) = 0 \qquad (1)$$

Equation 1 has 4 environmental factors (t_a, t_r, V and W_a) and 2 personal human factors (I_{cl} and M). The difference between left and right hand sides of Eq.1 yields the thermal load, which is then used to determine the Predicted Mean Vote (PMV). Using PMV, the Predicted Percentage Dissatisfied (PPD) is calculated for a given space. The PMV-PPD model does not take into account individual differences in thermal sensitivity. In addition, the model assumes that occupants are in steady-state conditions and does not account for transient conditions such as changes in outdoor temperature or sudden changes in metabolic rate. However, the model is thoroughly tested and is widely used for buildings with mechanical air conditioning all over the world.

Adaptive comfort refers to the range of thermal conditions that individuals can perceive as comfortable [6], which may vary based on factors such as clothing, activity level, and culture. The adaptive thermal comfort models recognize the fact that people can adjust to a wide range of thermal conditions, and that their preferences and behaviour are influenced by a variety of factors, including clothing, activity level, and expectations. These models consider the past interactions between the occupants and the environment to create a more nuanced and accurate understanding of thermal comfort. ASHRAE Standard 55, provides guidelines for thermal comfort in occupied spaces. It is the most commonly used standard worldwide. The adaptive thermal comfort equation for neutral temperature based on outdoor running mean temperature according to ASHRAE Standard 55 is given as:

$$T_n = 0.31 \times T_{RMT} + 17.8 \qquad (2)$$

Where, Tn is the neutral temperature in °C and T_{RMT} is the outdoor running mean temperature of 30 days in °C. The allowable range of outdoor running mean temperatures is between 10 and 33°C. In any adaptive thermal comfort model, the 80% acceptability range refers to the temperature range (across neutral temperature) within which 80% of occupants are likely to find the indoor environment thermally acceptable. This range is calculated based on field studies and statistical analysis of thermal comfort surveys. For equation 2, the 80% acceptable limits are Tn ± 3.5°C. If air velocity control is also available with the occupant then the comfort temperature can vary even further and the correction for increased air velocity as given by this standard is $3- < V_a < 0.6- \equiv 1.2$ ℃

Research indicates that Indians prefer higher indoor temperatures and relative humidity levels compared to people from temperate climates [8]. Comparative assessment of adaptive thermal comfort models for Indian tropical environments were conducted by Mishra [9]. In that study the adaptive cooling degree days were calculated using various standards. It was reported that the thermal comfort model EN15251 [10] is more accurate in predicting neutral temperatures for Indian conditions. Hence it was recommended until further studies on Indian climate are done. In India, where a significant portion of the population lives in hot and humid climates, there is a growing interest in understanding how to design buildings that promote adaptive comfort.

The Indian model for adaptive comfort [7] suggests that people in India have unique thermal preferences due to hot and humid living conditions. The IMAC study analysis of 6320 responses from various buildings showed that Fanger's PMV model consistently over-predicted warmer sensations, leading to unnecessary thermostat adjustments to low temperatures, which in turn lead to increased energy consumption during summers. To improve energy efficiency, the study advocates integrating passive cooling strategies and climate-responsive building designs, reducing reliance on energy-intensive systems. This approach can substantially save energy and lower carbon emissions, which can be crucial in a rapidly growing energy demand market like India [5]. An example on how to use these adaptive standards to analyse indoor conditions is shown in Fig.1, where comfort range can be seen coloured and indoor operative temperatures observed after an hour of simulation are scattered. Points lying outside the 80% zone are uncomfortable periods.

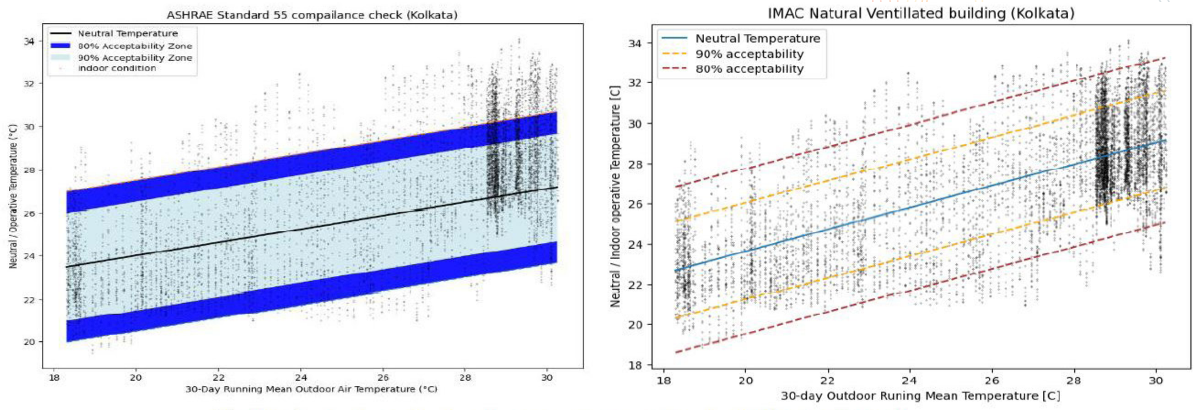

Figure 1: Applying adaptive thermal comfort models (a) ASHRAE-55 (b) IMAC

1.2 Exceedance metric and mixed-mode strategy

Numerous studies indicate that static models like Fanger's PMV-PPD over-predict discomfort in naturally ventilated or mixed-mode buildings. Though people living in naturally ventilated buildings tolerate higher indoor temperatures, extreme outdoor conditions can cause exceedance from comfort ranges, in which case it may be required to provide comfort through a mechanical air conditioning system, i.e., operating buildings in mixed mode. Quantifying exceedance, defined as uncomfortable hours, helps set occupant comfort expectations. For air-conditioned buildings, thermal comfort limits are based on PMV and PPD values. If PMV falls outside -0.5 to +0.5 or PPD exceeds 10%, thermal comfort is considered exceeded. For naturally ventilated building exceedance is considered to occur if the indoor temperature is beyond the 80% acceptability range. Generally, the exceedance metric aims for 3 to 5% of the occupied hours, as lower exceedance relates to higher HVAC installation costs or higher energy consumption.

In the study "Comfort Standards and Variation in Exceedance for Mixed-Mode Buildings" [1], the authors categorize exceedance metrics as: a) 'Percentage outside the range': Percent of occupied hours when PMV or operative temperature deviates from the range, b) 'Degree-hours criteria': Time the operative temperature exceeds the range during occupied hours, weighted by the degrees beyond the range and c) 'PPD weighted criteria': Accumulated time indoor temperatures fall outside the comfort range is weighted by PPD. Mixed-mode buildings require a tailored exceedance metric due to varying comfort temperatures which is currently not available. Adaptive model exceedance applies to them during natural ventilation (NV), while PMV exceedance applies when the air conditioning system is turned on.

Optimal opening and closing of external windows depending upon outside conditions plays an important role in mixed-mode buildings. A suitable control strategy is needed to control the window operation and the air conditioning system operation for an effective operation of mixed-mode buildings. The study "Optimal Control of HVAC and Window Systems for Natural Ventilation Through Reinforcement Learning (RL)"[2], compared a rule based heuristic control strategy with a reinforcement learning controller. The controller had five possible actions: [open window, cooling on], [open window, cooling off], [close window, cooling on], [close window, cooling off], and [close window, on heating], represented as [(1,1), (1,0), (0,1), (0,0), (0, -1)]. Specific cost and reward functions were designed to aid algorithm training. The model was simulated for Miami (hot-and-humid) and Los Angeles

(mild-warm) climates. The RL controller successfully maintained an indoor temperature of 24.5°C and relative humidity below 70%, outperforming the heuristic controller. In Miami, a 19% energy savings was achieved, while Los Angeles experienced 23% less energy consumption. The rationale behind selecting that particular temperature and humidity targets was however not provided in the publication. However, such studies are not available for Indian conditions. Many Indian houses have room air conditioners which are operated manually and sparingly whenever required to reduce energy bills. However, for large office or commercial buildings with potential for operation under mixed-mode, suitable control schemes are not available. Considering the increasing usage of air conditioning in large buildings, such as classroom complexes, mixed mode operation would be highly beneficial provided they are controlled optimally. Hence in the present study, the optimal, mixed-mode operation of a small building is proposed based on building simulation and appropriate thermal comfort standards. Though results are obtained for a small building, the methodology can be applied for any building given its specifications.

2. Methods

Before constructing naturally ventilated or mixed-mode buildings, climate suitability must be considered. For instance, regions consistently exceeding 35°C require mechanical cooling alongside natural ventilation. Thus, climate analysis is essential. This study's climate analysis is inspired by Borgeson's work [3] on Californian climatic zones. Examined cities, marked in red in fig. 2 [13], are major Indian tropical cities with moderate winter temperatures. Distances between these cities lead to substantial outdoor climate variations, allowing broader analysis of cooling loads and comfort across diverse conditions. The data needed for the present analysis was sourced from https://energyplus.net/weather uploaded by Indian Society for Heating Refrigeration and Air Conditioning (ISHRAE) in EnergyPlus weather format (.epw). Annual hourly TMY (Typical Meteorological Year) weather data captures median weather conditions over years.

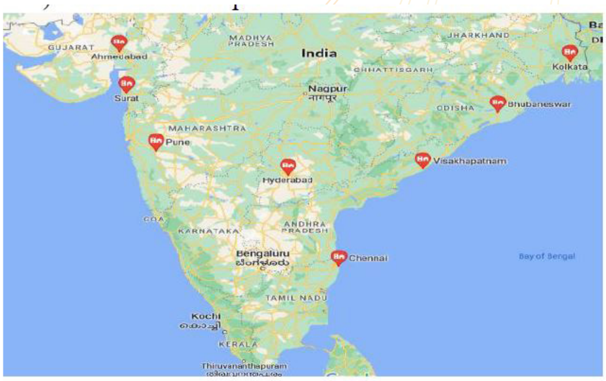

Figure 2: Location of the 8 cities considered for analysis

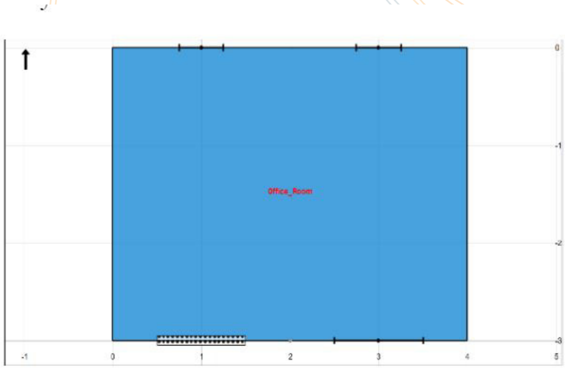

Figure 3: Building plan view. Typical hostel room size at IIT KGP

The climate analysis shows different city conditions and their impact on comfort. Climate isn't the only factor affecting comfort, building design matters too. Even if outside conditions are good for natural ventilation, a building's shape and orientation still affect thermal comfort of the occupant. So, the next step is creating a model of the building and analysing it in conjecture with outdoor conditions. OpenStudio - EnergyPlus package was used for this purpose. The model was created using FloorSpace JS available in the OpenStudio geometry tab, the plan can be seen in Fig-3. 3-D view of the model can be seen in Figs. 4 & 5. No windows or doors were placed on east and west side walls to reduce solar and fenestration loads.

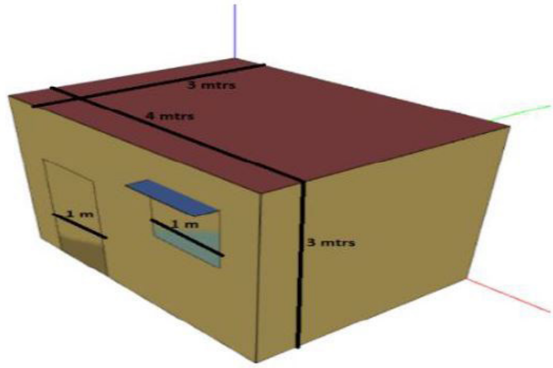

Figure 4: South facing view

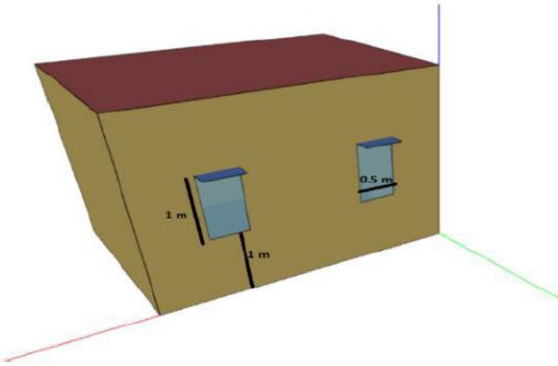

Figure 5: North facing view

The selection of materials of construction was based on ASHRAE 189.1-2009. The zone was assigned an occupancy of 2 people assumed to be present inside throughout the year (except heating design day). Of the total metabolic heat produced, 30 % was considered to be lost by radiation. Internal load of a computer (200W, fraction radiant=0.8) was added and an appropriate general scheduled usage was set for it. Similarly, an internal lighting load (60W, fraction radiant=0.5) with schedule was set. Constant infiltration rate of 0.5ACH (Air Changes per Hour) was set using LBNL method with 200 cm^2 effective leakage area. The daily indoor air velocity schedule was maintained at 0.1m/s from night 10PM to 6AM, from 7AM to 10 AM at 0.25m/s and from 10AM to 10 PM - 0.8m/s. While this assignment may appear arbitrary, it was designed to replicate the typical thermal loading conditions encountered within a standard hostel room at the institute (IIT Kharagpur). All the results obtained after the simulation of the model from the OpenStudio-EnergyPlus engine were converted to .csv format with the help of DView. Then statistical analysis on different city results was conducted with the help of Python libraries. All the Python codes developed during this study are available on GitHub public repository [12]. Using the simulation results an optimal window opening pattern was arrived at to maximise the indoor conditions (annual hours) at which 80% people feel comfortable (according to ASHRAE-55). Sensitivity analysis with this area opening pattern was performed by systematically altering some parameters, including room dimensions, door and window orientations, and window sizes, in the model room to obtain the impact of room design on occupant comfort.

3. Results and discussion

3.1 Climate Analysis

The primary driver of cooling loads and natural ventilation is the outdoor dry bulb temperature (DBT). Figure 6 illustrates the count of 'moderate' months in tropical climates, where the average daily maximum DBT is below 28°C and the average daily minimum DBT is above freezing point (0°C). Pune's climate aligns favourably with natural ventilation trends. To quantify favourable natural ventilation conditions, a better metric would be to examine the annual hours ideal for it. Figure 7 depicts the fraction of hours with DBT between 15°C and 28°C, coupled with outdoor relative humidity below 70%. Approximately 50% of annual time across these cities presents suitable conditions for natural ventilation. When humidity is high, fans can be used as they are generally available in every residential building. The ability to adjust clothing can further influence perceived comfort. Figure 8 shows the annual hours with outdoor DBT surpassing 28°C, portraying diverse nationwide conditions and illustrating the magnitude of cooling load scale. No specific threshold is set due to the fact that hot days can be followed by cold nights. Still it is obvious that Chennai and Ahmedabad will exhibit high cooling loads, with prolonged higher outdoor temperatures.

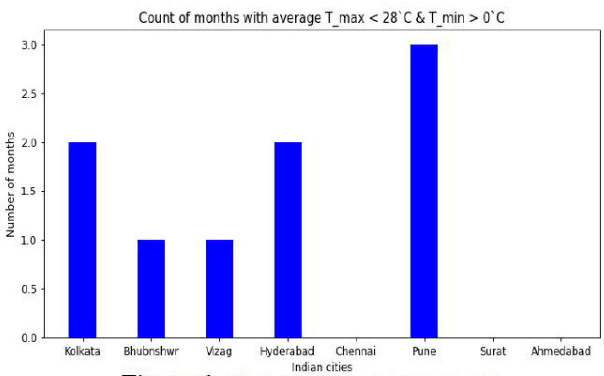

Figure 6: Moderate Temperature months

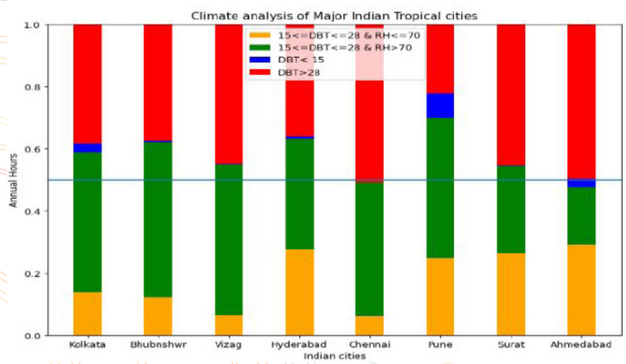

Figure 7: Natural Ventilation Favouring hours annual fraction

Evaluation of free cooling systems and structures considers available cooling resources. In absence of site-specific heat exchangers (e.g., water or earth), air around the structure is the primary heat exchange medium. Figure 9 shows yearly hours with DBT below 18°C for the eight cities. Insufficient overnight low temperatures might render radiant cooling systems ineffective the following day. It can be seen in Figure 9 Pune has the most annual hours for building envelope-air heat exchange, while Chennai has the fewest.

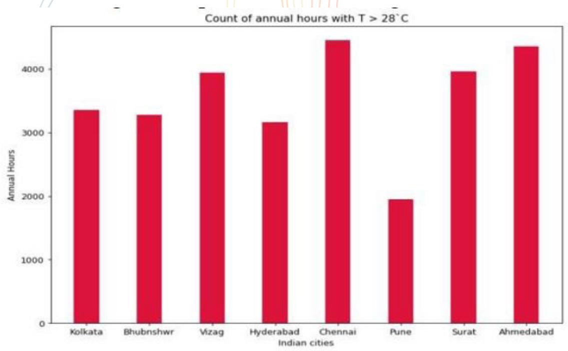

Figure 8: Annual hours above 28°C

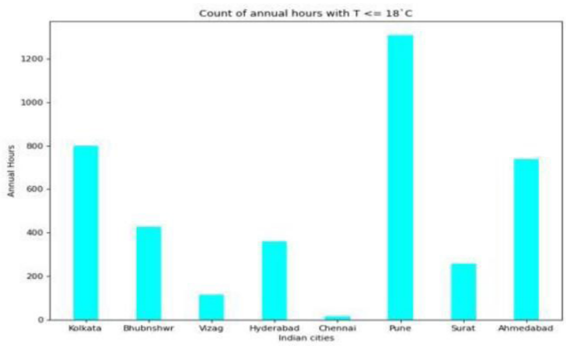

Figure 9: Annual hours equal or below 18°C

3.2 Window opening optimization

To emphasize the importance of windows, three cases were simulated: windows closed year-round, windows open constantly, and windows opened for favourable natural ventilation. Table-1 presents the results with simulations carried out for the city of Kolkata. As seen, open windows align room temperature with outdoor DBT. Thermal comfort varies as the outdoor temperature changes relative to ASHRAE-55 neutral temperature.

Table 1: Importance of proper window control

Case Type	Annual No. of hours when 80% are Comfortable (ASHRAE-55)	Number of hours annually when heating is required	Number of hours annually when A.C is required
Windows always open	6404	1177	986
Windows always closed	7002	35	1474
Optimized Window opening	7641	161	787

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Optimizing window control involves understanding complex human behaviour. Various researchers indicate varied views on key factors influencing window opening—indoor vs. outdoor temperature debate is still on. Simple window models used were in this study. Natural ventilation (NV) models in OpenStudio-EnergyPlus require optimization to maximise the number of hours indoor temperature is comfortable for occupants. EnergyPlus provides two objects "Design Flow Rate" and the "Wind and Stack with Open Area" object which can be added in the OpenStudio building model in the thermal zones tab to simulate it for NV. The former is named as ZoneVentilation:DesignFlowRate object and calculates a design flow rate of air that is modified by environmental conditions. The latter is based on equations of wind & stack effect as outlined in Chapter 16 of the ASHRAE Handbook of Fundamentals 2009, and is named as ZoneVentilation:WindandStackOpenArea object. If multiple ZoneVentilation: objects are defined for a single zone (as is the case in our model), the total zone ventilation flow rate is the summation of the ventilation air flow rates determined by each ZoneVentilation object After numerous simulation results and statistical analysis, the Key Performance Indices (KPIs) were set to optimum value by comparing the results. Delta Temperature (ΔT) indicates air temperature difference between indoor mean DBT & outdoor DBT below which the NV is shut down (i.e. area openings are closed). Results indicate that a value of ΔT=1°C provides best results, as it focuses on reducing indoor temperatures above 80% comfortable limits, considering tropical climate adaptability. Minimum Indoor Temperature(T_{zone_min}) and Minimum Outdoor DBT (T_{ODB_min}) below which NV will be closed are set at equal values, these serve as lower limit for NV, to avoid overcooling; varying these shut-off values from 15°C to 19°C, reduced number of hours heating was required. Maximum Indoor Temperature (T_{zone_max}) and Maximum Outdoor DBT (T_{ODB_max}) sets upper limit for NV shutoff as the area openings will be closed above if the temperature exceeds this value. Changing this threshold from 34°C to 40°C showed no change in the annual number of comfort hours. Analysis of the simulation results using pythermalcomfort [11] library supports these findings.

After the optimal natural ventilation area opening pattern was identified, the building model was then simulated for all the 8 cities using this pattern. Observed hourly indoor conditions were classified as comfortable, uncomfortable-heating required, and uncomfortable-cooling (air conditioning) required using the ASHRAE 55 Adaptive Thermal Comfort standard (Fig.10). From the bar graph it is evident that Bhubaneshwar, is having the best conditions for operating a mixed mode building as 7947 hours are comfortable. Whereas these hours are least for Ahmedabad, which can still operate in natural ventilation mode providing comfortable indoor conditions for 70% of annual hours (6476 hours). The same process repeated with IMAC model equations to get comparative assessment and to validate the simulation results. The regional sensitivity can be seen by comparing Figs. 10 and 11 as IMAC equation for mixed-mode buildings is classifying more hourly conditions as comfortable because it considers higher indoor temperatures as model comfort. However, this needs to be verified by conducting actual occupant comfort surveys.

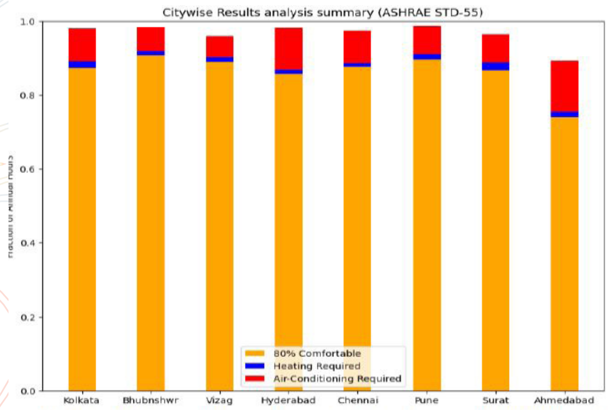
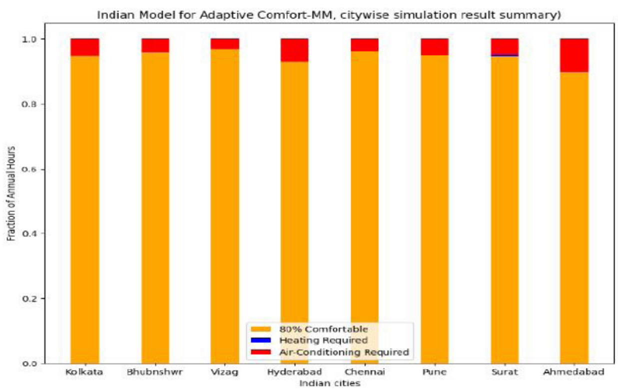


Figure 10: Annual Hours classified according to ASHRAE Std



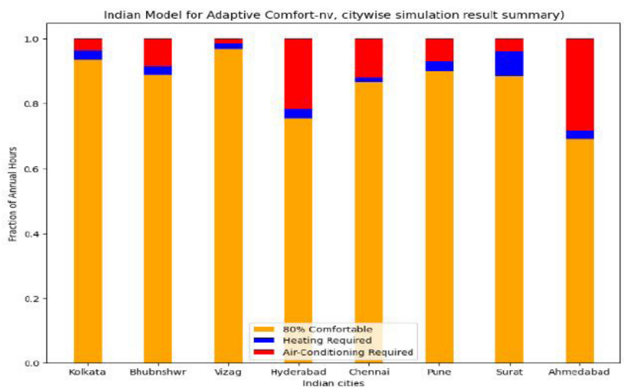


Figure 11: Annual Hours classified according to IMAC model (a) MM equation (b) NV equation

3.3 Sensitivity Analysis

In the context of Kolkata's climate, a 50% reduction in window size within the room led to a reduction in cooling demand by 137 hours and heating demand by 48 hours, illustrating the significance of smaller window openings in minimizing temperature fluctuations due to their reduced heat exchange area. Changing the room's window and door orientation from south-north to east-west resulted in a decrease in heating demand by 41 hours, while cooling demand remained largely unaffected, underscoring the influence of solar exposure on heating requirements. Moreover, increasing the room size from 12 m² to 20 m² decreased cooling demand by 678 hours but increased heating demand by 115 hours, implying that larger room dimensions may necessitate more heating in colder climates but reduce cooling demands in warmer climates due to the greater thermal mass involved. Using these simulation results and with the help of Python libraries mentioned earlier a mixed mode

Using these simulation results and with the help of Python libraries mentioned earlier a mixed mode assistance program code was developed. Mixed-mode buildings which blend natural ventilation and mechanical systems for energy-efficient comfort, face operational complexity due to weather, design, and occupant dynamics. Hence the proposed EnergyPlus simulation results driven algorithm for optimal mixed-mode operation can be very useful. The algorithm requires inputs like location, date, and time, then using the database, it helps occupants by guiding window, air-conditioning, and heating choices to sustain comfort and curb energy usage. Informed occupant decisions empowered by the algorithm will yield substantial energy reductions, contrasting conventional air conditioning-dependent strategies as can be observed by looking at Table 2. The total site energy was converted from kBtu to kWh and only electrical energy is used in this model. Visual examples illustrate the algorithm's efficacy in Fig.12.

. Table 2: Annual Power consumption trends

City	Annual electricity with HVAC [kWh]	Annual electricity without HVAC [kWh]	Potential electrical energy savings annually using MM [kWh]
Kolkata	7322.09	1258.45	6063.64
Bhubaneshwar	7144.49	1258.45	5886.04
Vishakhapatnam	7472.14	1258.45	6213.69
Hyderabad	5938.79	1258.45	4680.34
Chennai	7742.64	1258.45	6484.19
Pune	4883.44	1258.45	3624.99
Surat	7069.46	1258.45	5811.01
Ahmedabad	7141.56	1258.45	5883.11

```
Mixed-mode operation assistance provider

Select the city where you are located by entering the number mentioned in front of it:
 1.) Kolkata
 2.) Bhubaneshwar
 3.) Vishakhapatnam
 4.) Hyderabad
 5.) Chennai
 6.) Pune
 7.) Surat
 8.) Ahmedabad
 3

Now provide date, first by selecting the appropriate month:
 1.) January
 2.) February
 3.) March
 4.) April
 5.) May
 6.) June
 7.) July
 8.) August
 9.)Septemper
 10.) October
 11.) November
 12.) December
1
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Enter date of the month
1

Enter the time approximated to nearest hour mark for which you require information in 24-hour format {Eg. 6PM = 18 hrs 10AM = 10 hrs}
12

The annual hour {Starting from 00:00 AM on 1st January} provided by the user date and time is =  12


Based on our simulation results analysis, For the selected city and the time provided by the user.
At this hour
User should keep the windows:  Closed
Air-Conditioning System should be turned:  Off
Heater should be turned:  Off
```

Figure 12-*Mixed-mode assistance algorithm demonstration*

The algorithm's present static nature lacks adaptation to occupant behaviour changes or abrupt external influences on indoor conditions. To overcome this constraint, future enhancements could involve creating a model predictive controller capable of accommodating dynamic shifts in building operation and environmental variables, enabling more precise control signals. Also, future refinements should address limitations, such as assuming doors as area openings for stack effect, which may not consistently reflect real-world door usage and can impact the accuracy of predicted ventilation rates for indoor comfort. Different size building models can be studied and added as an option to enhance usability. IoT integration for real-time control of openings by a building management system can be done and verifying energy savings through meter data can be done.

4. Conclusions

The study on 8 major tropical Indian cities identifies optimal window opening criteria based on outdoor and indoor temperatures for efficient natural ventilation. Indoor conditions were assessed using 2 different adaptive comfort models. Sensitivity of indoor conditions to the room design was assessed. Mixed-mode suitability was established for all cities, particularly Bhubaneshwar and Pune. The technique developed can be replicated for any city and any building model. The developed algorithm aids residential building operation for comfort and energy reduction.

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