Integrating low energy cooling and ventilation strategies in Indian residences

MALCOLM JOHN COOK
YASH SHUKLA
RAJAN RAWAL
CHARALAMPOS ANGELOPOULOS
LUCIANO CARUGGI-DE-FARIA
DENNIS LOVEDAY
EFTYCHIA SPENTZOU
JAYAMIN PATEL

ABSTRACT

Rapidly developing economies of countries in hot climates face the risk of a significant increase in CO₂ emissions. This study developed strategies for low energy cooling and ventilation for Indian residences (LECaVIR). Ventilation and cooling techniques were developed and tested for India’s four climatic zones. The analysis shows that natural ventilation is possible in typical residential buildings for about 20–40% of the year. Using an enhanced natural ventilation mode with appropriately sized openable windows and controls, the total number of hours for which natural ventilation is able to offer satisfactory conditions for occupants can be extended by a further 13 percentage points, leading to a potential reduction of 46% in the mechanical cooling hours for residences. Dynamic thermal simulation models, coupled with control software, were used to test the most promising natural ventilation strategies as part of a mixed-mode approach to ensure year-round comfort at minimal energy cost. The simulation shows that energy savings of up to 55% are possible.

PRACTICE RELEVANCE

This paper demonstrates that it is possible to design and control cooling and ventilation strategies that make significant use of natural ventilation, despite hot climates. The paper contains details of innovative control algorithms that were tested using real designs for Indian residences where poor ventilation and overheating are common problems, often leading to the excessive use of inefficient, portable air-conditioning systems. Practitioners will also benefit from guidance on how to use dynamic thermal simulation coupled with control software to quantify the energy and thermal comfort performance of mixed-mode ventilation and cooling strategies.

TO CITE THIS ARTICLE:
Cook, M. J., Shukla, Y., Rawal, R., Angelopoulos, C., Caruggi-De-Faria, L., Loveday, D., Spentzou, E., & Patel, J. (2022). Integrating low energy cooling and ventilation strategies in Indian residences. Buildings and Cities, 3(1), pp. 279–296. DOI: https://doi.org/10.5334/bc.197
1. INTRODUCTION

Never in the history of humankind have the effects of global warming, driven by the increase in burning of fossil fuels, been so devastating and widespread around the world. One of the key drivers for this increase is the desire for thermal comfort coupled with the accessibility of affordable air-conditioning (AC) for delivering it (Randazzo et al. 2020). This is compounded further by an increasing global population in urban areas, relentless urbanisation and higher expectations of better living standards: matters that are especially pertinent in rapidly developing economies such as India. It is essential that these interconnected challenges are addressed if a sustainable future for the planet is to be provided.

Cities in India will grow to provide habitation to nearly 52% of the country’s total population by 2050 (UNDESA 2018), suggesting an increase in the new construction of dense, high-rise apartments. India’s major metropolitan cities have seen growth rates of 30% per year in AC usage. The CO₂ emissions from Indian buildings are predicted to increase by 700% by 2050, if unchecked (GBPN 2013). Rising global temperatures stipulate growing energy consumption, specifically for space cooling worldwide (IEA 2020). Currently, space cooling accounts for 30% of total building energy consumption (Manu et al. 2016a). Therefore, low energy cooling strategies are critical to circumvent the global escalation in carbon emissions due to AC.

In response to these challenges, substantive global collaborative initiatives such as Mission Innovation (M.I. 1.0 and M.I. 2.0) and Clean Energy Ministerial (CEM) have been launched collaboratively with the support of the European Union and various national governments, including India. These initiatives aim to promote clean energy innovation and smart cooling solutions to tackle climate change.

Establishing substantial reductions in carbon emissions in an accelerated timeframe whilst achieving desired thermal comfort levels requires a rigorous and methodical approach. Studies indicate that the majority of India’s residential building stock is designed to meet thermal comfort needs, specifically cooling, using spatial mixed-mode (MM) systems (GBPN 2014). This is because the installation and use of AC follow room type and design, allowing natural ventilation (NV) and AC to simultaneously operate in different spaces of the same building at the same point in time. Additionally, a lack of knowledge regarding its design and operation results in the minimum application of concurrent MM systems. Hence, low energy cooling systems such as evaporative cooling integrated with NV can form affordable energy-saving systems tailored to urban Indian apartments.

The influence of occupant behaviour in meeting the cooling needs suggests the importance of implementing windows with automated operation controls to optimise NV and cooling through MM systems, but without excluding occupants’ preferences and routines (Sorgato et al. 2016). Previous studies have shown that control optimisation using stochastic models of occupant behaviour can provide guaranteed energy conservative performance (Tanner & Henze 2016).

The potential for NV to contribute to thermal comfort and energy saving in buildings has been of interest internationally for a considerable time. Schulze et al. (2018) investigated the application of controlled NV for energy efficiency and thermal comfort for office-type buildings in Stuttgart, Germany. Bamdad et al. (2022) explored the impact of climate change on the energy-saving potential of NV and ceiling fans in MM buildings for a range of future Australian climates. In China, studies have explored where and when NV can be applied, based on studies for 100 cities across the country, these informing building design at the concept stage (Li & Chen 2021). Other studies (Costanzo et al. 2019; Liu et al. 2021) have considered the effects of built-up areas and particulate matter (PM2.5) pollution on NV potential for residential buildings.

In India, Khambadkone & Jain (2018) developed bioclimatic charts for the composite climate zone to evaluate passive heating and cooling strategies and comfort for a duplex housing typology, highlighting the need for the evaluation of other building typologies and other climate zones in India. Bhamare et al. (2020) used a bioclimatic analysis tool together with the India Model for Adaptive Comfort (IMAC) model for thermal comfort (Manu et al. 2016b) to evaluate the potential of NV, thermal mass and evaporative cooling strategies for cities across four Indian climatic conditions.
Ceiling fans are an important component in relation to indoor thermal comfort and airflow, and are used widely across India. The role of ceiling fans as ventilation-assisting devices is discussed in a review paper by Omrani et al. (2021), with knowledge gaps identified in relation to the interaction of NV and ceiling fans, and the effects of furniture on airflow in residential buildings.

Izadyar et al. (2020) review the impacts of facade openings on NV performance and occupants’ perception, identifying the need to quantify the impact of balcony geometries on NV, both technically and socially. Research on balcony effectiveness in climates with prolonged summers is suggested.

In terms of controllability of ventilation, a review by Guyot et al. (2018) recognises that ventilation needs to become smarter to address energy and indoor air quality (IAQ) issues. They present a meta-analysis involving 38 studies of various smart ventilation systems with control based on a range of environmental factors. Kim et al. (2019) developed an automatic ventilation control algorithm for a six-storey educational building in South Korea; and Cao et al. (2020) proposed a multiple-mode ventilator with air filtration, with mode switching according to outdoor and indoor air conditions. A validated model of the controller was applied to a hypothetical apartment located across five different climate zones in China.

Co-simulation has been used for the analysis of systems. Cucca & Ianakiev (2020) coupled a model of a district heating system built using Dymola-Modelica with the EnergyPlus model of the buildings, allowing for the development and evaluation of different control strategies. Hinkelman et al. (2022) present a systematic methodology for Modelica modelling and simulation of district cooling systems.

The present paper brings together coupled simulation incorporating dynamic thermal modelling (DSM) and Dymola-based control software with experimental validation using a room-scale environmental facility. These are applied to the situation of a typical residential apartment in India and across four of India’s climate zones to evaluate the potential for low energy cooling and ventilation for Indian residences (LECaVIR), including the effect of ceiling fans, as part of an MM approach for delivering year-round comfort at minimal energy cost.

2. METHODS

Climate analysis reported by Manu et al. (2018) was used to determine the potential for low energy ventilation and cooling in India’s four climatic zones. Based on this work, the cities selected for the current research were Ahmedabad (climate: hot and dry), Bangalore (climate: moderate), Chennai (climate: warm and humid) and Delhi (climate: composite). Dynamic thermal simulation, coupled with an equation-based simulation tool, was used to predict the performance of the control algorithms. These co-simulations were validated using extensive experiments carried out in a full-scale, purpose-built facility in India. Figure 1 overviews the research methods used.

2.1 SIMULATION OF CONTROL ALGORITHMS

The first step in developing suitable control algorithms was to identify all the parameters that may influence the performance of an MM control algorithm. These included operative temperature, occupancy density and external conditions. For this research, change-over MM systems were used. It has also been shown that ceiling fans, which are routinely used in Indian residences, increase the operating range of NV (Babich et al. 2017a).

To illustrate the use of the proposed control algorithms and simulation approach, a validation study was conducted using data from an experimental chamber in India. Finally, a demonstration two-bedroom case study was used to analyse the performance of the proposed control algorithms using co-simulations.
2.1.1 Description of the two-bedroom demonstration case

The applicability of the newly developed control algorithms to real buildings was assessed to predict their energy saving potential. For this purpose, a typical two-bedroom apartment block was selected based on Rawal & Shukla’s (2014) identification of the most typical residential layout built using reinforced concrete floor plates, with brick and concrete block masonry walls. Two different types of building envelopes were considered in this study: one denoted as business as usual (BAU) and the other from the Energy Conservation Building Code (ECBC), with envelope properties presented in Table 1, and air infiltration rate of 1 ach (air change per hour) (Rawal & Shukla 2014). Three different thermal zones were analysed in the present study (bedroom 1, bedroom 2 and the kitchen/living room), while other zones (bathrooms, balcony and hall) were considered to be isothermal relative to the adjacent zones. The three-dimensional (3D) model shown in Figure 2 gives the location of the windows/dampers for the two-bedroom apartment.
2.1.2 Description of the ventilation and cooling strategies for the two-bedroom demonstration case

Four ventilation and cooling control strategies (VCSs) were examined. The selection of the strategies was based on the climate, energy saving potential, indoor environmental conditions and ease of implementation. VCS 1 and VCS 2 include the windows and/or dampers and mechanical cooling systems to maintain thermally comfortable internal conditions. These systems are widely used in residential apartments in India. VCS 3 incorporates the use of ceiling fans. Lastly, VCS 4 additionally incorporates a dehumidifier and mechanical ventilation, which was anticipated to achieve the optimal thermal comfort conditions. For all strategies, the analysis focused on the predicted energy savings and the change in thermal comfort conditions based on the adaptive theory (Manu et al. 2016a). The control algorithm for each system was developed in independent modules that were operated by master algorithms to allow scalability based on the available systems. Four ventilation and cooling scenarios were developed to balance the flexibility and complexity of operation. Further, this approach also allows the user to determine an appropriate scenario (e.g. choose scenario VCS 3 instead of VCS 4 to keep the operation simpler) based on the desired complexity in the residential buildings.

Table 1: Building envelope properties.

Note: BAU = business as usual; ECBC = Energy Conservation Building Code; XPS = extruded polystyrene.

Sources: Bureau of Energy Efficiency (2009), GBPN (2014), Rawal & Shukla (2014).

Figure 2: Floor plan for the two-bedroom apartment case study.
Note: Dimensions = mm.
A base case scenario was developed representing a fully AC mode. In this mode, all windows and dampers designed for NV remain closed, and when heating or cooling was needed, the mechanical system was turned on. This offers the ideal case for thermal comfort, but is the worst-case scenario regarding energy consumption. For this specific scenario, no minimum ventilation rate to ensure IAQ levels was considered because the focus of the analysis was cooling ventilation effectiveness. The environmental chamber remained unoccupied at all times during the experimentation period.

Each ventilation scenario (Table 2) was evaluated for all four cities with the aim of assessing the energy savings and thermal comfort conditions possible using the new control algorithms. The free areas ($A_f$) of the openings were dimensioned using analytical techniques for buoyancy- and wind-driven ventilation strategies for one or multiple openings found in CIBSE (2005, 2010). For the detailed application of the method for sizing openings for NV with examples for residential buildings in the Indian climates, see Cook et al. (2020) and de Faria et al. (2018, 2019). No shading devices were considered in any case to allow direct comparison of the results representing worst-case scenarios.

| APARTMENT SPACE | WINDOWS | DAMPERS | CEILING FAN | MECHANICAL COOLING–AC SPLIT UNIT | DEHUMIDIFIER | MECHANICAL VENTILATION |
|-----------------|---------|---------|-------------|---------------------------------|--------------|-----------------------|
| Living room     | Yes     | Yes     | Yes         | Yes                             | Yes          | Yes                   |
| Master bedroom  | Yes     | Yes     | Yes         | No                              | No           | No                    |
| Small bedroom   | Yes     | Yes     | Yes         | No                              | No           | No                    |

Table 2: Summary of the different ventilation and cooling scenarios and systems per space.
Note: AC = air-conditioning; VCS = ventilation and cooling control strategy.

### 2.1.3 Mixed-mode control algorithms

Several control algorithms were developed for the different thermal zones depending on the occupancy levels and time of day. Presented in the form of flow charts (Figure 3), these prioritise the use of passive techniques whenever ventilation or cooling is needed during occupied hours. When the internal air temperature is between the heating and cooling setpoint, the control algorithms operate the dampers and the windows to maintain acceptable internal conditions. Dampers have the highest priority to operate over the windows, and only when the dampers are 100% open are the windows enabled. The modulation of the windows or dampers is a dynamic process where the control algorithms use a linear relationship to calculate the appropriate opening factor for the opening so as to provide the required airflow rate.

The windows were restricted to 20% of their maximum openable area during the night-time to use the well-known benefits of night-time ventilation whilst also maintaining security.

When outdoor and indoor conditions do not favour the use of NV, the control algorithm activates the mechanical system to meet the cooling requirements. When the internal air temperature is below the heating setpoint, and the external air temperature is below the internal air temperature, the windows and dampers are kept closed and the mechanical heating systems are activated. Whenever the control algorithms activate the dampers/windows, mechanical systems are switched off automatically. All the algorithms provide the option to the occupants to override the built-in algorithm either by selecting the manual override function or by adjusting the setpoints to control a specific component. In cases where the network or power communication is lost for a prolonged period (30 min), all the ventilation and cooling systems will move to a position defined by the safety protocol.
Window control was performed in accordance with the required airflow rate for delivering cooling in response to internal heat gains rather than in response to the internal/external temperature difference, which is the common approach for window operation in EnergyPlus (Angelopoulos et al. 2018). Modulation of the windows was implemented to match the calculated required effective area for the given conditions. To represent windows and dampers in the simulation model, the airflow network module in EnergyPlus (DOE 2018) was used to simulate the indoor–outdoor air exchange.

It was assumed that the ceiling fan could operate at three fan speeds, resulting in internal air velocities of 0.6, 0.9 and 1.2 m/s (Babich et al. 2017b). In the scenarios where ceiling fans were modelled, the setpoint temperature for NV was increased based on the air velocity. To represent the operation of ceiling fans in EnergyPlus, the setpoint temperature for cooling was increased according to the fan speed. ASHRAE Standard-55 (ASHRAE 2013) has incorporated in its documentation the advantages of the use of a ceiling fan by increasing the acceptable range for operative air temperature by 1.2, 1.8 and 2.2°C for internal air velocities of 0.6, 0.9 and 1.2 m/s, respectively. The energy consumption of the ceiling fan was assumed to be 50 W (Babich et al. 2017b).

2.1.4 Description of the simulation approach

Dynamic thermal modelling (DTM) tools are designed to handle annual energy performance simulation rather than to assess an advanced control strategy for passive or active systems. To improve the accuracy of DTM tools when assessing the controls of mechanical systems, co-simulations, coupling DTS with other programs, can be used (Nouioui & Wetter 2014; Angelopoulos et al. 2018; Borkowski et al. 2018). A standardised method to facilitate the exchange of information between the two simulation tools known as the Functional Mock-up Interface (FMI) (MODELISAR 2017) was used.

When performing a co-simulation, one simulation tool is considered the master simulator handling the communication time step and the exchange of variables, and the other tools are the slaves. The current study used the DTM EnergyPlus v8.6.0 and Dymola v2017 FD01 (Dymola 2018), which is the commercial simulation environment based on the Modelica language, along with the FMI standard v1.0. Dymola was used as the master simulation tool, and EnergyPlus was the slave. Dymola was used to handle the communication time step and variable exchange information (Bastian et al. 2011).
To access all the components needed for the control algorithms, the use of the Energy Management System (EMS) module in EnergyPlus was used (DOE 2017). In EnergyPlus, the building envelopes, mechanical systems, occupancy schedules, and internal heat gains were created and modelled whilst the new control algorithms were developed in Dymola, allowing for simulation flexibility as the same control algorithms could be used with different models without changing the control logic (Angelopoulos et al. 2018). Internal air temperature, internal heat gains, occupancy schedule and weather conditions were transferred from EnergyPlus to Dymola (Figure 4). Dymola then runs the control algorithms and sends information to EnergyPlus about the operation mode, position of the windows, ceiling fan speed, mechanical fan speeds, operation of the mechanical ventilation unit, operation of the dehumidification unit and setpoint temperatures. As mentioned above, the ceiling fan speed information was converted into an adjusted cooling setpoint temperature in EnergyPlus.

The simulation time step in EnergyPlus was equal to the sampling time in Dymola (600 s, or 10 min), allowing synchronisation of the two simulation tools. Information exchange between the two simulation platforms occurred automatically in each time step and throughout the whole simulation period (one year). The small time lag in practice caused by the time required for the control algorithm to activate the windows/dampers and the time required by the BMS to send them the signal is not present during the co-simulations, so the signal is assumed to be transferred instantaneously.

2.1.5 Simulated scenarios for the validation analysis

For the validation study, average hourly data were used to compare the simulated results with data measured in the experimental chamber (see Section 2.3). Steady-state data were used for the validation study to examine the validity of the proposed control algorithms and the co-simulation technique. By selecting hourly data, it was feasible to examine a variety of different outdoor and indoor conditions and windows/dampers configurations.

To quantify the discrepancies in the results, two statistical indices were used to provide evidence of the validation method:

- Mean bias error (MBE), which captures the mean difference between the measured and the simulated data, and is a good indicator of the overall bias in the model (Coakley et al. 2014). A limitation of this method is that the positive and negative errors cancel each other out when summed, which might lead to positive bias compensating for negative bias:

\[
\text{MBE}\% = \frac{\sum_{i=1}^{N_i} (m_i - s_i)}{\sum_{i=1}^{N_i} m_i}
\]

where \(m_i\) is the measured data; \(s_i\) is the simulated data; and \(N_i\) is the number of data points.

Figure 4: Variable exchange between the EnergyPlus and Dymola simulation tools.
• Coefficient of variation of root mean square error (CVRMSE), which captures the error between the measured and simulated data without the cancellation effect described for MBE (Granderson & Price 2014):

\[
CVRMSE(\%) = \sqrt{\frac{\sum_{i=1}^{N_p} (m_i - s_i)^2}{N_p}}
\]

(2)

where \(m_i\), \(s_i\) and \(N_p\) are as defined in equation (1); and \(m\) is the average of the measured data. CVRMSE was recommended by ASHRAE Guideline 14 (ASHRAE 2014) and previous studies (Coakley et al. 2014; Granderson & Price 2014). The simulation results were evaluated against the measured data from the experimental chamber.

### Table 3: Scenarios examined for the validation study.

| SCENARIO | DATE       | TIME (HOURS) | \(T_{\text{out}}\) (°C) | \(T_{\text{internal}}\) (°C) 1 H BEFORE THE EXPERIMENT | WINDOW OPENING AREA (m²) | DAMPER NV1 OPENING AREA (m²) | DAMPER NV2 OPENING AREA (m²) | ASSUMED AIR VELOCITY (m/s) | TOTAL INTERNAL HEAT LOAD (W) |
|----------|------------|--------------|--------------------------|------------------------------------------------------------|--------------------------|-------------------------------|-----------------------------|----------------------------|-----------------------------|
| 1        | 2 July     | 23.00–00.00  | 29.3                     | 31.3                                                       | 0.440                    | 0.171                         | 0.173                       | 0.6                        | 305                         |
| 2        | 4 August   | 08.00–09.00  | 27.4                     | 27.9                                                       | 0.501                    | 0.183                         | 0.184                       | 0.0                        | 216                         |
| 3        | 11 March   | 21.00–22.00  | 27.3                     | 29.4                                                       | 0.416                    | 0.170                         | 0.173                       | 0.9                        | 324                         |
| 4        | 14 May     | 03.00–04.00  | 27.3                     | 29.4                                                       | 0.398                    | 0.170                         | 0.172                       | 0.0                        | 262                         |
| 5        | 5 December | 00.00–01.00  | 20.5                     | 25.0                                                       | 0.281                    | 0.150                         | 0.155                       | 0.0                        | 285                         |
| 6        | 16 August  | 02.00–03.00  | 26.3                     | 29.7                                                       | 0.315                    | 0.156                         | 0.159                       | 1.2                        | 322                         |
| 7        | 6 November | 22.00–23.00  | 23.8                     | 30.2                                                       | 0.0                     | 0.092                         | 0.102                       | 1.2                        | 322                         |
| 8        | 31 January | 07.00–08.00  | 18.3                     | 23.2                                                       | 0.0                     | 0.133                         | 0.133                       | 0.0                        | 267                         |
| 9        | 7 August   | 06.00–07.00  | 25.6                     | 30.7                                                       | 0.0                     | 0.133                         | 0.139                       | 0.6                        | 326                         |

To determine suitable conditions for the validation experiments, co-simulations were performed using the geometry of the experimental chamber and the weather file of Ahmedabad, and the control algorithms presented in Figure 3. Findings were analysed and clustered into groups based on outdoor air temperature. Outdoor air temperatures were grouped into 1°C intervals for each group; the number of hours for which the windows and/or dampers operated was counted. This allowed the calculation of the frequency that each scenario occurred. The cases with the highest occurrences were selected to be simulated in the experimental chamber (Table 3).

### 2.3 EXPERIMENTAL CONFIGURATION AND METHODS

Experimental measurements were conducted in a full-scale low energy characterisation chamber located at CEPT University, Ahmedabad. The facility consists of an outer chamber (10 × 8 × 8 m) and an inner chamber (5.05 × 3.95 × 3.00 m), which represent the external and internal environments, respectively. The inner chamber represents a typical Indian bedroom. Two air-handling units are installed, one per chamber. The outer chamber can maintain a wide range of conditions (10–45 ± 0.3°C air temperature, 15–95% ± 3% relative humidity—RH). The inner chamber is equipped with a motorised window (1.2 × 1.2 m) and four motorised vents (0.4 × 0.4 m). Building materials and properties are presented in Table 4.

A total of 13 flexible air temperature sensors were used, arranged using a 3 × 3 × 3 m grid (Figure 5). Four air temperature and RH sensors and six CO₂ sensors were installed and calibrated in an externally accredited laboratory. A CO₂ source used as a tracer gas was placed at the centre of the inner chamber to represent the internally generated CO₂. CO₂ sensors were placed in the centre of the low- and high-level vents and in the outer chamber.
Before each individual experiment was performed, the process comprised a ‘warming up and stabilization’ period to reach a steady state (phase A), followed by the release of the CO\textsubscript{2} (phase B), the experimentation period (phase C) and finally the period required to cool the chamber in preparation for the next experiment (phase D). In phase B, the fan, window and AC were set up as per the configurations shown in Table 5, and all internal loads were maintained as per Table 3. The experiment used tracer gas-decay measurement techniques to estimate air exchange rates of the chamber under different scenarios (ASTM International 2011). The tracer gas-decay technique injects known concentrations of tracer gas into a space and solves the mass balance equations on the injection rates and measured concentrations. These techniques and their uncertainties

| MATERIAL          | CONDUCTIVITY (W/(mK)) | SPECIFIC HEAT (J/(kgK)) | DENSITY (kg/m\textsuperscript{3}) |
|-------------------|-----------------------|-------------------------|-----------------------------------|
| Kota stone        | 3.02                  | 668                     | 3102                              |
| Sand mortar       | 0.88                  | 896                     | 2800                              |
| Plain cement concrete | 0.72              | 840                     | 1860                              |
| Cement putty      | 0.114                 | 742                     | 1070                              |
| Plaster (dense)   | 0.50                  | 1000                    | 1300                              |
| AAC block         | 0.35                  | 1100                    | 780                               |
| Insulation (XPS)  | 0.029                 | 1525                    | 37                                |
| RCC (2% steel)    | 2.50                  | 1000                    | 2400                              |
| Cement mortar     | 0.720                 | 920                     | 1650                              |
| Ceramic tiles flooring | 0.920             | 820                     | 1950                              |
| Acrylic paint     | 0.201                 | 1342                    | 745                               |

Table 4: Construction materials and thermal properties of the experimental chamber.
Note: AAC = autoclaved aerated concrete; RCC = reinforced cement concrete; XPS = extruded polystyrene.

Figure 5: Sensor location in the experimental chamber.
are well documented in the literature, with the detailed methodology and governing equations provided for each technique (McWilliams 2003; Persily 1988, 2016). The CO₂ tracer flow was maintained to achieve 2000 ppm (parts per million) inside the indoor chamber. In phase C, the indoor conditions (temperature, RH and CO₂ level) were monitored for more than four hours (Figure 6). The experiment collected data from all the sensors are listed in Table 5.

3. RESULTS

3.1 VALIDATION OF THE DYNAMIC THERMAL MODEL AND CONTROL ALGORITHM

Validation of the co-simulation method (Figure 7) shows a high level of agreement. For most scenarios, air changes per hour (ach) were predicted to be higher for the co-simulations relative to the measured values, although within the error margins. This was due to wind being taken into consideration in the simulations, whereas only buoyancy-driven cases were evaluated in the chamber, resulting in the prediction of lower ventilation rates. The wind was not removed from the weather files because the intention was to validate the co-simulation approach and then use the same model and inputs to predict the energy savings.

The highest impact of the wind occurred in scenarios 3 and 6 where the highest wind speeds were observed (5.9 and 7.2 m/s, respectively).

Simulations overpredicted the air change rate by approximately 5–11% compared with measurements, due to being dynamic and steady state, respectively. Parameters such as external air temperature and heat gains, etc. varied constantly over time, but for the determination of the results from the experiment, hourly averages were used. This further explains the small discrepancies in the results.

The analysis showed that the MBE and CVRMSE were 7.25% and 20.64%, respectively. Based on ASHRAE Guideline 14 (ASHRAE 2014), the acceptable limits for the hourly calibration of building energy simulation models were 10% and 30% for MBE and CVRMSE, respectively. Hence, both indices are within the proposed limits, providing evidence that the co-simulations provided acceptable results.
3.2 PREDICTED THERMAL COMFORT CONDITIONS

The use of more night-time NV has benefits because it can take advantage of the cooler outside air to cool the thermal mass of the building and possibly to mitigate the risk of uncomfortable internal conditions due to high internal air temperature during the next day. However, the use of night-time ventilation is not always favourable, mainly for safety and noise reasons. When a 20% night-time restriction was imposed for security reasons, mechanical cooling was used more during the day due to the systems’ inability to use the diurnal temperature difference. In cases without any restrictions, the algorithms calculated the opening area to be approximately 50–60% of their maximum allowable opening area during the night-time. This resulted in lower internal air temperatures, which favoured the use of NV during the daytime, as preconditioning had occurred. Similar window-operation patterns were predicted for all four climates.

For all four climatic conditions, the use of ceiling fans significantly increased the operation of the windows due to the higher setpoint temperatures for NV (see Section 2.3), leading to predictions of larger openable areas for windows/dampers compared with cases without ceiling fans. In Bangalore, with the most moderate climate compared with the other cities, the co-simulations predicted a more frequent operation of the windows/dampers throughout the year. On the other hand, in Chennai, with high outdoor air temperatures and RH, the co-simulations predicted that the windows/dampers operated less frequently, approximately 5–35%, compared with the other cities.

The hourly average zone internal air temperature was compared with the hourly comfort temperatures proposed by the IMAC model for 90% acceptability. Table 6 summarises the hours of the year that NV was able to provide ventilation/cooling and maintain the internal conditions within the comfort limits due to the controls. NV hours are the hours of the year that the co-simulations predicted exclusively NV/cooling mode. Comfort hours are the total hours that the internal operative temperature was within the comfort limits, provided by the IMAC thermal comfort model, during the NV operational mode.

The use of ceiling fans can result in 8–25% more use of NV compared with VCS 2 for all the cities studied, which is supported by the findings of Omrani et al. (2021). The higher percentages of thermal comfort were predicted in the city of Bangalore due to the moderate climatic conditions.

The most significant improvement from case VCS 1 of the predicted hours of NV was observed for the city of Chennai, with a warm and humid climate. The introduction of the dampers and ceiling fan, VCS 3, increased the predicted hours of NV by 1329 h (74%) compared with VCS 1, which
aligns well with that predicted by others (e.g. Li & Chen 2021). Chennai has a high mean yearly outdoor air temperature, hence the use of only windows was unable to maintain a thermally comfortable internal environment. Dampers (VCS 2) and ceiling fans (VCS 3) used NV and increased the predicted hours for thermal comfort by 18%.

The use of stand-alone dehumidifier units leads to decreased NV due to the thermodynamic process of a dehumidifier. The humid air of the room enters the dehumidifier, where it is cooled to its dew point and releases its moisture. The dry air is then heated, due to latent heating, which is a natural process that occurs in the condenser. Also, the compressor releases heat, which can result in higher air temperature of the exhaust air compared with the inlet temperature. This results in the higher internal air temperature and reduced predicted hours of NV for VCS 4 compared with VCS 3.

Regardless of the climatic conditions or cooling system, the analysis showed that for approximately 60–75% of the hours when NV was used, the internal operative temperature was within the comfortable limits. In Bangalore, with moderate climatic conditions, the co-simulations predicted the highest percentage of comfort hours for both cooling systems, although these were outside the desirable limits. The use of windows/dampers alone could not provide the adequate provision of outside air. In addition, considering the strict comfort limits imposed by the IMAC model, the analysis showed that it is not feasible to rely only on the windows/dampers to achieve comfort conditions. The introduction of ceiling fans in the bedrooms and living rooms resulted in higher setpoint temperatures, suggesting that NV was selected for a wider range of external temperatures. This justifies the higher percentages of thermal comfort conditions predicted for VCS 3 over VCS 1 and VCS 2. The application of ceiling fans in the control algorithms increased the number of comfort hours for all cities and cooling systems. The most significant improvement was observed for both the moderate climate of Bangalore and the hot and dry climate of Ahmedabad. For no window night-time restriction, 90% acceptability was met for Bangalore and Ahmedabad. For Chennai and Delhi, up to 85% comfort hours were predicted, which is very close to the acceptability limit.

| CITY          | AHMEDABAD | BANGALORE | CHENNAI | DELHI |
|---------------|-----------|-----------|---------|-------|
| Window operation with up to 20% night-time restriction or none | Restrict | None | Restrict | None | Restrict | None | Restrict | None |
| VCS 1 (without ceiling fan) | | | | | | | | |
| Comfort hours (h) | 1287 | 1557 | 2788 | 2977 | 948 | 1458 | 986 | 1247 |
| NV hours (h) | 2247 | 2398 | 4673 | 4879 | 1797 | 2647 | 1876 | 2247 |
| Comfort hours/(NV hours) (%) | 57% | 65% | 60% | 61% | 53% | 55% | 53% | 56% |
| VCS 2 (without ceiling fan) | | | | | | | | |
| Comfort hours (h) | 1758 | 2018 | 3578 | 3987 | 1267 | 1787 | 1685 | 1934 |
| NV hours (h) | 2378 | 2680 | 4757 | 5087 | 2058 | 2700 | 2230 | 2487 |
| Comfort hours/(NV hours) (%) | 74% | 75% | 75% | 78% | 62% | 66% | 76% | 78% |
| VCS 3 (with ceiling fan) | | | | | | | | |
| Comfort hours (h) | 2457 | 2788 | 4673 | 5304 | 2449 | 2946 | 1968 | 2315 |
| NV hours (h) | 2745 | 3058 | 5087 | 5677 | 3126 | 3575 | 2384 | 2679 |
| Comfort hours/(NV hours) (%) | 90% | 91% | 92% | 93% | 78% | 82% | 83% | 86% |
| VCS 4 (with ceiling fan) | | | | | | | | |
| Comfort hours (h) | 1977 | 2249 | 3973 | 4079 | 2143 | 2317 | 1578 | 1789 |
| NV hours (h) | 2687 | 2788 | 4869 | 4939 | 2887 | 2967 | 2047 | 2177 |
| Comfort hours/(NV hours) (%) | 74% | 81% | 82% | 83% | 74% | 78% | 77% | 82% |

Table 6: Total number of hours of natural ventilation (NV) and comfort hours for all cities when split air-conditioning (AC) units were used as the cooling systems

Note: VCS = ventilation and cooling control strategy.
3.3 ENERGY SAVINGS FOR THE VENTILATION AND COOLING STRATEGIES

The co-simulations were performed for the whole year, and the predictions of the total energy demand were compared against the base case, which was the fully mechanical mode case with no window operation. To calculate energy savings, all systems (mechanical heating/cooling, ceiling fans, humidifiers) were included.

The total energy for the base case (fully AC mode) scenario is shown in Figure 8 by the red bar, while the percentages show the energy savings for each scenario. For all VCSs, the difference between having the night-time window restriction and not is approximately 5–10%. As expected, when there is no restriction at the openings, the total energy demand is lower as the building thermal mass cools during night-time, relying less on mechanical cooling during the following day. However, the difference in the energy savings between these two cases is not significant, mainly because of the small effective window area (assumed to be 50% free area of the geometric area of the window). As expected, the co-simulations predicted that the highest energy savings can be achieved in Bangalore (Figure 8b), since the moderate climatic conditions favour the use of NV for a longer period compared with the rest of the cities.

The use of ceiling fans (VCS 3 and VCS 4) resulted in the highest percentages of energy savings for all cities: approximately 40–55% compared with the base Case (fully AC mode) scenario. This is comparative with the work of Omrani et al. (2021). The ventilation and cooling setpoints due to the air movement proved to be the most efficient measure to reduce the use of mechanical cooling systems. For instance, by including the ceiling fan as part of the control strategies, the co-simulations predicted an additional 20–25% energy savings compared with the cases without the ceiling fan (VCS 2). The positive effects of the use of the ceiling fans are more significant in warm and humid climatic conditions, such as Chennai, since the air movement increases the convective and evaporative heat exchange between the occupant and the environment. The convective heat exchange is driven by the temperature difference, whilst the evaporative heat exchange by the water vapour pressure difference. For the same temperature difference, the air motion has
a greater effect on increasing thermal comfort in the humid climates compared with the drier climates. The occupants in warm and humid climates are more likely to use higher fan speeds to maintain the same levels of thermal comfort for the same temperature compared with the occupants in drier climates. This can also be reflected in the predictions of energy savings, since the co-simulations calculated that the inclusion of the ceiling fans can result in up to 25% additional energy savings for Chennai and Delhi, whilst for Bangalore or Ahmedabad the additional savings were up to 20%. Overall, the energy saving potential by using the ceiling fan is higher than the additional energy consumption by operating the ceiling fan. The ceiling fans consumed a fraction compared with overall energy consumption by the rest of the mechanical systems. Additionally, the study showed that the additional heat gains by the ceiling fans had a minimum impact on the overall indoor conditions.

Additionally, the use of stand-alone mechanical ventilation and dehumidifier units slightly decreased the energy saving potential for VCS 4 compared with VCS 3 (Figure 8), due to the thermodynamic process of a dehumidifier.

4. CONCLUSIONS

Climate analysis has shown that, even in the most challenging of climates in India, there is greater scope for low energy ventilation than current residential design allows, which corroborates and expands the work of others (e.g. Li & Chen 2021). The key is to combine good design, i.e. ventilation openings which are appropriately positioned and sized, with innovative control algorithms that maximise the use of natural ventilation (NV) and night-time cooling such that air-conditioning (AC) is used sparingly and effectively. With the adoption of such controls to provide ‘smart ventilation’ (Guyot et al. 2018), comfort hours can be increased from 1287 to 2457 h in hot dry climates, from 948 to 2449 h in warm humid climates, from 2788 to 4673 h in temperate climates, and from 986 to 1968 h in composite climates. This is possible with reductions in energy consumption of 55% compared with a fully AC case. Regardless of the climatic conditions or cooling system, the analysis showed that for approximately 60–75% of the hours when NV was used, the internal operative temperature was within the comfortable limits. The dynamic thermal simulation predictions confirmed the belief that ceiling fans play an essential role in achieving comfortable conditions with reductions in energy consumption of 40–55%.

The proposed low energy cooling and ventilation for Indian residences (LECaVIR) solutions for enhanced NV confirmed that thermal comfort can be achieved under extended temperature conditions where the outdoor air temperature is 28°C and a mean radiant temperature of 33°C with calculated, near-neutral dynamic thermal sensation values ranging between ±0.5 and with a calculated predicted percentage of dissatisfaction of about 11%.

The control algorithms developed and tested in this study provide the only missing information for the widespread deployment of low energy cooling and ventilation systems in challenging climates such as found in India. Components such as dampers and actuators, and their integration into a building management system (BMS), is straightforward.

Such control algorithms provide a robust solution by overcoming the problems posed by non-engaged users, whilst at the same time assisting those users who actively engage with window operation. For both user types, the control algorithms will lead the system to the lowest energy consumption whilst maintaining thermal comfort. The control algorithms can be overridden by the users of the space. In cases where a BMS is not available, the control algorithms can be easily adapted to present alerts to the occupants on how to operate the systems, both mechanical and passive, to achieve energy savings and maintaining thermally comfortable internal conditions.

Limitations of the study include assumptions made about the outdoor environment. The work assumes that the outdoor air quality is acceptable for indoor use without filtration or treatment. It also assumed that the surrounding buildings and vegetation presented no restrictions to the flow of air through the windows or dampers. It is likely that urban planning and urban density will become key considerations for the future design and planning of low energy cooling and ventilation. A further limitation is the assumption about the restriction of openings due to security.
This is more important for lower compared with upper floors, but no distinction was made in this study. Further design enhancements, such as external solar shading, will further improve the performance of this LECaVIR approach. Meanwhile, the predicted savings reported offer encouragement for reducing energy associated with ventilation and cooling in the cities studied under current climate conditions.

**AUTHOR AFFILIATIONS**

Malcolm John Cook  [orcid.org/0000-0002-7102-8778]
School of Architecture, Building and Civil Engineering, Loughborough University, Loughborough, UK

Yash Shukla  [orcid.org/0000-0003-3313-3080]
Centre for Advanced Research in Building Science and Energy, Building Energy Performance, CEPT University, K. L. Campus, Navarangpura, Ahmedabad, IN

Rajan Rawal  [orcid.org/0000-0001-7914-6069]
Centre for Advanced Research in Building Science and Energy, Building Energy Performance, CEPT University, K. L. Campus, Navarangpura, Ahmedabad, IN

Charalampos Angelopoulos  [orcid.org/0000-0002-6370-9928]
School of Architecture, Building and Civil Engineering, Loughborough University, Loughborough, UK

Luciano Carughi-De-Faria  [orcid.org/0000-0001-5404-4218]
School of Architecture, Building and Civil Engineering, Loughborough University, Loughborough, UK

Dennis Loveday  [orcid.org/0000-0002-9029-0296]
School of Architecture, Building and Civil Engineering, Loughborough University, Loughborough, UK

Eftychia Spentzou  [orcid.org/0000-0001-8578-4980]
School of Architecture, Building and Civil Engineering, Loughborough University, Loughborough, UK

Jayamin Patel
Centre for Advanced Research in Building Science and Energy, Building Energy Performance, CEPT University, K. L. Campus, Navarangpura, Ahmedabad, IN

**COMPETING INTERESTS**

The authors have no competing interests to declare.

**FUNDING**

The authors acknowledge the Engineering and Physical Sciences Research Council (grant number EP/P029450/1) for financial support for this work.

**REFERENCES**

Angelopoulos, C., Cook, M. J., Spentzou, E., & Shukla, Y. (2018). Energy saving potential of different setpoint control algorithms in mixed-mode buildings. Paper presented at the BSO 2018: 4th Building Simulation and Optimization Conference, Cambridge, UK, 11–12 September.

ASHRAE. (2013). Thermal environmental conditions for human occupancy: ASHRAE Standard 55. American Society of Heating and Air-Conditioning Engineers (ASHRAE).

ASHRAE. (2014). Guideline 14: Measurement of energy, demand and water savings. American Society of Heating and Air-Conditioning Engineers (ASHRAE).

ASTM International. (2011). Standard test method for determining air change in a single zone by means of a tracer gas dilution.

Babich, F., Cook, M. J., Loveday, D., Rawal, R., & Shukla, Y. (2017a). A new methodological approach for estimating energy savings due to air movement in mixed mode buildings. Paper presented at the Building Simulation Applications 2017: 3rd IBPSA-Italy Conference, Bolzano, Italy.

Babich, F., Cook, M., Loveday, D., Rawal, R., & Shukla, Y. (2017b). Transient three-dimensional CFD modelling of ceiling fans. Building and Environment, 123, 37–49. DOI: [https://doi.org/10.1016/j.buildenv.2017.06.039](https://doi.org/10.1016/j.buildenv.2017.06.039)

Bamdad, K., Motour, S., Izadyar, N., & Omrani, S. (2022). Impact of climate change on energy saving potentials of natural ventilation and ceiling fans in mixed-mode buildings. Building & Environment, 209, 108662. DOI: [https://doi.org/10.1016/j.buildenv.2021.108662](https://doi.org/10.1016/j.buildenv.2021.108662)
Cook, M., Shukla, Y., Rawal, R., Loveday, D., de Faria, L. C., & Angelopoulos, C. (2020). Low energy cooling and ventilation for Indian residences design guide. CEPT Research and Development Foundation (CRDF). www.buildingsandcities.org/insights/reviews/design-guide-low-energy-cooling-indian-residences.html
Kim, H., Hong, T., & Kim, J. (2019). Automatic ventilation control algorithm considering the indoor environmental quality factors and occupant ventilation behavior using a logistic regression model. *Building & Environment*, 153, 46–59. DOI: https://doi.org/10.1016/j.buildenv.2019.02.032

Li, W., & Chen, Q. (2021). Design-based natural ventilation cooling potential evaluation for buildings in China. *Journal of Building Engineering*, 41, 102345. DOI: https://doi.org/10.1016/j.jobe.2021.102345

Liu, S., Song, R., & Zhang, T. (2021). Residential building ventilation in situations with outdoor PM2.5 pollution. *Building & Environment*, 202, 108040. DOI: https://doi.org/10.1016/j.buildenv.2021.108040

Manu, S., Patel, C., Rawal, R., & Brager, G. (2016a). Occupant feedback in air conditioned and mixed-mode office buildings in India. *Paper presented at the 9th Windsor Conference: Making Comfort Relevant*, Windsor, UK.

Manu, S., Shukla, Y., Rawal, R., Thomas, L. E., & de Dear, R. (2016b). Field studies of thermal comfort across multiple climate zones for the subcontinent: India Model for Adaptive Comfort (IMAC). *Building and Environment*, 95, 55–70. https://doi.org/10.1016/j.buildenv.2015.12.019

Manu, S., Vyas, D., Caruggi-de-Faria, L., Cook, M., Rawal, R., Loveday, D., & Angelopoulos, D. (2018). Climatic potential for low-energy cooling strategies in India. *Paper presented at PLEA 2018: Smart and Healthy within the 2-Degree Limit*, Hong Kong, China, pp. 1048–1050.

McWilliams, J. (2003). Annotated bibliography 12. Review of airflow measurement techniques. *Air Infiltration and Ventilation Centre*. www.aivc.org. DOI: https://doi.org/10.2172/809884

MODELLAR. (2017). https://fmi-standard.org/

Nouidui, T. S., & Wetter, M. (2014). Tool coupling for the design and operation of building energy and control systems based on the functional mock-up interface standard co-simulation. *Paper presented at the 10th International Modelica Conference*, Lund, Sweden, pp. 311–20. DOI: https://doi.org/10.3384/ecp14096311

Omrani, S., Motaur, S., Bamdad, K., & Izadyar, N. (2021). Ceiling fans as ventilation assisting devices in buildings: A critical review. *Building & Environment*, 201, 108010. DOI: https://doi.org/10.1016/j.buildenv.2021.108010

Persily, A. (1988). Tracer gas techniques for studying building air exchange. National Institute of Standards and Technology (NIST). DOI: https://doi.org/10.6028/NBS.IR.88-3708

Persily, A. K. (2016). Field measurement of ventilation rates. *Indoor Air*, 26(1), 97–111. DOI: https://doi.org/10.1111/ina.12193

Randazzo, T., De Cian, E., & Mistry, M. N. (2020). Air conditioning and electricity expenditure: The role of climate in temperate countries. *Economic Modelling*, 90, 273–287. DOI: https://doi.org/10.1016/j.econmod.2020.05.001

Rawal, R., & Shukla, Y. (2014). Residential buildings in India: Energy use projections and savings potentials. *Paper presented at the ECEEE Summer Study Proceedings*, Ahmedabad, India.

Schulze, T., Gürlich, D., & Eicker, U. (2018). Performance assessment of controlled natural ventilation for air quality control and passive cooling in existing and new office type buildings. *Energy & Buildings*, 172, 265–278. DOI: https://doi.org/10.1016/j.enbuild.2018.03.023

Sorgato, M. J., Melo, A. P., & Lamberts, R. (2016). The effect of window opening ventilation control on residential building energy consumption. *Energy and Buildings*, 133, 1–13. DOI: https://doi.org/10.1016/j.enbuild.2016.09.059

Tanner, R. A., & Henze, G. P. (2016). Stochastic control optimization for a mixed mode building considering occupant window opening behaviour. *Journal of Building Performance Simulation*, 7(6), 427–444. DOI: https://doi.org/10.1080/19401493.2013.863384

UNDESA. (2018). *World urbanization prospects: The 2018 revision*. United Nations Department of Economic and Social Affairs (UNDESA), Population Division. https://esa.un.org/unpd/wup/Country-Profiles/