Calibrated model of an experimental building to test passive thermal comfort solutions for the Global South

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1 Abstract

India is the third largest carbon emitter in the Global South, with millions of people facing the threat of climate related impacts. Buildings currently account for about a third of its energy consumption, and the anticipated new construction presents a huge opportunity not just for climate mitigation but also to provide comfort and shelter in a rapidly changing climate. Designers and builders are innovating in several net-zero buildings, but beyond the annual or monthly energy consumption, detailed performance studies of such buildings are often not available. This paper presents the findings from a model calibration exercise for an experimental building in India that uses passive design techniques and has been built as a prototype to test several technologies and operation practices where the learning can be applied to a larger campus effort. Hourly data for one entire month with significant diurnal variation were used in the calibration of the Energy Plus model. While the ASHRAE Guideline 14 thresholds for Mean Bias Error (MBE) and Root Mean Squared Error (RMSE) were met (at 9% and 14% respectively) through the calibration process, several issues were uncovered during the calibration. These included: challenges with using the pyranometer radiation data in the Actual Meteorological Year (AMY) weather, because changing the Global Horizontal Radiation had no impact on the results; the importance of window operation for calibrating a model of a passive building; the inability of the MBE and RMSE to capture significant errors in the shape of the indoor temperature profiles; and the usefulness of the calibrated model in uncovering problems with the measured data. Beyond this, the rigor of the modelling effort instilled confidence in the executives who were making investment decisions for the larger campus, which enabled discussion on the Life Cycle Cost of the proposed systems against several baseline scenarios.

2 Key Innovations

- Use of hourly air temperature and surface temperature data to calibrate the model of a naturally ventilated building.
- Demonstration of the strength of deep understanding of building physics and calibrating a model beyond ASHARE Guideline 14 error indices to expose problems in measurement equipment.

3 Practical Implications

The rigour of the calibrated model described here developed confidence in the CFO to enable investment discussions for future buildings on campus using a Lifecycle Analysis. This model will be also used to evaluate the impact of insulated building envelope to provide comfort in future weather scenarios of climate change.

4 Introduction

Globally, the building sector generates 37 percent of energy-related CO_2 emissions and about 24 percent of total energy and process-related CO_2 emissions are from India (IEA, 2021). Further, India's CO_2 emissions are projected to rise by 50% in the next 20 years. Therefore, the buildings sector has a significant responsibility for reducing greenhouse gas emissions. Designers and builders have an opportunity significant to decarbonize the building sector with the use of innovative passive design techniques to meet the 1.5°C target.

Apart from decreasing the building energy consumption, improving thermal comfort through passive solutions has also been important due to global carbon emissions and requirement of good quality of life (Mohelníková et al., 2020). Therefore, evaluation of building passive design techniques and thermal comfort is necessary.

Calibrated energy models have shown utility for commissioning building systems, measurement, and verification of building retrofit projects, and predictions of savings from energy conservation measures (O'neill et al., 2011.). The evaluation of the measured and simulated data for energy and thermal comfort have provided opportunity to analyse the possibilities of improving the design, control strategies and also the choice of most cost-effective measures. (Taylor et al., 2008, Bernardo et al., 2017).

Calibration of simulation models require greater level of accuracy to enable more meaningful analysis (Royapoor & Roskilly, 2015). Calibration of a model of a building is a measure of model accuracy and the availability of measured energy and comfort data increases the model accuracy (Royapoor & Roskilly, 2015, Tahmasebi & Mahdavi, 2013).

Fabrizio & Monetti, (2015) note various levels of calibrating a building model. The most detailed level of calibration is where the short term and long-term monitoring data and a detailed audit are used.

This paper presents such a detailed model calibration of an experimental building of 432 m^2 in Bangalore, India which was constructed with different construction technologies and materials to document performance and cost parameters, and test passive innovative technologies. The wall systems included the use of cement stabilised earth block (CSEB), rammed earth (RE), and autoclaved aerated concrete (AAC) blocks, extruded polystyrene (XPS) insulation, granite stone cladding, china mosaic, and plaster.

Figure 1: Experimental Building

These wall systems are all insulated, and their performance has been monitored. Bangalore has a temperate climate, with average daily temperature hight at around 27°C with annual maximum temperature of 35°C. To assess the impact of several wall assemblies and operation practices in a climate like Bangalore, a model calibration exercise was conducted for the experimental building. This was carried out so that the learnings can be applied to a larger campus effort.

As-built drawings and construction records of materials were used to define the physical characteristics of the building in the model. The lighting, equipment, and occupant densities and schedules were based on a detailed energy audit that included short term monitoring of the lights and equipment. A weather station installed on the building, sensors for interior/ exterior surfaces, and indoor temperature and humidity are part of an IoT-based system for the building which provides continuous data.

According to ASHRAE Guideline 14 the two commonly used statistical indices evaluate the accuracy of the calibration are Mean Biased error (MBE) and Coefficient of variation of the root mean squared error (CV(RMSE)). The contribution of this study is that it has resulted in a deeper understanding of the thermal behaviour of indoor spaces using passive technologies. Another contribution is the ability to assess such technologies to provide affordable thermal comfort in the face of rapidly changing climate and extreme weather events.

5 Methods

5.1 Model Data Input

The building energy simulation model for the experimental building was built using Design Builder which runs the EnergyPlus simulation engine. The model includes the building geometry, envelope characteristics, internal loads for lighting, equipment, and people, HVAC system characteristics, and operation schedules for internal loads, HVAC operations and window operation. This information was collected and organised to allow effective review and verification of the model results.

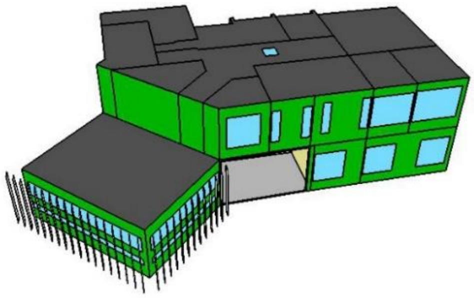


Figure 2: Calibrated energy plus thermal model of the experimental building

5.1.1 Weather data

For modelling, the weather data used was actual meteorological data (AMY) from the weather station installed on the building. The parameters that were used from the weather station data were:

1. Dry Bulb Temperature {°C}
2. Relative Humidity {%}
3. Global Horizontal Radiation {Wh/m^2}
4. Wind Direction {deg}
5. Wind Speed {m/s}

5.1.2 Building Envelope

Table 1 shows the characteristics of the building envelope and the glazing types. These details were collected from the as-built construction drawings. All the inputs for the walls, windows, floors, ceiling, doors, including shading devices were loaded into DesignBuilder.

5.1.3 Ventilation

HVAC system for the building is Split-Air Conditioning with outdoor units located on the roof. The building is operated in mixed mode. The HVAC system modulation was implemented using the "Simple HVAC" option in DesignBuilder software. CoP of the system used is 3.52. The cooling set point temperature is set to 26°C. There is no heating provided in the building. 140 m^2 (32%) of the building is cooled during occupied hours from 10:00-13:00 and 14:00-16:00. The lab spaces on the first floor and the board room on the ground floor are conditioned (see table 1) for the months of March through October. Other spaces in the buildings are naturally ventilated. Windows are open from 9:00-18:00 throughout the year except on the weekends. The window and the HVAC operation schedules were collected from on-site surveys, and interviews with the operations team.

Table 1: Building envelope characteristics

Envelope	U-Value (W/m^{2}K)
External wall	
CSEB wall with insulation and cladding (CSEB-I-C)	0.52
Rammed earth wall with insulation and cladding (RE-I-C)	0.54
AAC and CSEB wall with insulation and china mosaic (AAC-I-CSEB-CM)	0.35
Internal wall	
CSEB wall	1.95
Rammed earth wall	2.86
Roof	
Precast RCC Joist (Clay Tile Flooring, 75 mm XPS Insulation, cement screed and Kota stone slab)	0.40
Filler slab (Clay Tile Flooring, 100mm Exfoliated vermiculite Insulation, cement screed and clay trough)	1.48
RCC flat slab (China mosaic tile, 50mm XPS insulation and RCC slab)	0.40
Ceiling	
Precast RCC Joist (Floor finish, cement screed and Kota stone slab)	2.37
Filler slab (Floor finish, cement screed and clay trough)	2.53
Jack Arch (Floor finish, cement screed and hollow clay block)	2.31
Ground	2.85
Window (6mm DGU with 12mm air cavity)	2.68
Doors (6mm DGU with 12mm air cavity)	2.68
Source: The U value data have been retrieved from the CARBSE, Assembly U-Factor Calculator.	

5.1.4 Thermal zones and Internal loads

Each space in the building was modelled as a separate thermal zone. The summary of the internal loads considered for each space is shown in table 2. These internal loads include, occupancy load, lighting load and equipment load. Occupant density was collected from the operations team while the lighting and equipment load were considered based on the detailed energy audit that was conducted for the building.

5.2 Model calibration

The simulation model was calibrated in four steps. Hourly energy data was not available at the time of the study. However, since 70% of the building is naturally ventilated, we used the indoor temperature, inside wall surface temperature and outside wall surface temperature to calibrate the thermal behavior of the model. Simulations were run after each step and the results were compared with hourly measured data for the month of September 2021 (720 data records). Indoor air temperature and surface temperature of the west wall (WW) and south wall (SW) were used for calibration. The calibration exercise was done in a series of 4 steps to document the error indices systematically, and to understand the impact of each step in reducing the error.

Table 2: Internal loads (conditioned spaces)*

Thermal Zones	Floor	Floor area (m^2)	Occupant density (people/m^2)	Equipment - Power density (W/m^2)	Lighting power density (W/m^2)
Cd Team Workstations	Ground	35	0.29	29.2	5.6
Meeting Room 1		10.5	0.29	7.4	1.5
Cabin		11.4	0.09	9.5	2.7
Common Passage 1		38	0.05	1.9	2.4
Toilet GF		15.7	0.06	5.7	3.5
Kitchen		21.9	0.09	198.6	2.1
Electrical Room		4.2	0	11	3.8
Board Room*		58.7	0.1	101.6	6.1
Chief CD Office		23.4	0.04	7.4	1.3
Meeting Room 2		12.8	0.08	1.4	1.9
Main Lab*	First	35	0.03	445.9	1.8
Meeting Room 3		10.5	0.1	0	1.5
Guest Room		22.9	0.04	7.5	3.2
Toilet FF		21.2	0.05	4.2	2.6
Caretaker		19.1	0.05	10.5	1.6
Common Passage 2		35.9	0.06	0	1.3
Workstation Lab*		10.5	0.1	16.7	1.5
Technology Media Lab*		23.9	0.08	15.5	2.9
Solar Battery Room		7.8	0	11	2.1
Small Lab*		12.9	0.08	4.9	1.2

The 4 steps are:

Step 1: Correct the design stage model for geometry and size, thermal properties of window, door, roof and wall the construction assemblies, and occupancy schedule.

Table 1 shows the description of the characteristics of the building envelope and glazing details.

Step 2: Correction of the lighting loads
The lighting power density (LPD) which was collected from the energy audit was used as input in the model. The lighting schedule collected from the on-site surveys, and interviews with the operations team was also corrected.

Step 3: Correction of the lighting equipment loads
Equipment power density (EPD) which was collected from the energy audit was used as input in the model. The equipment schedule collected from the on-site surveys, and interviews with the operations team was also corrected.

Step 4: Weather data correction

In the previous steps, simulations were run with the typical meteorological year (TMY) weather file used in the design stage model. In this step, the actual meteorological year (AMY) file was developed with data from the weather station atop the building. Only global radiation data was available from the weather station data, and the direct and diffused radiation were calculated. Energy plus weather conversion tool was used to format the weather file to be used in the energy model.

6 Results

5.3 Calibration for MBE and RMSE

For hourly data, ASHRAE guideline 14-2014 prescribes that the MBE should be less than 10% and the RMSE should be less than 30%.

Figures 2 and 3 show the MBE and RMSE that were calculated at of the 4 steps for indoor air temperature and surface temperature. Both MBE and RMSE are around 20% for the first 3 steps showing that correcting the design model for envelope and internal loads had minimal impact. However, the AMY weather data reduced the MBE and RMSE significantly to 13% and 17% respectively. This demonstrates the importance of actual and highly local weather data for a calibrated model. In the process of using the AMY data, it was found changing the global horizontal radiation had no impact on the simulation results. It appears that EnergyPlus simulation engine does not consider of the global horizontal radiation from the weather file. However, it does considers the direct and the diffused radiation.

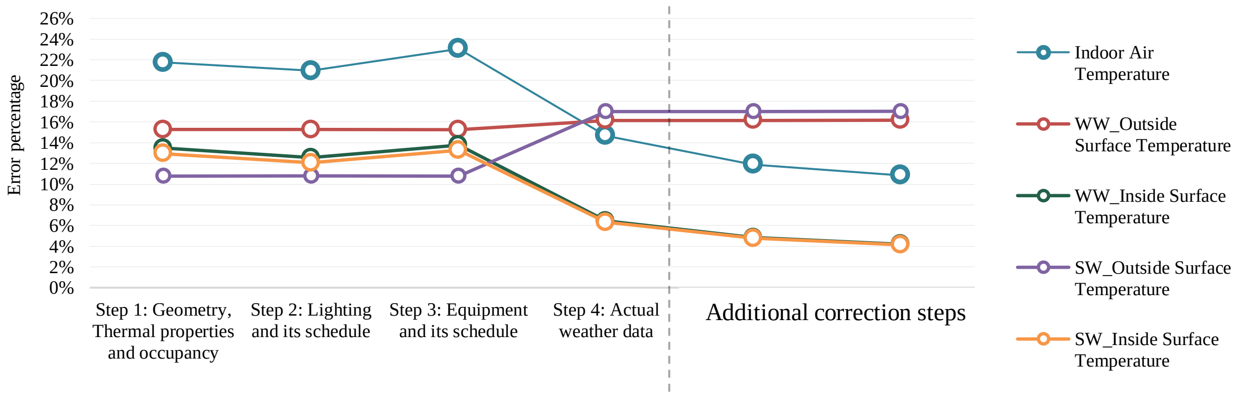


Figure 2: Root mean squared error (RMSE) of the four steps that was followed for calibration (WW is west wall, and SW is south wall)

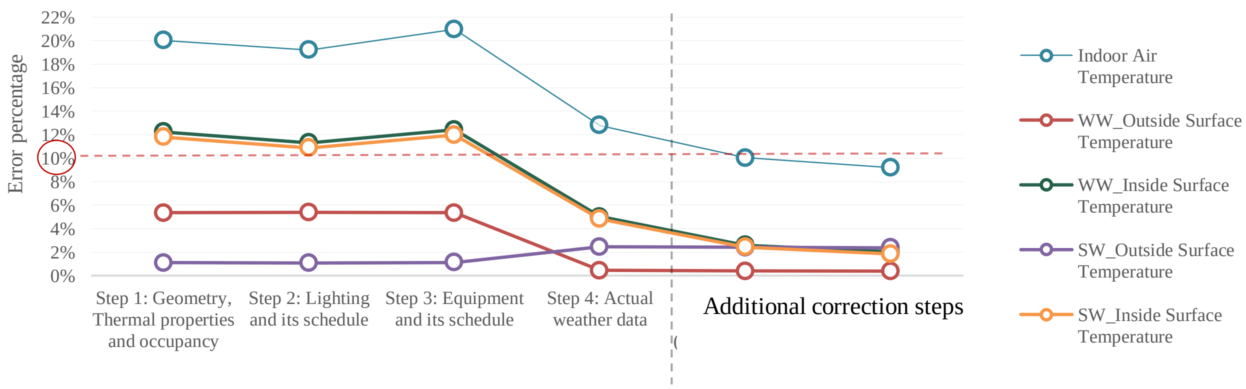


Figure 3: Mean bias error (MBE) of the four steps that was followed for calibration (WW is west wall, and SW is south wall)

5.4 Additional correction of the model

The MBE (13%) achieved at step 4 was not within the acceptable tolerance, therefore further investigation was carried out for the indoor air temperature and surface temperature data. It was observed that the measured indoor air temperature for the unoccupied hours were higher than the simulated data (see figure 4). The indoor air temperature was within 1°C for occupied hours and 4 °C for unoccupied hours as shown in figure 4. The profile inspection of the indoor air temperature revealed the dip in the profile from 8-10 am. This led to the correction of the window opening schedule after verifying with the operations staff. Changing the window schedule showed an impact in the reduction of the error (as shown in figure 4). For the higher nighttime temperatures, two possible causes hypothesized, i.e envelope insulation and internal loads. Accordingly, a sensitivity analysis for changes in insulation and internal loads was conducted. The error increased when the insulation was degraded but reduced when internal loads for the unoccupied hours were increased (figure 4). A thermal imaging survey of the interiors was undertaken to identify the source of the internal loads.

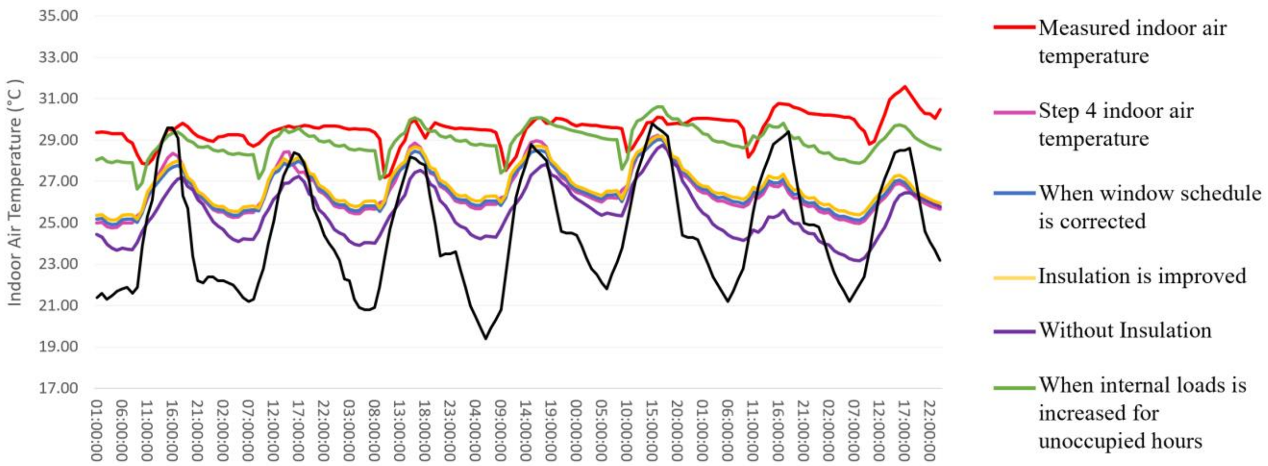
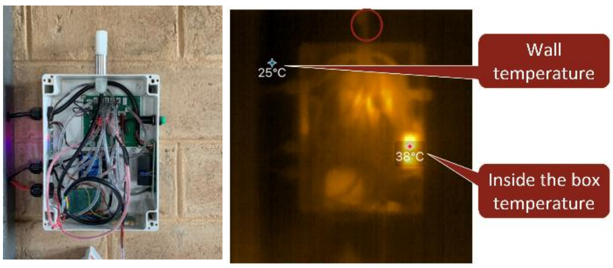


Figure 4: Measured and simulated indoor air temperature for additional steps that were carried out

This survey showed that the IoT box itself was a source of heat. Thermal images of the interior of the IoT sensor led to the discovery of components inside the IoT sensor box that produced heat and affected the temperature sensor, causing the readings be higher with a constant profile (see figure 5). This constant temperature profile was disturbed for a short period when there were gusts of air, as with the window opening in the mornings.

Figure 5: IoT box (left) that measures air temperature and the thermal image of this box inside (right).



The IoT box data for indoor air temperature was compared with HOBO equipment. Data were logged for one week. The air temperature read by IoT box was 3°C higher than the HOBO data logger. This was similar to the temperature difference observed between the measured and the simulated results at step 4. Further the surface temperature data were also assessed to understand temperature differences between the measured and the simulated data. No time lag was observed between the air temperature and the inside surface temperature which implies a zero thermal mass of wall. In the same data, when the outdoor air temperature drops, there is no drop in the indoor air or surface temperature, which implies extremely high thermal mass (as shown in figure 6). These two observations were contradictory. Upon further investigation it was found that the surface temperature probes were cylindrical with only tangential contact with the wall. The probes were also uninsulated. Therefore, more surface area of the probe was in contact with air and less with the wall. Hence, the surface temperature sensors were reading air temperature and therefore no time lag was observed in the data.

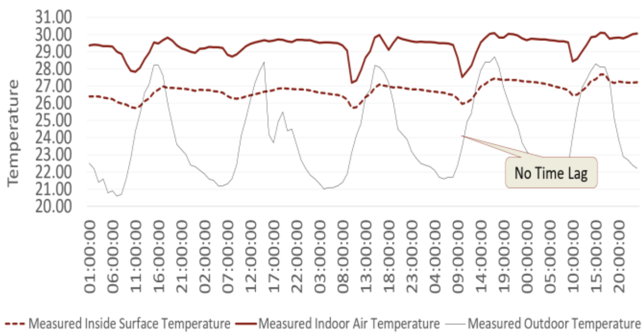


Figure 6: Measured Indoor air temperature and inside surface temperature of the wall.

This led to a conclusion that both air temperatures from the IoT boxes and surface temperature readings could not be used for the calibration exercise. Therefore, Hobo equipment was used to collect air and surface temperature data for a week, and suggestions were provided to correct the IoT box equipment.
The Hobo readings were collected for a week in December 2021, and simulation results for that week were than compared with the HOBO readings. The MBE was 1% and RMSE was at 17%. Therefore, both RMSE and MBE are within the acceptable tolerances of ASHRAE guideline 14-2014. Maximum temperature difference observed between the measured and simulated was 1°C (as shown in figure 7).

The indoor air temperature sensors of the IoT box are now separated from the box at 300mm distance. For the surface temperature sensors, the sensors are now replaced with a flat surface probe, and they are insulated from the room air. Note, the IoT box data shown in figure 7 is before these changes were made to the equipment.

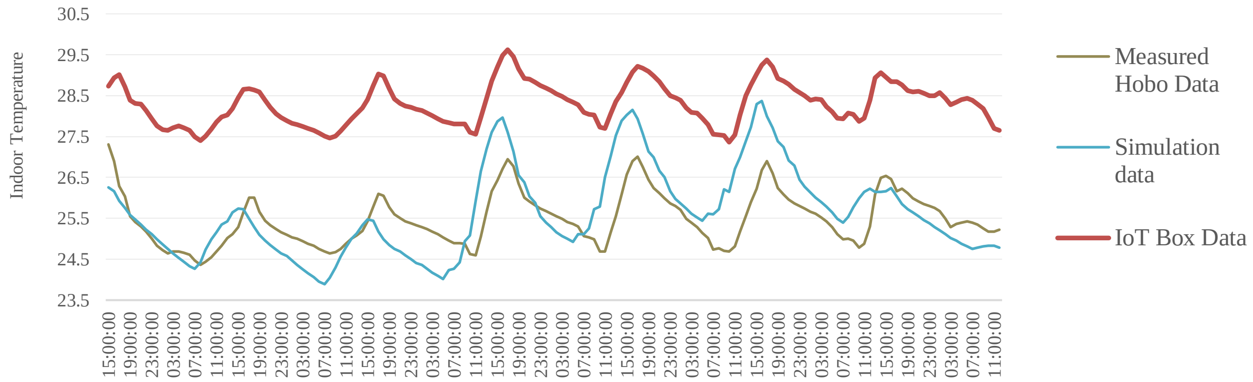


Figure 7: Measured and simulated indoor air temperature for the validation of the model result

7 Use of calibrated model

The calibrated model was used to determine the value of the insulation in terms of the thermal comfort that it provided. This was done because the cost for insulation for the other buildings on the campus was USD 700K. The calibrated model was used to simulate the three wall assemblies. Each assembly was simulated with and without insulation (six wall assembly).

Figure 8 shows the Operative Temperature (OT) in the naturally ventilated space for the rammed earth wall, plotted for 1 year against the adaptive thermal comfort band in the National Building Code of India (NBC, 2016).

The OT lies below the upper limit of the band except for a few hours of the year without insulation. With, insulation, the space is about 3°C cooler. Similar analyses were done for the CSEB and AAC walls. The results are summarised in figure 9.

In figure 9, we see that comfort hours are higher without insulation because the OT values are less than the lower limit of the comfort band. Given the warming climate and potential heat island effect in future, this analysis can now be conducted for future weather conditions.

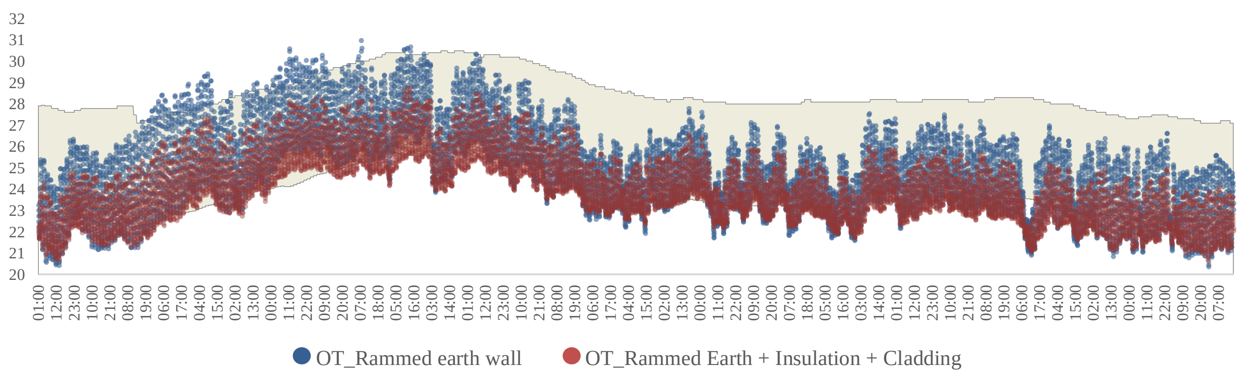


Figure 8: OT of the workstation room with rammed earth wall (with and without insulation), the grey area shows the adaptive thermal comfort band according to the National Building Code of India.

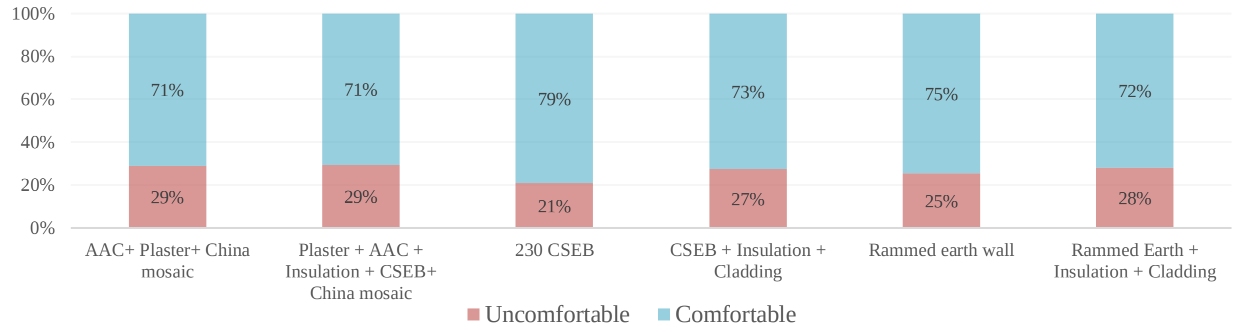


Figure 9: Percentage of comfortable and uncomfortable hours of the six wall assemblies for a naturally ventilated scenario during the occupied hours

The rigour of the calibration of the model led to the Chief Financial Officer (CFO) having confidence in the simulation results. We were able to present a life cycle cost (LCC) for insulated walls and discuss the value of the investment.

The calibrated model was also used to generate the operative temperature (OT), mean radiant temperature (mrt) and air temperature for 10 different building operation scenarios using the calibrated model to train and test the Machine learning (ML) algorithm for predicting OT.

In future we intend to use the calibrated model for dashboarding an hourly, daily, monthly, annual benchmark to compare the actual performance of the building. Other future work also includes using the model to simulate for future weather files to test the performance of passive approach to provide affordable comfort solutions.

8 Conclusion

This paper summarizes the calibration process of an experimental building and employed it to simulate and analyse the thermal comfort of various wall assemblies. Necessary data inputs and information of the building were collected as an input of the model. The model was calibrated to meet the acceptable tolerance specified by the ASHRAE guideline. The Mean Bias Error (MBE) was found to be within +/- 10% (+1% achieved) and Root Mean Squared Error (RMSE) achieved was < 30% (17% achieved).

The calibration process also showed the value of closer inspection of results even if MBE and RMSE are in the acceptable range, especially to build confidence among non-researchers like the CFO, and for investment grade decisions.

This paper also demonstrated the value of a deep understanding of building physics to track down issues with calibration. The paper also showed a unique case where the simulated model data helped in identifying problems with the measurement equipment.

Once calibrated, such a model becomes a powerful tool that can be used in multiple scenarios for improved operations, benchmarking, and future capital investment decisions.

9 References

Bernardo, H., Quintal, E., & Oliveira, F. (2017). Using a Calibrated Building Energy Simulation Model to Study the Effects of Improving the Ventilation in a School. *Energy Procedia*, *113*, 151–157. https://doi.org/10.1016/j.egypro.2017.04.044

Energy Agency, I. (n.d.). *India Energy Outlook 2021 World Energy Outlook Special Report*. www.iea.org/t&c/

Fabrizio, E., & Monetti, V. (2015). Methodologies and advancements in the calibration of building energy models. In *Energies* (Vol. 8, Issue 4, pp. 2548–2574). MDPI AG. https://doi.org/10.3390/en8042548

Mohelníková, J., Novotny, M., & Mocová, P. (2020). Evaluation of school building energy performance and classroom indoor environment. In *Energies* (Vol. 13, Issue 10). MDPI AG. https://doi.org/10.3390/en13102489

NBC. (2016). *National Building Code of India. 80*.

O'neill, Z., Eisenhower, B., Yuan, S., Bailey, T., Narayanan, S., & Fonoberov, V. (n.d.). *Modeling and Calibration of Energy Models for a DoD Building*.

Royapoor, M., & Roskilly, T. (2015). Building model calibration using energy and environmental data. *Energy and Buildings*, *94*, 109–120. https://doi.org/10.1016/j.enbuild.2015.02.050

Tahmasebi, F., & Mahdavi, A. (n.d.). *A TWO-STAGED SIMULATION MODEL CALIBRATION APPROACH TO VIRTUAL SENSORS FOR BUILDING PERFORMANCE DATA.*

Taylor, P., Fuller, R. J., & Luther, M. B. (2008). Energy use and thermal comfort in a rammed earth office building. *Energy and Buildings*, *40*(5), 793–800. https://doi.org/10.1016/j.enbuild.2007.05.013