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Futureproofing with Passive Buildings: Is It Cost Effective and Is It Thermally Adequate?

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Highlights

- The paper summarizes the calibration process used to analyze thermal comfort and LCC in different wall assemblies.
- The calibration process met the thresholds for Mean Bias Error (MBE) and Root Mean Squared Error (RMSE) outlined in ASHRAE Guideline 14.
- The calibrated model proved useful in identifying problems with the measured data.
- Preliminary results indicate that insulated walls are cost-effective in a 50-year lifecycle analysis when the entire building is air-conditioned.
- The study underscores the significance of including future weather files in Life Cycle Cost (LCC) analysis, enhancing accuracy, and facilitating informed decision-making in construction and energy efficiency.

Abstract

The paper aims to highlight the importance of employing a robust Life Cycle Cost (LCC) method that incorporates future weather files and a calibrated model. The study evaluates a 50-year LCC for wall insulation in an experimental building in Bangalore. It compares the LCC calculated using the future weather data with results obtained using the Typical Meteorological Year (TMY) file, providing a more accurate assessment of long-term cost-effectiveness.

The results show that insulated walls have a lower LCC when fully air-conditioned, while mixed-mode settings show higher LCC. A detailed thermal comfort analysis indicates that insulated walls offer adequate thermal comfort (11-13% discomfort hours) under full adaptation to thermal conditions. Without full adaptation, when the adaptive comfort equation of the National Building Code (NBC) does not work, discomfort could rise to 31%. However, with ceiling fans (6-7 ºC cooling power index), it would suffice to provide comfort in the experimental building. The study underscores that well-designed buildings in Bangalore with insulation, passive strategies, and natural ventilation can ensure prolonged comfort without mandatory air-conditioning.

Keywords: Calibrated model; LCC analysis; MBE and RSME; adaptive thermal comfort; future weather file

Introduction

Globally, the building sector generates 37% of energy-related CO_2 emissions, and about 24% of total energy and process-related CO_2 emissions are from India [1]. Further, India's CO_2 emissions are projected to rise by 50% in the next 20 years. Therefore, the building sector has a significant responsibility for reducing greenhouse gas emissions. Designers and builders have an opportunity to decarbonize the building sector with the use of innovative passive design techniques to meet the 1.5°C target. Apart from decreasing building energy consumption, improving thermal comfort through passive solutions has also been important due to global carbon emissions and the requirement for a good quality of life [2]. Therefore, evaluation of building passive design techniques and thermal comfort is necessary.

Figure 1: Experimental Building

This paper presents the analysis of an experimental building (see Figure 1) of 432 m^2 in Bangalore, India, which was constructed with different technologies and materials to test passive innovative technologies that could be implemented in buildings on a 55-acre campus. The wall insulation was considered a significant investment. The insulation cost for the larger campus was estimated at 50 million INR. If cladding of insulation was considered, that added another estimated 270 million INR. The cladding also had a high maintenance cost. This was the motivation behind the detailed cost-benefit analysis presented in this paper.

The wall systems in the experimental building were built with cement stabilised earth blocks (CSEB), rammed earth (RE), autoclaved aerated concrete (AAC) blocks, extruded polystyrene (XPS) insulation, granite stone cladding, china mosaic, and plaster. Three wall systems built from combinations of these materials are all insulated, and their performance has been monitored. Bangalore has a temperate climate, with an average daily high temperature of around 27°C with an annual maximum temperature of 35°C. To assess the cost and benefit of these wall assemblies, a detailed audit, longer-term monitoring, and model calibration were conducted for the experimental building.

Using a calibrated model, a life cycle cost benefit analysis was conducted for the three wall types built and an additional 5 types of wall types (total of eight) to understand the value of investment for the upcoming buildings in the 55-acre campus. These eight wall systems (Table 1) were identified by the design and construction team as viable alternatives for the campus. The calibrated model was also used to determine the value of the insulation in terms of the thermal comfort that it provided. The initial analysis was done with a TMY file and the current weather data.

However, running a simulation using the TMY file is not adequate. Many studies have concluded that the need for space cooling will increase in the future due to climate change [3]. Factors like rising temperatures and urban heat islands (UHIs) play a significant role in causing discomfort in buildings [4] [5]. Therefore, it is important to simulate buildings to test performance with future weather scenarios to identify the cost-effectiveness of energy conservation measures, achieve thermal comfort, and create buildings that can withstand future climate change.

Therefore, this paper uses future weather files to establish the difference in LCC and thermal comfort for insulated versus uninsulated walls. The significance of this research is the rigorous methodology used to establish the value of insulated walls and, in the process, demonstrate the difference in LCC between fully air-conditioned spaces and mixed-mode operation of those spaces, as well as the difference in thermal comfort achieved in unconditioned spaces between current and future weather scenarios.

Table 1: Eight wall systems and their civil cost

Alternate	Wall systems	Civil Cost (INR/m^2)
Alt 1	AAC+ Plaster+ China mosaic	2,485
Alt 2	Plaster + AAC + Insulation + CSEB+ China mosaic	3,337
Alt 3	230 CSEB	1,466
Alt 4	CSEB + Air gap (50mm) + CSEB	2,932
Alt 5	CSEB + Insulation + CSEB	3,784
Alt 6	CSEB + Insulation + Cladding	7,303
Alt 7	Rammed earth wall	1,983
Alt 8	Rammed Earth + Insulation + Cladding	7,819

Method

Calibrated energy models have shown utility for commissioning building systems, measuring and verifying building retrofit projects, and predicting savings from energy conservation measures [6]. The evaluation of the measured and simulated data for energy and thermal comfort has provided the opportunity to analyse the possibilities of improving the design, control strategies, and the choice of the most cost-effective measures [7][8]. Calibration of simulation models leads to a greater level of accuracy to enable more meaningful analysis [9]. Accuracy and the availability of measured energy and comfort data increase the model's accuracy [9][10]. Fabrizio & Monetti [11] 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.

Model Data Input

The energy simulation model of the experimental building was created using DesignBuilder with its EnergyPlus simulation engine. It included information on building geometry, envelope characteristics, internal loads, HVAC system characteristics, and operation schedules. Weather data for the modeling was sourced from the weather station on the building, encompassing parameters like dry bulb temperature, relative humidity, global horizontal radiation, wind direction, and speed. Details concerning the building envelope and glazing types, including inputs for walls, windows, floors, ceilings, doors, and shading devices, were extracted from construction drawings and incorporated into the model. About 30% of buildings are conditioned with Split-Air Conditioning HVAC system with outdoor units on the roof, with a coefficient of performance (CoP) of 3.52 and a cooling set point temperature of 26°C. The rest of the building is naturally ventilated with no air-conditioning equipment. But even the spaces with the split ACs are operated in temporal mixed mode. Implementation of HVAC modulation was executed through the "Simple HVAC" option in DesignBuilder. The window and HVAC operation schedules were based on on-site surveys and interviews with the building occupants. Each space in the building was modeled as a separate thermal zone. Internal loads, including occupancy load, lighting load, and equipment load, were established through a detailed building audit.

Table 2: Building envelope characteristics

Envelope	U-Value (W/m²K)
External walls	
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 walls	
CSEB wall	1.95
Rammed earth wall	2.86
Roofs	
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
Ceilings	
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

Model Calibration

The simulation model underwent a four-step calibration process. Since hourly energy data was not available, hourly data for indoor temperature, inside wall surface temperature, and outside wall surface temperature were used to calibrate the model's thermal behavior. Simulations were compared with measured data for September 2021 to assess accuracy. The calibration process involved correcting the model's geometry, size, thermal properties, construction assemblies, and occupancy schedule.

Life Cycle Cost Analysis

When the model was calibrated, additional wall systems were modeled, and LCC analysis was conducted for a total of eight wall systems. The cost components of the LCC used material costs, installation costs, maintenance costs, and energy consumption data. Additional parameters, including utility tariffs, power factor, discount rate, and inflation rate, were identified and obtained from reliable sources. Table 3 below shows the parameters that were considered for the LCC.

Table 3: All the inputs that were used for the Life cycle cost calculation

Parameters	
Electricity consumption charge (INR/kWh)	21.4
Electricity demand charge (INR/kVA)	240
Power factor	0.75
Social cost of carbon (INR/kWh)	12.8
Cost of air-conditioning system INR Per TR	65000
Service factor (cooling)	1.15
Discount rate	8%

Inflation rate	7%
GST	1.18
Project management cost (Capex)	1.15
Energy consumption data	From the calibrated model
Civil Cost of all Wall systems (materials + labour)	**(INR/m^2)**
1. AAC+ Plaster+ China mosaic	2,485
2. Plaster + AAC + Insulation + CSEB+ China mosaic	3,337
3. 230 CSEB	1,466
4. CSEB + Air gap (50mm) + CSEB	2,932
5. CSEB + Insulation + CSEB	3,784
6. CSEB + Insulation + Cladding	7,303
7. Rammed earth wall	1,983
8. Rammed Earth + Insulation + Cladding	7,819

A comprehensive calculation framework was developed to account for all relevant cost components for the 50-year life of the wall systems. This framework included all the parameters that are listed in Table 3. Other parameters like maintenance costs, repair costs, and replacement costs are also considered based on the wall system type.

Using the collected data and the established calculation framework, the LCC analysis was conducted for each wall system. LCC was conducted for two reasons: (1) to understand the benefit of insulation in the wall system and (2) to understand the importance of using future weather files.

Future weather files

This step investigates the impact of future weather files on LCC by utilizing a weather file generator specifically developed for India. The generator, developed by Manapragada et al. [13], employs a geo-filtering-based spatial technique, temporal downscaling, and machine learning (ML) based bias correction proposed by Belcher et al. [14]. The generated future weather files encompass three representative concentration pathways (RCPs) - 2.6, 4.5, and 8.5 - for the years 2030, 2050, 2070, 2090, and 2100. Historical data from present-day weather files, specifically the typical meteorological year, are utilized for testing and training ML models to correct biases. Using this weather file generator, simulations were conducted for the years 2020, 2050, and 2080 for Bangalore to be used in the calibrated model. Simulations were run for a rammed earth wall, with and without insulation, for a mixed mode and fully air-conditioned operation to get the energy consumption and indoor operative temperature values.

Interpolation of the energy data

The LCC is calculated for 50 years of the life cycle. Future weather files were made for 2020, 2050, and 2080 for simulations for those years. The energy consumption for these years was plotted to get a quadratic equation that was then used to interpolate energy consumption data for the intermediate years. LCC analysis used this annual energy consumption data. The results were then compared with the LCC calculated using the TMY file.

Results

Calibration for MBE and RMSE

For hourly data, ASHRAE guideline 14-2014 [12] prescribes that the MBE should be less than 10% and the RMSE should be less than 30%. The MBE and RMSE were calculated in 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 actual meteorological year (AMY) measured data reduced the MBE and RMSE to 13% and 17%, respectively, as shown in Figure 2.

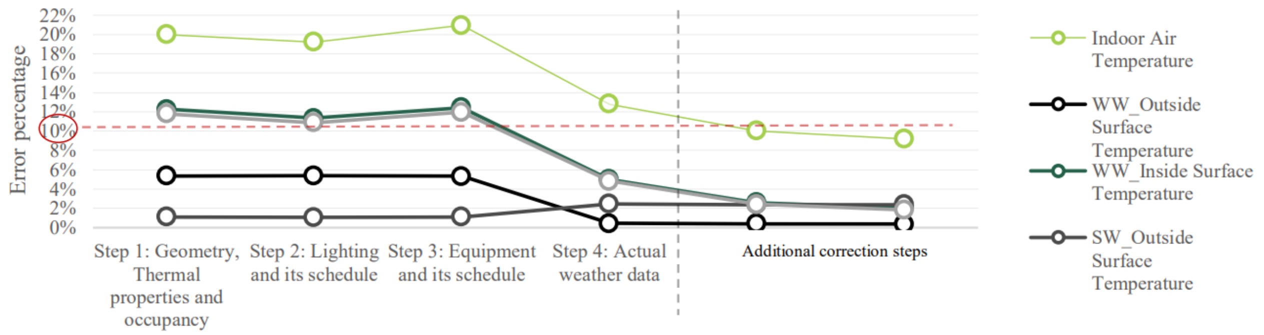

Figure 2: Mean bias error (MBE) of step six that was followed for calibration (WW is west wall, and SW is south wall)

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 was higher than the simulated data. A thermal imaging survey of the interiors was undertaken to identify the source of the internal loads.

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 to be higher with a constant profile (see Figure 3 a and b). This constant temperature profile was disturbed for a short period when there were gusts of air, as with the window opening in the mornings. When compared with data from HOBO sensors, the air temperature read by the IoT box was 3°C higher. This led to a reconfiguration of the sensors and electronics for the IoT box.

No time lag was observed between the air temperature and the inside surface temperature, which implies a zero thermal mass of the 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 3c). 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. This, too, was corrected in the building.

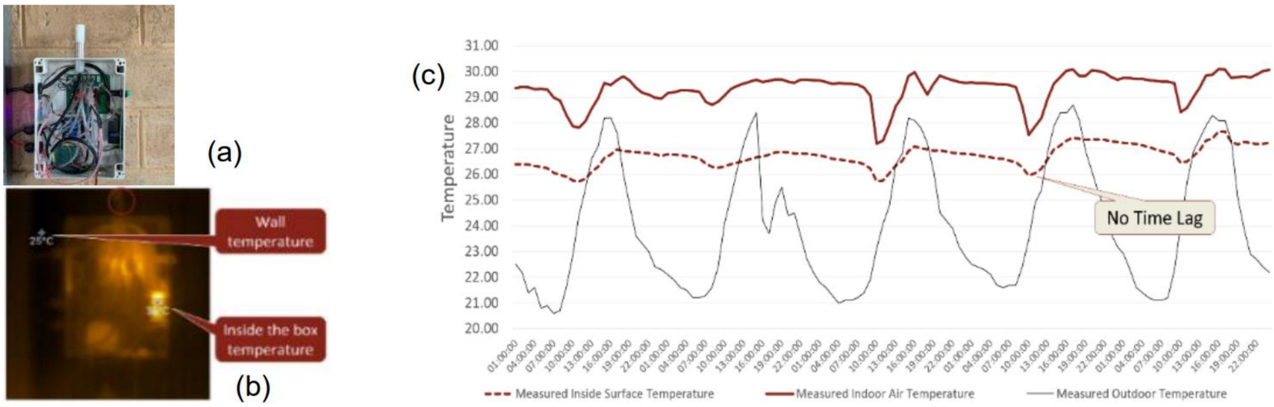

Figure 3: IoT box (a) and the thermal image of the box inside (b), Indoor air temperature, and inside surface temperature (c)

Meanwhile, the study continued using HOBO sensors and data loggers.

When the simulation results were compared with the HOBO readings, the MBE was at 1%, and the RMSE was at 17%. Therefore, both RMSE and MBE are within the acceptable tolerances of ASHRAE guideline 14-2014. The maximum temperature difference observed between the measured and simulated was 1°C (as shown in Figure 4).

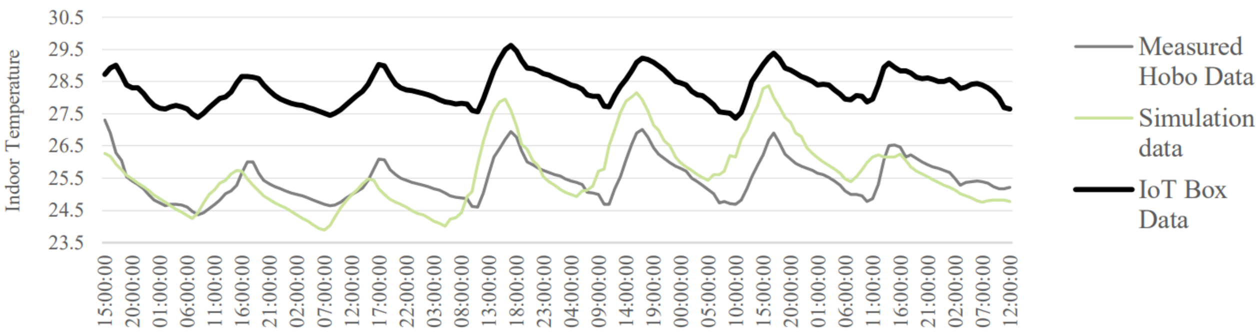

Figure 4: Measured and simulated indoor air temperature for the validation of the model result

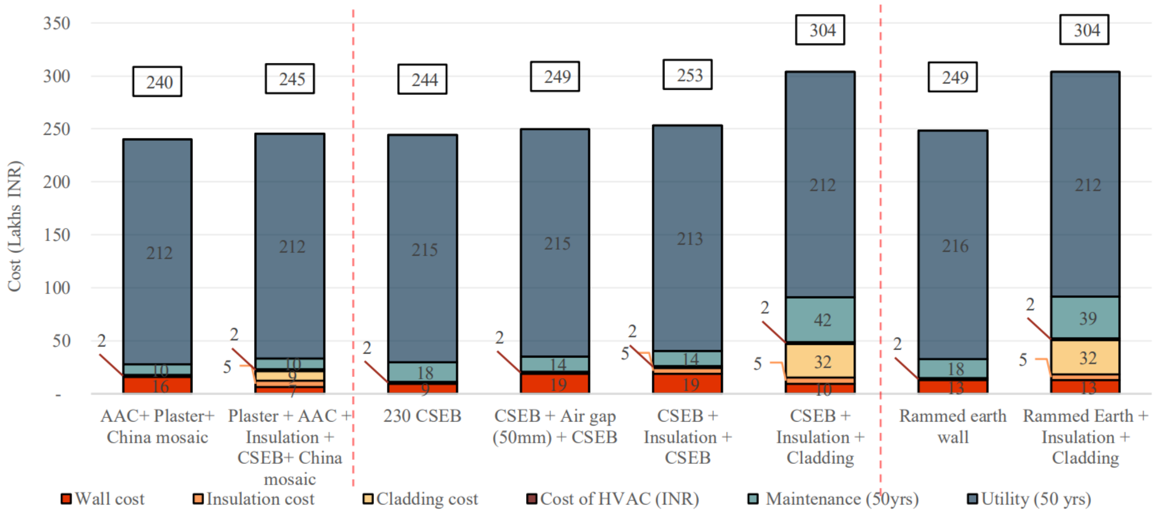

Figure 5: LCC summary for mixed mode

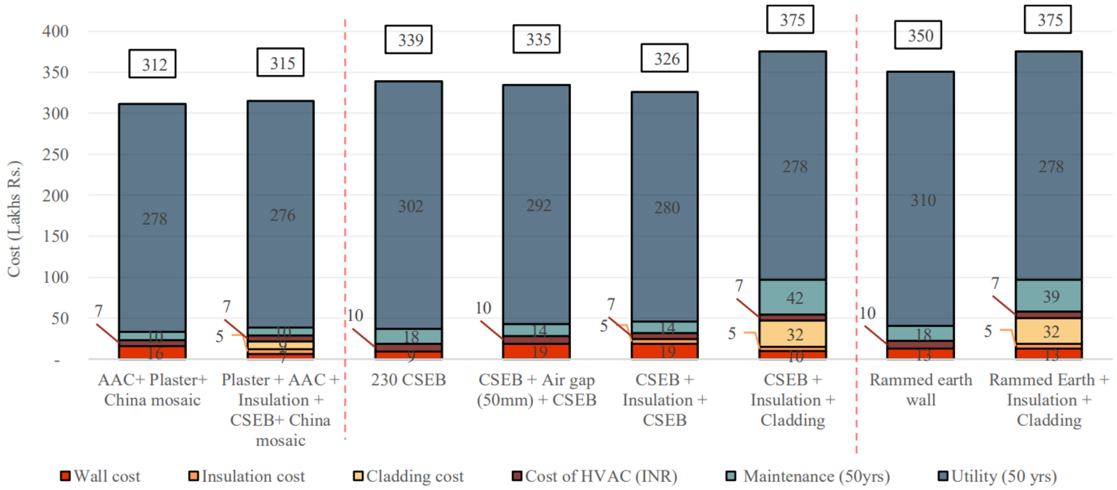

Figure 6: LCC summary for fully conditioned

LCC Analysis using the TMY weather file

The results from the mixed mode scenario showed that when the walls are insulated, the LCC increases by about 2-25% (see Figure 5). It is to be noted that the walls that include insulation, as well as cladding, have a significant increase in the LCC.

For the fully conditioned operation, LCC for the insulated walls increased by about 1-10% see Figure 6). However, when we look at the results of the four CSEB walls, we can see that LCC reduces as insulation is added, except in the case where cladding is also included. Looking at all the wall options, we can observe that even though utility (energy) costs are reduced significantly for all options that have insulation, it is the cost of cladding (capex as well as maintenance) that drives the LCC to make the insulated walls expensive.

LCC Analysis using the future weather files

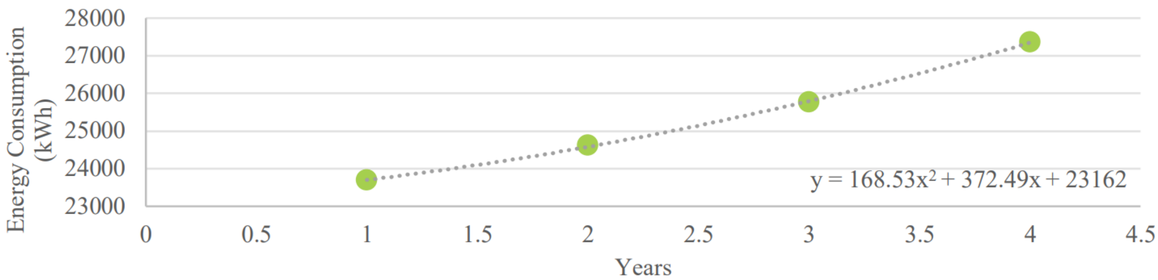

Figure 7: Energy data for 2020, 2050 and 2080 and the quadratic equation for Non-insulated (Rammed earth wall) in mixed mode scenario

Figure 7 shows a quadratic equation for a non-insulated rammed earth wall in a mixed-mode scenario. Similar equations for insulated rammed earth wall in mixed mode scenario, Non-insulated (Rammed earth wall), and insulated rammed earth wall in the fully air-conditioned scenario were also generated. These equations were then used to interpolate the energy consumption across the 50 years. LCC was then calculated using the interpolated energy data. This part of the analysis focuses on the rammed earth walls (with and without insulation) and mixed-mode and fully air-conditioned operations.

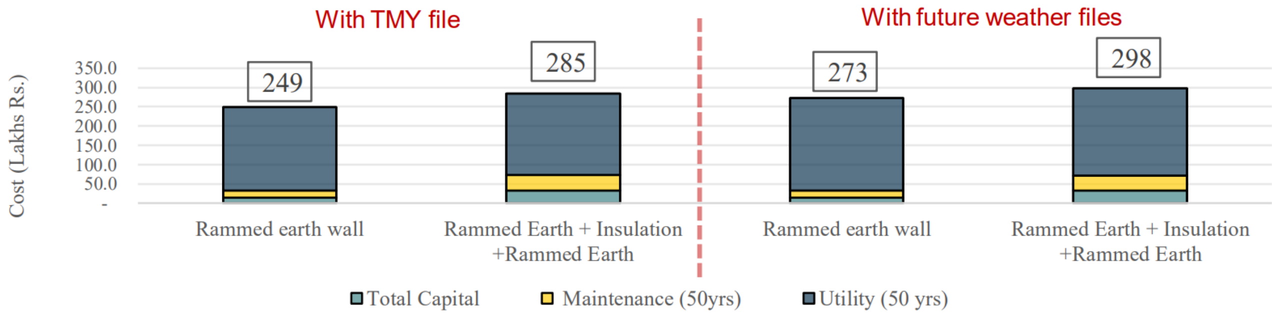

Figure 8: LCC comparison for mixed mode operation between TMY file and future weather file

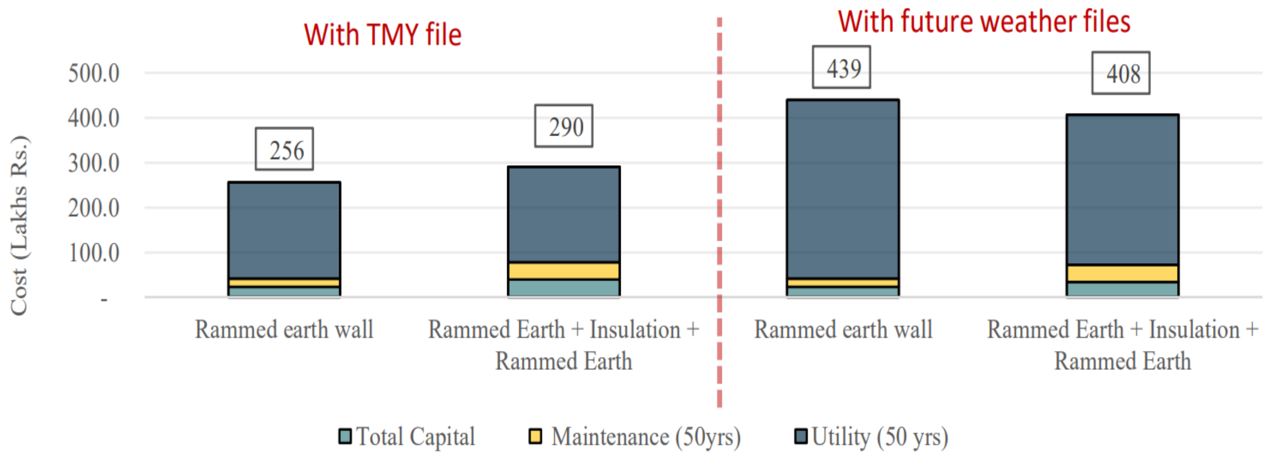

Figure 9: LCC comparison for fully air-conditioned operation between TMY file and future weather file

In Figure 8, which shows the results for the mixed mode operation, we can see that LCC increases for the insulated walls by 9% to 16% in both the TMY weather LCC and the future weather LCC. This is primarily the result of the large increase in Capex and maintenance resulting from the insulation and the fact that the insulated walls have 2 rammed earth layers.

In Figure 9, on the other hand, we see that with the fully air-conditioned operations, the TMY weather LCC has increased by about 13% for the insulated walls, but the future weather LCC shows a reduction in LCC by 10% for the insulated walls.

Thus, for mixed-mode operation buildings, where the utility cost is smaller, a TMY weather-based LCC may be adequate, but for fully air-conditioned operation buildings, where the utility cost is higher, a future weather-based LCC may provide a more realistic cost-benefit view.

Thermal comfort assessment using the TMY and future weather files

While we established that mixed-mode operation (with 70% naturally ventilated spaces) does not show an LCC benefit to convince investors, some questions about the value of insulation remain:

- Does the insulation provide adequate thermal comfort in current weather scenarios, based on a TMY weather-based comfort analysis, such that these spaces can indeed be operated without additional mechanical means for conditioning?
- Does the insulation provide adequate thermal comfort in current weather scenarios, say until 2080, such that these spaces can indeed be operated in the future without additional mechanical means for conditioning?
- If the answers to either of the above questions are a "no", then is the mixed mode operation LCC an appropriate analysis to be presented to investors?

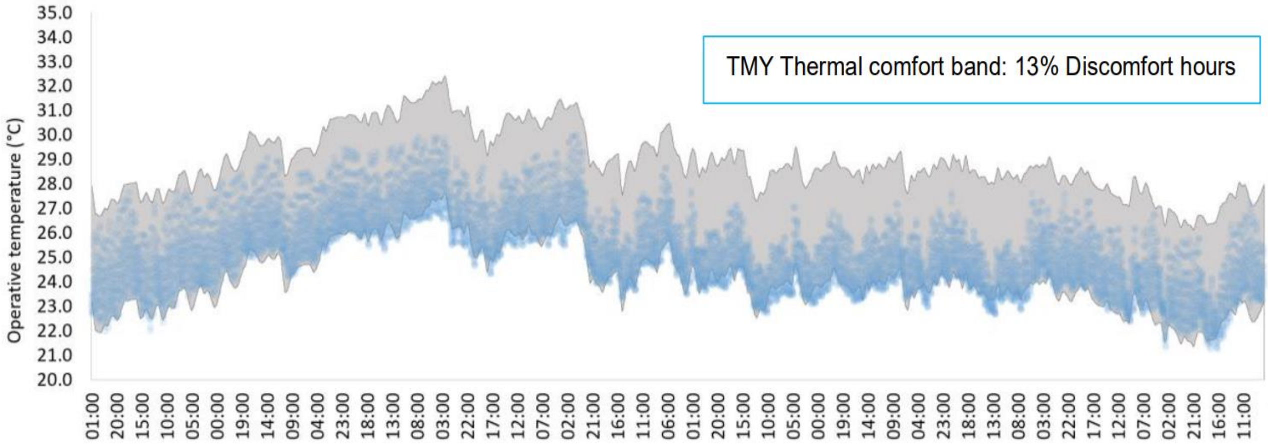

*Figure 10: OT with rammed earth wall (with insulation), the grey area shows the adaptive thermal comfort band (**TMY**) according to the National Building Code of India*

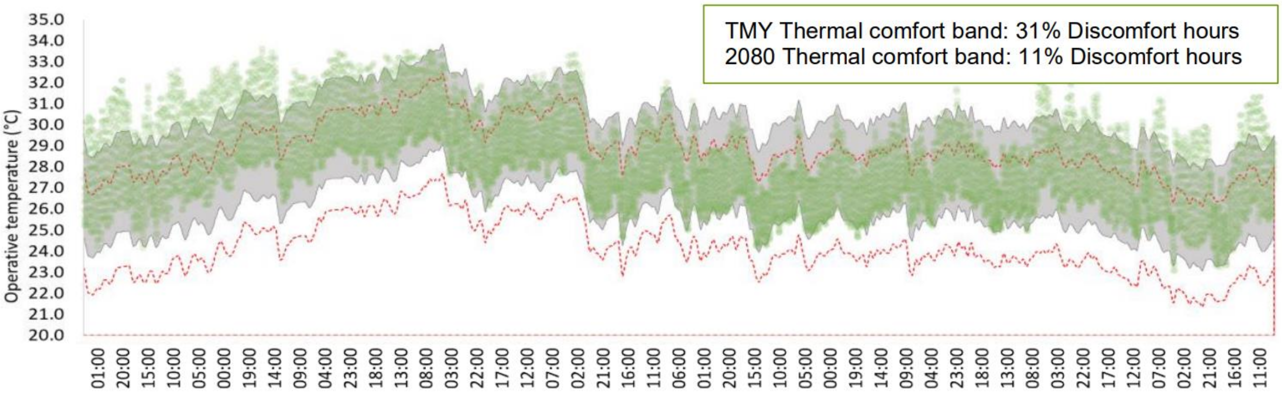

*Figure 11: OT of the workstation room with rammed earth wall (with insulation), the grey area shows the **future weather,** and the two red lines show the **TMY** adaptive thermal comfort band according to NBC*

Figure 10 shows the OT achieved with natural ventilation for the rammed earth wall with insulation using the recent historic weather data (TMY weather file). When compared with the NBC adaptive thermal comfort band for mixed mode operations, it shows that only 13% of the annual hours may be uncomfortable, where the discomfort hours are largely below the thermal comfort band. This is not a cooling problem and could easily be solved by aggressively closing the windows during times when the ambient temperatures are particularly low.

Figure 11 shows the OT achieved with natural ventilation for the rammed earth wall with insulation, using future (2080) weather files. The OT results are plotted against the NBC adaptive thermal comfort band for mixed mode operations. Here, there are 2 thermal comfort bands shown: one that uses the 2080 weather to calculate the 30-day running mean outdoor temperature (assuming we have adapted to much warmer conditions) and the other that uses the current (TMY based) weather (assuming we will not adapt so drastically to a set of warmer global and local temperatures). The 2080 building operation OT against the 2080 NBC band shows that the naturally ventilated building will have only 11% discomfort hours, with the OT going a maximum of 3ºC above the upper limit of the band. Literature shows that ceiling fans may have adequate cooling power index to compensate for this and provide comfort to the occupants [15]. The 2080 building operation OT against the TMY NBC band shows that 31% of the hours may be uncomfortable, with the OT going a maximum of 6ºC above the upper limit of the band. Literature shows that even under this less adapted scenario, ceiling fans may have an adequate cooling power index to compensate and provide comfort to the occupants [15].

Conclusion

This paper summarizes the lifecycle cost-benefit analysis of wall insulation for an experimental building in Bangalore, India. The method includes detailed audits of the building, long-term monitoring, and a calibrated energy model. The 50-year LCC was conducted with recent historical weather (TMY weather files), as well as with future weather files (2020, 2050, and 2080 synthetic weather). The overall results of the LCC analysis show that insulated walls have a lower LCC if the building is fully air-conditioned, whereas mixed-mode operations (70% naturally ventilated and 30% airconditioned) show a higher LCC for the insulated walls. This is true for both the TMY weather-based analysis and the future weather-based analysis.

A Detailed thermal comfort analysis for TMY weather and 2080 weather showed that the insulated building is able to provide adequate thermal comfort with 11-13% discomfort hours over the year (3ºC outside the thermal comfort band) under a fully adapted scenario. If the 2080 case does not include the full adaptation of thermal conditions consistent with the adaptive comfort equation of the NBC, the worst case would be 31% discomfort hours (5ºC outside the thermal comfort band). Cooling power index of ceiling fans is shown to be 6-7ºC, and therefore, ceiling fans would suffice to provide comfort in the experimental building in Bangalore.

The large question that this study is able to answer is whether a building such as the one studied, with adequate good passive design, thermal insulation, and natural ventilation, can provide comfort without the use of air-conditioning in Bangalore well into the future. Air conditioning in such a building may only be needed if ceiling fans are reported to be noisy or excessive air movement is reported to be problematic by the occupants. If an LCC cost-benefit analysis for insulation were to be conducted, the authors recommend that the insulated building be costed without any air-conditioning and the non-insulated building be costed with air-conditioning.

Acknowledgement

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