Optimising indoor air temperatures and thermal comfort measures for a low-income residential building in Ahmedabad, India

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Abstract. This study evaluates indoor thermal comfort conditions in a low-income residential building in Ahmedabad, India, with an aim to identifying passive strategies for reducing summer discomfort. Despite being designed with environmental and passive strategies in mind, the building's indoor temperatures during the summer reached an uncomfortable average of 37.1^0C during a 3-day measurement period. The study employs optimisation algorithms and parametric modelling to fine-tune simulation settings and parameters, aligning simulated results with measured data. It utilises energy simulations conducted using Climate-Studio in the Rhino-Grasshopper platform to assess various building parameters like window size, orientation, shading, and ventilation shaft. The results reveal that keeping windows open for natural ventilation significantly reduces indoor air temperatures with a 0.56^0C reduction on average over a 3-months period. Moreover, various design scenarios, including changes in window size, shading, and the inclusion of a chimney, demonstrate their potential to enhance thermal comfort. However, it is noted that passive strategies alone may not achieve optimal comfort levels and should be complemented by broader landscape and urban planning strategies on an urban scale to create comfortable indoor conditions. Overall, the study provides valuable insights into improving indoor thermal comfort in low-income housing in hot climates, with implications for sustainable architectural design.

Keywords. Indoor air temperature, indoor thermal comfort, hot climate, design optimisation, passive strategies.

1. Introduction

Comfortable indoor environment is essentail for meeting the basic health and wellbeing requirements of residents in low-income houses, particularly in tropical climates. A well-designed and thermally comfortable house can offer better resilience to the increasing frequency of extreme heat events and urban heat island effects. Chronic heat stress in tropical urban informal settlements suggests: high temperatures are approaching limits of human survivability (Ramsay et al. 2021). Therefore, the study aims to identify opportunities for reducing summer discomfort through passive design strategies in low-income residential buildings. Using actual measurements and through a simulation-based energy-comfort-optimisation model the study evaluates the indoor thermal conditions in a low-income residential building in Ahmedabad, India. The case-study building is situated within a marginalised, former leprosy-affected low-income housing community that experiences annual flooding. The building itself is the result of an inclusive and collaborative participatory design process, where residents actively participated in the planning, design, and implementation alongside professional experts. Even though the architect adopted suitable environmental and passive design strategies, the house was found uncomfortably hot during the summer with an average temperature of 37.1°C during a 3-day measurement period. Since this house is part of larger construction scheme, a proper analysis of traditional and passive design strategies will aid in identifying the potential parameters for achieving an optimal design solution that is energy-efficient, thermally comfortable and addresses the sociocultural need of the community.

2. Methods

Optimisation algorithms and parametric modelling play a crucial role in the development of sustainable building designs, offering valuable tools for enhancing efficiency and effectiveness in the design process. This study introduces a calibration methodology that involves multiple stages of fine-tuning simulation settings and parameters until a satisfactory correlation is achieved between the simulated results and the measured data. The energy simulation is carried out using Climate Studio in the Rhino-Grasshopper platform which facilitated the testing of relevant building parameters (window material, size, location, orientation, shading, and use of ventilation shafts) through a number of iterations. The idea is to identify optimal solutions that align with sustainable principles to improve the indoor environmental conditions through optimisation algorithm.

2.1 Study area

The paper is based on a field study in a former leprosy-affected low-income housing located on the outskirts of Ahmedabad, India at 22°59'58.6"N and 72°38'40.0"E which is 8.41 km south-east of Sardar Vallabhbhai Patel International Airport. Named by the Gandhi Leprosy Seva Sangh as the Loving Community, it was formed in 1968 after the land was provided by the Government of Gujarat to accommodate leprosy-affected people from all over India who were socially excluded due to the contagious nature of the disease. The community has 125 houses with a population of approximately 500 people. In this study, we have exmined a new architecturally-built house which was build under a UK-India Charity Programme.

Case Study House: The primary living spaces within the house consisted of four distinct rooms, namely the main living area, kitchen, bathroom, and toilet facilities comprising a floor area of 24.60m^2 (Figure 1). Adjacent dwellings were situated to the east and west of the aforementioned house, while to the south and north lay one private courtyard and one public courtyard, respectively.

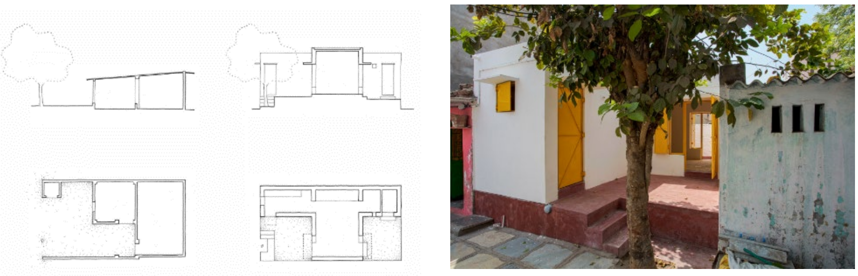


Figure 1: *Study House, view of the public courtyard in the front of the house*

2.2 Measurements

A measurement campaign was carried out in the Loving community during the hot summer months of May. Measurements included air temperature (Ta), relative humidity (RH), wind speed and mean radiant temperatures (MRT) using Testo 480 with humidity/temperature probe (accuracy of up to ± 1% RH), comfort probe for turbulence measurement and globe thermometer (TC type K) for the measurement of radiant heat.

2.3 Energy simulation and validation

Modelling: We created a digital model of the house using the Rhinoceros (Rhino) 3d modeling software and Grasshopper with ClimateStudio for optimisation and environmental simulations. ClimateStudio is an advanced environmental performance analysis software for simulations, predictions, and optimisations of buildings to enhance energy efficiency, daylight use, electric lighting performance, visual and thermal comfort, and various factors contributing to occupant well-being. ClimateStudio enables multi zone thermal simulations using the US Department of Energy's EnergyPlus comprehensive building simulation program.

Thermal Zoning: The case study house was divided into four areas for thermal modelling. Zone 1 is the main living area, with zone 2 being the kitchen connected to an open wall in the north, and zone 3 is a bathroom in the south. Zone 4 is a toilet located next to the bathroom, which can be accessed from outside (Figure 1). We focused on three main factors to make the house comfortable in terms of temperature and humidity: 1. the size of the windows, 2. the depth of shading, and 3. the stack or chimney.

Material and Construction Details: The materials for construction and the plans for scheduling (including people, equipment, lighting, and ventilation) were made based on the on-site survey. The various components used in building construction are outlined below:

- *External Walls (Load Bearing):* 210 mm thick brick walls with 6 mm plaster and paint on the exterior and the interior.
- *Internal Walls:* 100 mm thick brick walls with 6 mm plaster and paint on the exterior and the interior.
- *Plinth:* Constructed using brick Bats and Morrum soil filling, with a 20-25 mm thick IPS (Indian Patent Stone) flooring over a concrete base at a height of 900 mm.
- *Roof (Single-Storied Building):* 125 mm thick concrete roof with 20-25 mm waterproofing layers.
- *Doors and Windows:* Windows and doors are made of 6 mm steel shutters; some were reused from old houses.

Ventilation: The study has considered natural ventilation. Window opening schedule was determined from the survey data based on the occupancy schedule (Figure 2). The ventilation settings includes: Operable area of 0.9, Discharge coeffiient of 0.65, AFN (airflow network) Temperature setpoint of 20^0C and AFN window availability "AllOn".

Validation: Thermal analysis is validated against the in-situ measurements. The measurements included data collected over three days, from May 19 to 20 with a five minutes resolution. The model predicted the Zone Mean Air Temperature to be 34.27^0C, while the survey recorded it as 37.14^0C *(Figure 2)*. The Mean Absolute Percentage Error (MAPE) was 8.38%, and the correlation was 87.7%, which is considered acceptable.

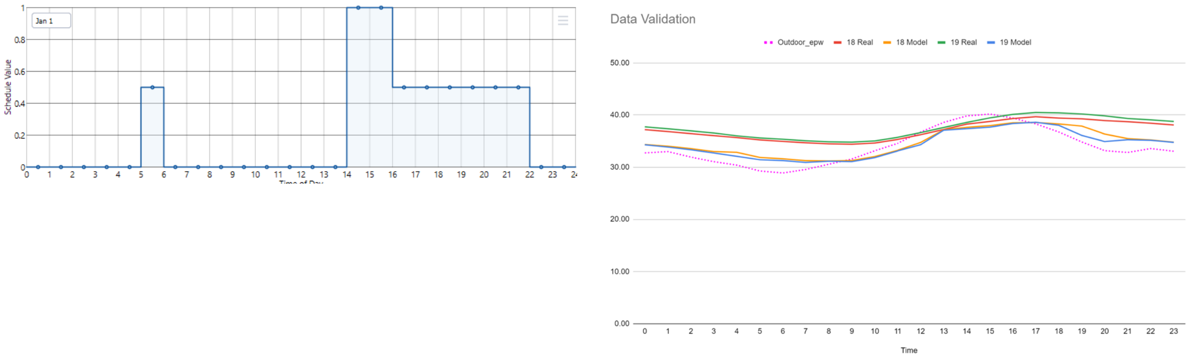


Figure 2: *Occupancy Schedule and Data Validation*

2.4 Optimisation

At this stage, indoor thermal conditions were examined by applying multi-objective optimisation algorithm for identifying the most effective set of design parameters for the optimal thermal comfort situation. The multi-objective optimisation algorithm involved the following objective functions shown in the Equations (1) and (2).

Minimise relative humidity = $f\{(a_1x_1) + (a_2x_2) + \ldots + (a_nx_n)\} + b$ ..(1)

Minimise indoor air temperature (due to outdoor solar radiation) = $f\{(a_1x_1) + (a_2x_2) + \ldots + (a_nx_n)\} + b$ ..(2)

where $x_i(i = 1\ldots n)$ depicts the indoor design variables, $a_i(i = 1\ldots n)$ are the derived coefficients.

The objective functions were based on the following design constraints as seen in Table 1.

Table 01 : *Design Parameters for multi-objective optimisation*

Design Parameters for multi-objective optimisation		
Design variables	Upper range	Lower range
Window size (horizontal extension from existing size)	1.4 m	0.4 m
Presence and height of stack or chimney	3.0 m	1.0 m
Depth of window shade	1.0 m	0.5 m

Modeling Scenarios (Figure 3):
We examined seven different situations to see how specific factors affect optimisation.

- *Scenario 1:* We checked how changing the size of windows *(from 0.4m to 1.4m)* affected the microclimate. We had two existing 0.4m wide windows, one facing north and one facing south. These windows could expand to 1.4m towards the east. The height of the window remained the same in all cases. We ran 121 simulations for this.
- *Scenario 2:* We kept the shading depth fixed at 0.5m (actual depth) and explored how extending the window width affected things. We ran the same number of simulations as in Scenario 1.
- *Scenario 3:* In this scenario, we played with both window and shading sizes, ranging from 0.4m to 1.4m and 0.5m to 1.0m, respectively. Since both windows were exposed directly to the outside, increasing the shading depth could create a semi-outdoor space, potentially affecting the microclimate during optimisation. We ran a total of 1296 simulations for this scenario.

- *Scenario 4:* We added a chimney to the living space. The chimney's height varied from 1.0m to 3.0m for optimisation. Other features remained the same as in the existing setup. Since there was only one change (the chimney), we ran a total of 6 simulations.
- *Scenario 5:* Similar to Scenario 4, but this time we considered a larger window with a fixed width of 1.4m on both the north and south walls. The number of simulations remained the same as Scenario 4.
- *Scenario 6:* We combined variations in both the chimney (1.0m-3.0m) and window size (width 0.4m-1.4m). This resulted in 80 simulations.
- *Scenario 7:* While scenarios 1 to 6 looked at changing individual parameters, Scenario 7 is a combination of all of them. We altered the window and shading sizes, and chimney height to find the best overall design solution and understand their relationships. We ran a total of 1280 simulations for this comprehensive scenario.

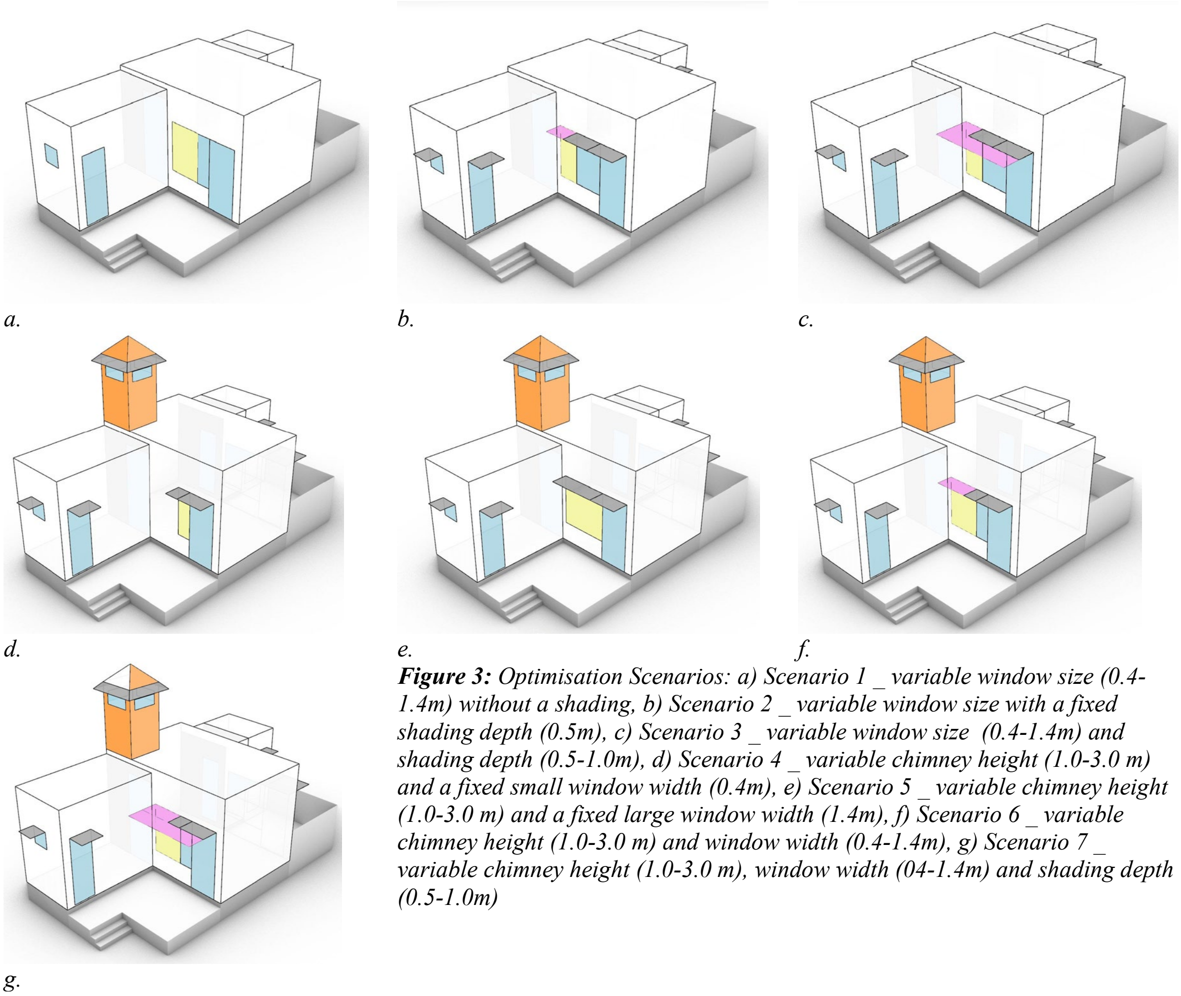

a. *b.* *c.* *d.* *e.* *f.* *g.*

Figure 3: *Optimisation Scenarios: a) Scenario 1 _ variable window size (0.4-1.4m) without a shading, b) Scenario 2 _ variable window size with a fixed shading depth (0.5m), c) Scenario 3 _ variable window size (0.4-1.4m) and shading depth (0.5-1.0m), d) Scenario 4 _ variable chimney height (1.0-3.0 m) and a fixed small window width (0.4m), e) Scenario 5 _ variable chimney height (1.0-3.0 m) and a fixed large window width (1.4m), f) Scenario 6 _ variable chimney height (1.0-3.0 m) and window width (0.4-1.4m), g) Scenario 7 _ variable chimney height (1.0-3.0 m), window width (04-1.4m) and shading depth (0.5-1.0m)*

3. Results

The average air temperature in the Model Zone from April to June was 33.25^{0}C, and the average humidity was 67.48% by following the occupancy schedule and ventilation schedule from the survey (Figure 2). Next, by keeping the same occupancy schedule, we let the windows open for 24 hours rather than responding to actual window opening schedule. This resulted in air temperature reduction to 32.69^{0}C, which is 0.56^{0}C less or 1.7% lower from the existing model. This means only by keeping the windows open throughout the day and night, it is possible to acieve a significant reduction in air temperature. We used this ventilation schedule in all our simulations.

Figure 4 presents the optimisation results and Table 02 presents the summary of finding from each scenario. In scenario 1, we tested a larger window on the south side. It lowered the average air temperature to 32.62^{0}C, which is 0.07^{0}C or 1.96% cooler compared to the existing window. When there's shading, the window's size affects the temperature, and the existing window increased the temperature to 32.73^{0}C.

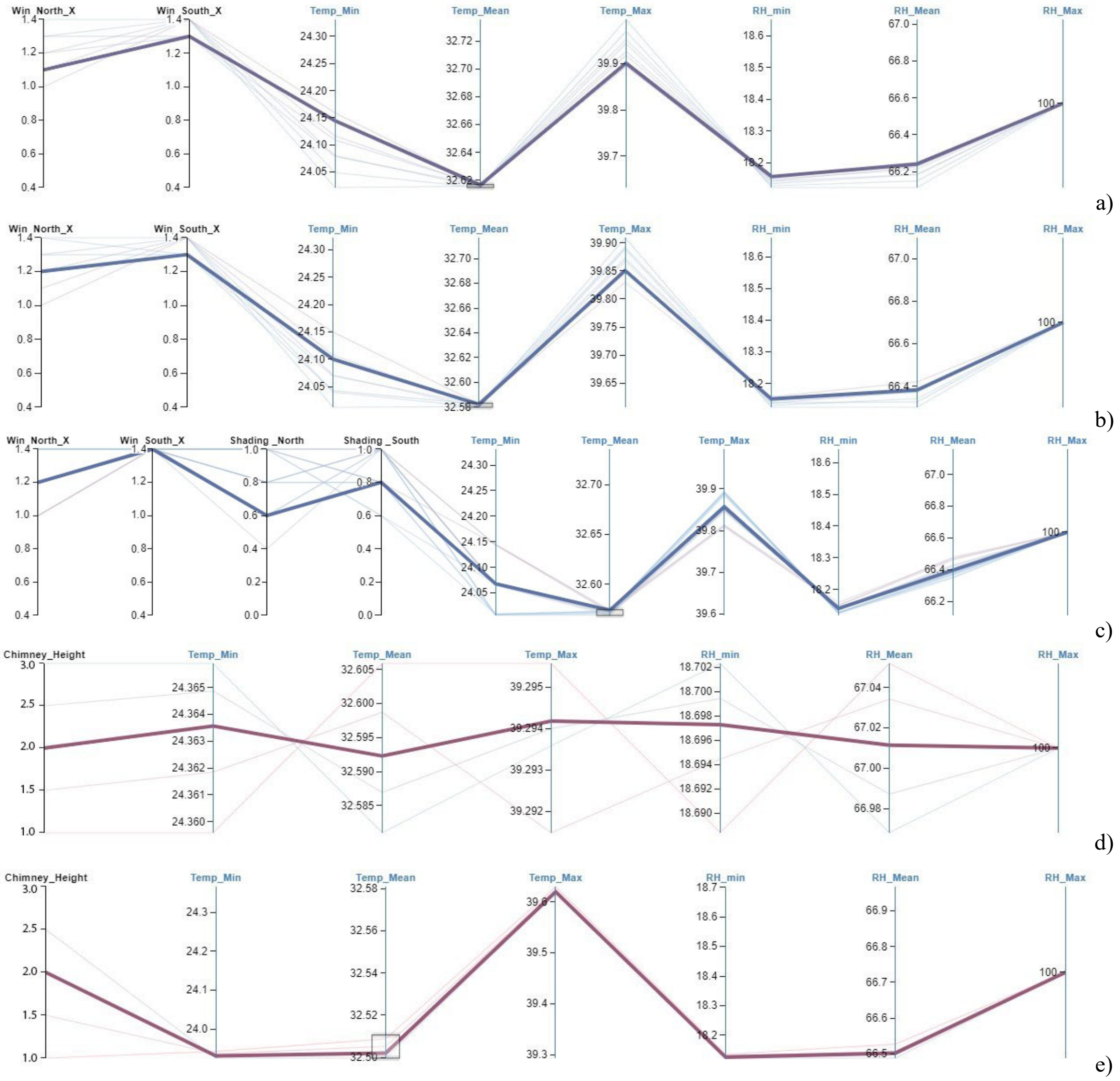
In scenario 2, we introduced shading, which improved conditions. The average temperature dropped to 32.58^0C, a 2.07% reduction from the initial condition.

In scenario 3, we optimised the size of both the north window and north shading to 0.8 meters and 0.6 meters, respectively, making them smaller compared to the south wall.

In scenario 4, we found that even with a smaller window, adding a chimney significantly reduced the temperature by 2.04%. However, it is possible to lower the chimney height by using a larger window, especially on the south side, as seen in scenario 5.

Scenario 6 Shows by increasing the chimney height from 2.0 meters to 2.5 meters, window sizes both in south and north wall have decreased to 1.0 meters, and resulting temperature is 2.32% lower .

Scenario 7 combines all the previous ones and offers various design solutions, achieving highest reductions in air temperature, by 2.38% in some cases. It presents options to adjust parameters like chimney height, shading size, or window size within a reasonable range to find a suitable design solution.



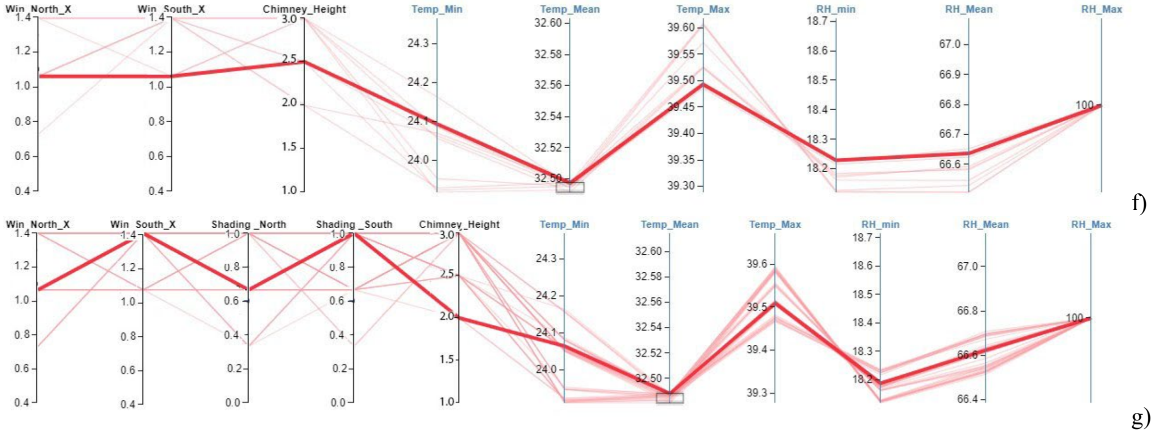
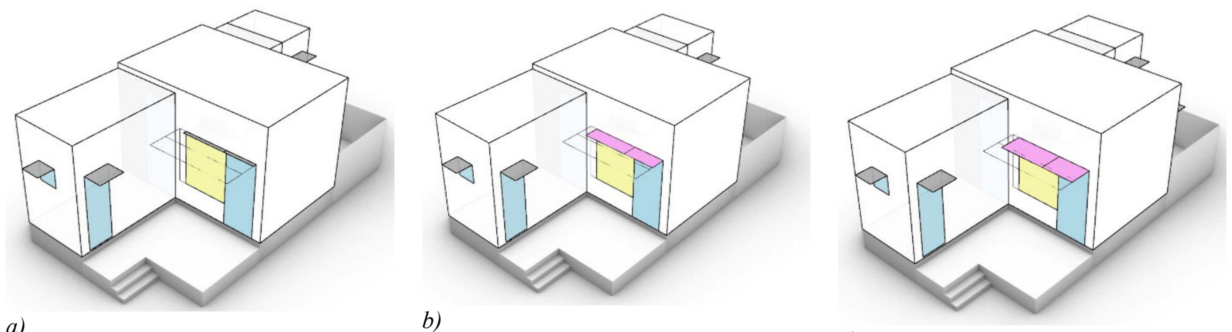


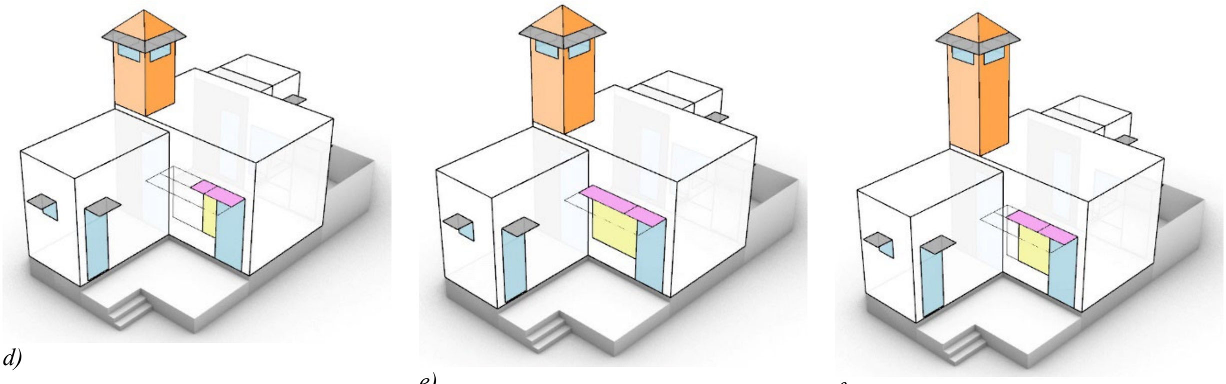
Figure 4: *Optimisation result of: a) Scenario 1, b) Scenario 2, c) Scenario 3, d) Scenario 4, e) Scenario 5, f) Scenario 6, g) Scenario 7*

Table 02 : *Finding of scenarios*

Scenario	Temp Mean, ^{0}C	Temp Drop from 33.25^0C _(Existing)	RH Mean	Window South	Window North	Shading South	Shading North	Chimney
Scenario_1 Window Size Only	32.62	1.96%	66.21	1.3m	1.1m	-	-	-
Scenario_2 Window Size + Fixed Shading	32.58	2.07%	66.38	1.3m	1.2m	0.5m	0.5m	-
Scenario_3 Window Size + Shading	32.58	2.07%	66.40	1.4m	1.2m	0.8m	0.6m	-
Scenario_4 Chimney + Existing Window	32.59	2.04%	67.01	0.4m	0.4m	0.5m	0.5m	2.0m
Scenario_5 Chimney + Large Window	32.51	2.29%	66.51	1.4m	1.4m	0.5m	0.5m	2.0m
Scenario_6 Chimney + Window	32.50	2.32%	66.62	1.0m	1.0m	0.5m	0.5m	3m
Scenario_7 Chimney + Window + Shading	32.48	2.38%	66.61	1.4m	1.1m	1m	0.7m	2.0m



a) *b)* *c)*


d) e) f)

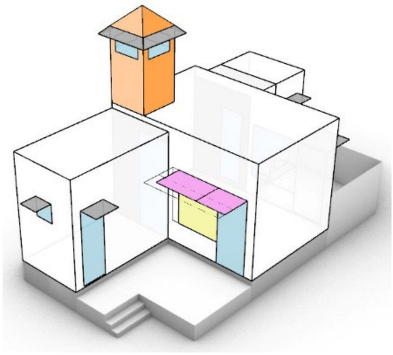
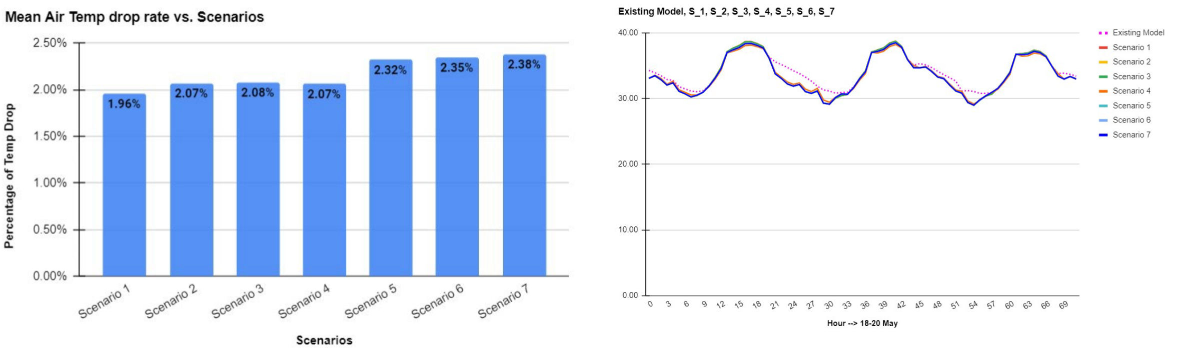

g)

Figure 6: *Optimized model of: a) Scenario 1, b) Scenario 2, c) Scenario 3, d) Scenario 4, e) Scenario 5, f) Scenario 6, g) Scenario 7*



a) b)

Figure 7: a) *Zone Mean Air Temperature drop rate in different scenarios with the existing model, b) Comparison of Zone Mean Air Temperature from May 18-20 in different scenarios with the existing model*

4. Discussion

The National Building Code of India establishes a maximum thermal comfort limit of 32.0°C and 60% relative humidity (RH) for naturally ventilated buildings, assuming an air velocity (AV) of 1.6 m/s. Research conducted by (Sharma and Ali 1986) sets the upper limit of thermal comfort at 30.0°C, based on the Tropical Summer Index (TSI). According to the adaptive model for free-running buildings in the hot-dry climate of Ahmedabad, neutral temperature ranges between 25.0°C–31.0°C in summer and 21.5°C –27°C for winter (Udaykumar and Rajasekar 2015). Oropeza-perez and Alberg (2014) has identified 26.85°C as a realistic measure of comfort for indoor conditions in the tropical climate for the whole year. In a more recent study, Rawal et al. (2022) have developed an adaptive thermal comfort model called the India Model for Adaptive Comfort - Residential (IMAC-R) based on yearlong field surveys in eight cities located across five climate zones of India. The IMAC-R suggests an indoor operative range of 16.3–35 °C. From the on-site measurements, the case study house was found far above the optimum comfort operative temperature with the maximum air temperature reaching up to 40.6°C which is detrimental to the health, wellbeing, and productivity of the occupants. Final simulation results have shown acceptable accuracy in correlation to the measurements from the site for the house, where the air temperature during summer ranged between 23.97°C and 39.54°C. This allows for optimising the thermal performance of the spaces and reaching for acceptable predictions for its simulations in the next steps. The optimisation algorithm will lead to an improvement in usable space and reduced thermal load in the house. The process and results of the study will help architects and designers to find a more sustainable design for the local context.

5. Conclusion

The study has presented passive design strategies to reduce indoor air temperature in the tropical climate of Ahmedabad during summer. Most significant finding was that only by keeping the windows open for natural ventilation during the day and night, it is possible to achieve significant reductions in air temperature. Particularly, during the hot-dry summer seasons, it is possible to cool down the building indoors through the principle of night cooling when outdoor temperature drops down after the sunset. In addition, we have tested 7 scenarios which have a combination of different design parameters related to window size, orientation, shading depth and inclusion of a chimney or stack. Increase of window sizes, especially on the south side of the building showed positive impact in air temperature reduction. Similarly, inclusion of window-shed and their increasing depth alongside use of chimney or stack shows positive outcomes. Although, increasing the height of chimney from 2m to 3m did not have much impact. The optimal size of south window and north window were found to be 1.4m and 1.1m with an ideal depth of 1.0m and 0.6m for the window-shed in north and south side respectively and a chimney height of 2.0m. However, it is possible to have numerous combinations of the above parameters to achieve similar thermal conditions which needs to be further analysed with a parallel cost-benefit analysis to select the optimal conditions. Most importantly, it is obvious that the proposed passive strategies were unable to bring down the mean air temperatures in summer within the recommended comfort ranges of 25.0°C–31.0°C or below the upper threshold of 32.0°C as recommended by the National Building Code of India, although all strategies were found have significant impacts. This suggests that passive strategies applied to individual buildings are not sufficient to create comfortable indoor conditions. This must be supported by appropriate landscape and urban planning through climate-responsive strategies in an urban scale.

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