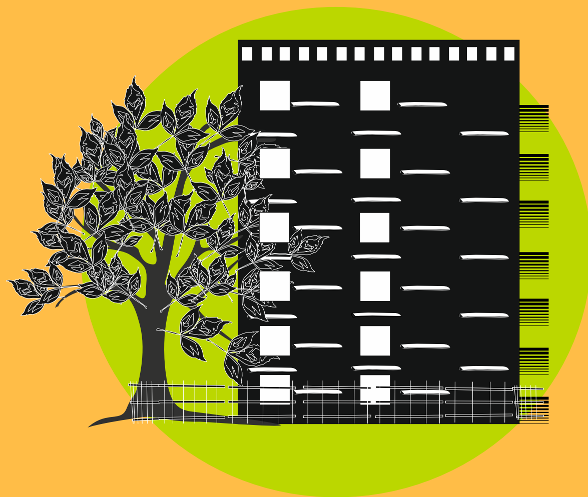

LITERATURE REVIEW (IMPACT OF PASSIVE MEASURES IN NATURALLY VENTILATED & MIXED MODE BUILDINGS) & SIMULATION METHODOLOGY

June 2022

Development of Thermal Comfort Action Plan 2050 and Thermal Comfort Performance based Design Standard cum Guidelines for Affordable Housing in India. [REF: 8338 0638]

Environmental Design Solutions Private Limited

Wuppertal Institute for Climate, Environment and Energy GmbH

Hunnarshala Foundation for Building Technology and Innovations

Quality Control Log

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Disclaimer

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Contents

1 Intent and outcomes

This report performs an exhaustive review of literature across peer reviewed journals and reports available in the public domain. This review attempts to support the development of Design Standard with focus on thermal comfort in affordable housing. This document outlines (**1**) the impact and sensitivity of key passive design strategies in tropical climates, (**2**) modeling methodologies for evaluating various passive strategies, and, (**3**) low energy systems to improve thermal comfort.

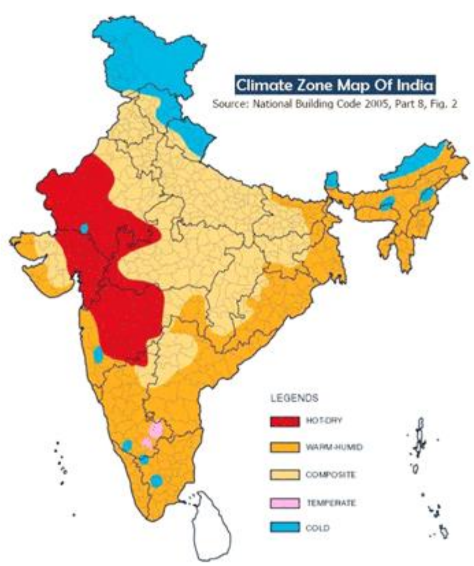
This study informs the choice of passive design and low energy strategies, and fine tunes the methodology for integrating these into the simulations for the development of Design Standard.

2 Scope and process

A literature review has been conducted to analyse the impact of various passive architectural design strategies on human thermal comfort satisfaction in residential buildings, with a focus on the affordable housing segment. Several research papers and technical reports have been reviewed to understand the impact of passive measures and natural ventilation.

Various passive strategies, climate zones and models, indices and metrics for thermal comfort have been analysed. While few studies report the impact of individual passive strategies on thermal comfort, others only report cumulative impact of various strategies. In the following, they are analysed and presented to aid the development of the proposed standard by emphasizing their applicability and limitations in various climate zones of India.

This review analyses literature from all over the world. It is critical to interpret climate classifications on a uniform scale for consistency in analysis. Therefore, India's climate classification has been mapped with the universal classification systems (Koppen-Geiger). Further, since the climate zones in India are predominantly of the hot and warm classification, emphasis has been laid on evaluating passive strategies that improve thermal comfort in tropical wet-dry climate (Aw), cold semi-arid climate (BSk), hot semi-arid climate (BSh), Mediterranean/dry summer (Csa)/dry-summer subtropical (As) climates.



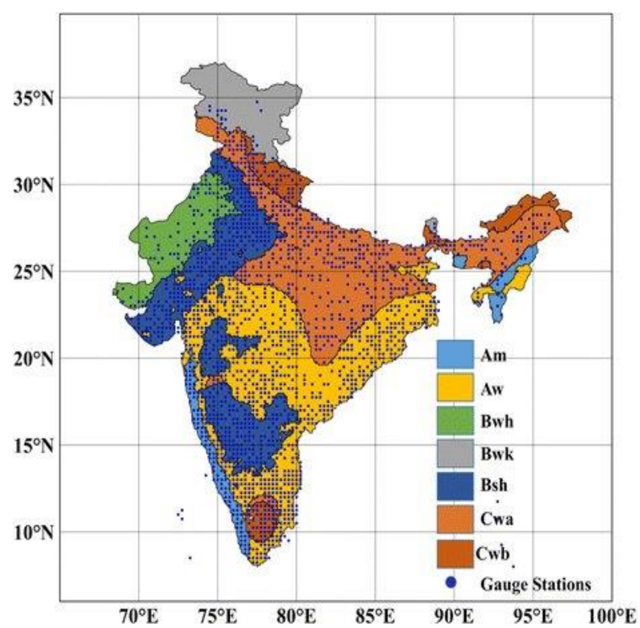


*Figure 1 **(a)** India's climate Zone classification. Source: National Building Code 2005, Part 8. **(b)** Koppen-Geiger climate classification for India (Am is Tropical Monsoon; Aw, Tropical Savannah; Bwh, Arid Desert Hot; Bwk, Arid Desert Cold; Bsh, Arid Steppe Hot; Cwa, Temperate Dry Winter Hot Summer; Cwb, Temperate Dry Winter Warm Summer). Source:(Upadhyaya & Ramsankaran, 2018)*

3 Literature review: Impact of passive strategies

This section outlines studies from China, Thailand, Yemen, India, Singapore, USA, Iran, Mexico, and others. In addition to the literature review, analyses and outcomes from the review have been presented in the following sub-sections as well.

3.1 Detailed summary of selected papers

A summary of selected, peer reviewed journals and reports is compiled here.

Sustainable Passive Design for Building Performance of Healthy Built Environment in the Lingnan Area (Li et al., 2021)
Country and climate: China. Hot summer and warm winter. The average temperature in January is higher than 10 °C. The average temperature in July is 25–29 °C.
Methodology & tools: On-site measurement combined with Building Performance Simulation tools. Thermal-K value, Ecotect, EnergyPlus.
Passive measures and impact: The design under consideration already included a courtyard. In addition, optimized shading was employed as a passive measure to improve thermal comfort without affecting daylight and noise performance. Post optimization, the design met Level I and II comfort levels. Comfort levels have been quantified using the Adaptive Predicted Mean Vote (APMV) criterion.
Relevant findings: Comfort is evaluated based on the APMV criterion. The APMV criterion has been incorporated in the Chinese Standard GB/T 50785. It combines Fanger's PMV approach and field studies to account for culture, climate and occupants' long term thermal adaptation (GB/T 50785, 2012; Li et al., 2018; Yao et al., 2009). The Assessment Standard for Healthy Buildings in China (T/ASC 02-2016) defines requirements for inner surface temperatures and daylight requirements among other things. The maximum exterior annual daily average serves as the threshold for maximum inner surface temperature for building envelope elements. For daylight requirements, minimum number of sunshine hours are defined.

Improving Thermal Comfort of Low-Income Housing in Thailand through Passive Design Strategies (Bhikhoo et al., 2017)
Country and climate: Thailand. Tropical wet–dry climate (Aw) characterised by hot and humid conditions throughout the year.
Methodology: Dynamic thermal simulations have been conducted on a baseline model for thermal comfort assessments based on CIBSE TM52. Simulation outcomes underwent uncertainty and sensitivity analysis using Morris' method to identify key parameters that influence thermal performance. The modelled case is from a mass scale government housing program that aims to deliver one million affordable homes. Each floor consists of 6 units 33 m^2 in area and arranged around a 36 m long a hallway.
Tools: Integrated Environmental Solutions—Virtual Environment (IES-VE), SimLab2.2, R Studio.

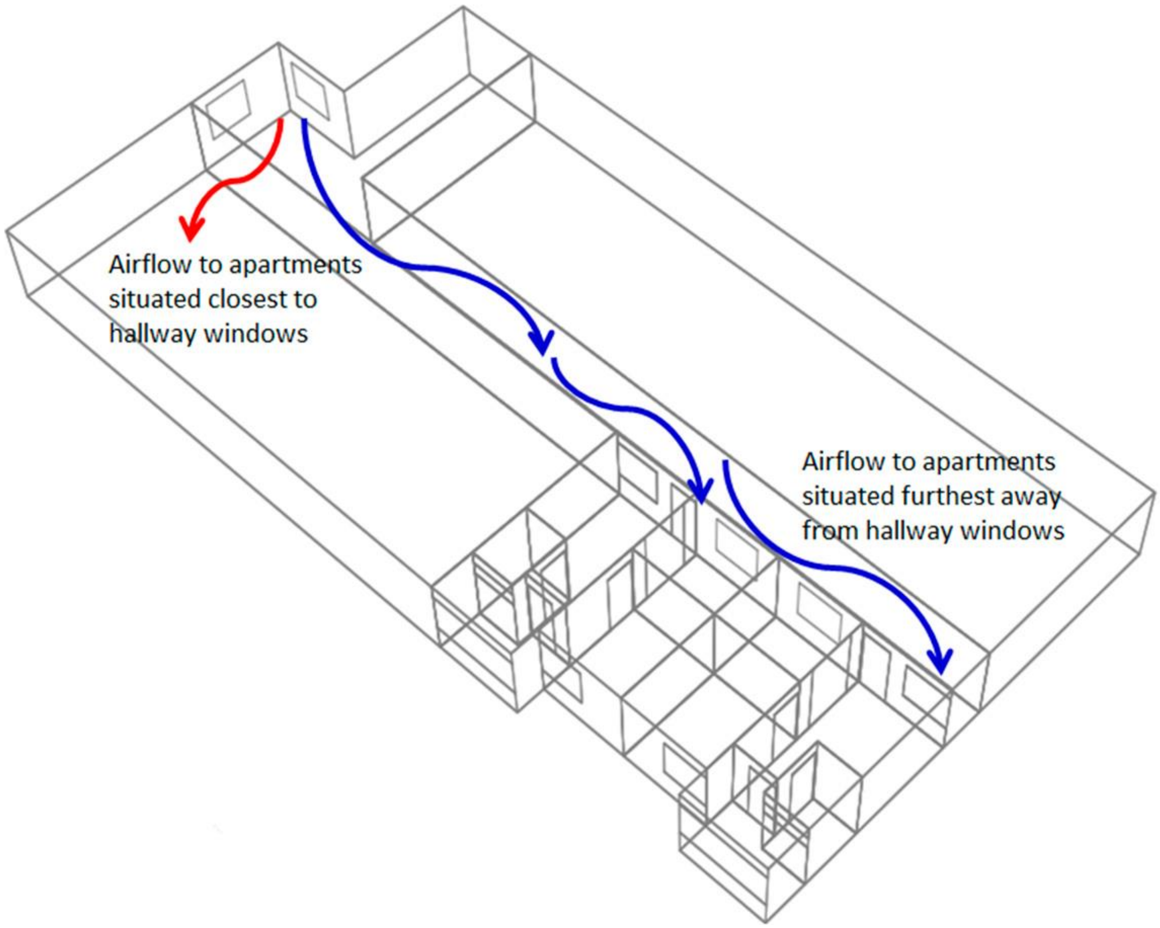


Figure 2 Layout of proposed cluster used for analyses in this study.

Passive measures and impact: The results identified roof material and balcony (as shading) had the greatest influence. Inclusion of roof insulation led to 21.43% reduction in overheating days. Removing the balcony increased overheating days by 19.94%. Owing to security and social reasons, night ventilation has not been modelled. However, analysis reveals that night ventilation has potential of improving operating temperatures by 2°C. The author highlights that natural ventilation has limited impact due to the cluster design.
Relevant findings: The research evaluates comfort on hours of exceedance, weighted exceedance and exceedance over temperature differential in line with CIBSE TM 52 assessment criteria. This research is relevant to the Warm-humid climate in Indian context. The research notes that with limited diurnal variation and availability of natural ventilation, there is limited impact of thermal lag. High radiation incident on the roof surface adversely impacts thermal performance in the top-most dwelling units. Finally, the study acknowledges unit and cluster layout are governing factors in impact assessment.

A Comparative Study of the Thermal Comfort of Different Building Materials in Sana'a, (Alhaddad & Jun, 2013)
Country and climate: Yemen (Sana'a). Arid climate in Sana'a is characterized by cold winters and warm summers. Winter temperatures in December-January are near or below freezing.
Methodology: The study analyses the comfort performance of traditional as well as modern materials such as factory manufactured extruded hollow brick, concrete blocks, sun dried mud-brick and aerated blocks to identify affordable and thermally comfortable construction techniques. The analysis uses actual site measurements for weather conditions and interviews on thermal comfort perception of users. The obtained data was used for thermal simulations.

Tool: Ecotect
Passive measures and impact: The outcomes indicate that while fired brick provides best overall thermal comfort, it's performance during summers is worst. The outcomes conjectured that if natural ventilation (during summers) were to be included thermal comfort performance would improve further.

A Methodology for Thermal Comfort Enhancement in Housing Design, (Prasad & Jones, 2001)
Country and climate: India (Delhi). Composite climate
Methodology: Research presents a methodology for thermal comfort enhancements in housing developments in India. The study uses a case study in Delhi to demonstrate incremental thermal comfort enhancements viz orientation, insulation (walls and roof), thermal mass, natural ventilation, glazing relocation, glazing area, glazing type and shading. Through BPS, these measures have been evaluated to calculate PMV. The best performing case is further subject to re-design and subsequent PMV evaluation. The redesign addresses measure like self-shading, orientation, natural ventilation, glazing orientation, glazing area, and earth-coupling. Evaporative cooling has been accommodated as a measure as well.
Tool: Visual DOE 2.6
Passive measures and impact: The baseline case outlines the significance of cooling. Based on the simulated cases, the study concludes that;

- for cases with insulated envelope, R-12 insulation in walls, R-20 insulation in roof and air change rate of 7 ACH performs best.
- most favourable conditions are exhibited by 8" thick thermal mass coupled with 12 ACH,
- summer PMVs were notably reduced at window to floor area ratio of 8%, however, this was insufficient to maintain night ventilation,
- fenestration improvements include double glazing and shading.

Relevant findings: The paper presents a methodology that may be suitably adapted to developing the analyses methodology. A detailed cost-based analysis was beyond the scope of this research. However, cost information provided a broad framework for incremental analysis. For example, orientation is considered as a no-cost measure and therefore the first improvement in a series of incremental measures. Further, high-cost measures like high efficiency glass (at the point in time), roof pond, etc. were discarded at the outset. The methodology acknowledges the complexity of achieving ventilation rates purely through inlet/outlet sizes and therefore uses fan/blower to maintain air exchange.

Analysis of Architectural Façade Elements in Tropical Climates for Daylight, Thermal Comfort and Passive Climatization, (Mccormick et al., 2017)
Country and climate: Singapore, Tropical Climate (hot and humid)
Methodology: This study evaluates10 housing developments in Singapore to establish a relationship between RETV values and physical building features against qualitative aspects of daylight and comfort. The study selected 10 buildings from over 200 private and public buildings. Laser scanners have been used to take point cloud measurements for each building. For additional information on window operability, etc. visual surveys and photographs have also been conducted. The collected information has been used to create shoe-box models for daylight and thermal simulations. BCA's "Code on Envelope Thermal Performance for Buildings" (2008) has been used for RETV and ETTV calculations. Simulations and analyses were conducted placing these buildings in eight cardinal directions. The outcomes compared RETV, solar heat gain, metrics across ownership (Private and Public), shading, vintage and occupant comfort. The simulations account for natural ventilation only. `ZoneVentilation:WindandStackOpenArea` model considers window opening fraction of 0.5 and auto-calculated wind coefficients depending on the hourly wind direction. Buoyant flow is not considered. Windows are assumed open when outdoor temperatures are below 28.5 ^{O}C.
Tools: DIVA (Daysim engine), Archsim (EnergyPlus engine)

Passive measures and impact: The analysis computes comfort as percentage of hours indoor operative temperature is less than 28.5 ^{O}C. Of the studied housing developments, newer private buildings reported poorer average RETV compared to older public buildings. While the sample size is small, primary reason for lower average RETV in older public housing may be attributed to lower average WWR. The analyses concludes that the correlation of design parameters with comfort is limited. Only high WWR, RETV and SHGC values can be attributed as direct indicators of low comfort levels. Impact-wise the 10 studies identify, in declining order, orientation, shading coefficient of glazing, thermal transmittance of wall, WWR and thermal transmittance of fenestration as key factors affecting RETV.
Relevant findings: The outcomes have been drawn from a limited data set. Absence of correlation between RETV and thermal comfort potential, even in the limited data set indicates that RETV is not indicative of occupant comfort. The outcomes indicate RETV does not accommodate key performance measures of daylight and thermal comfort potential.

Comfort standards and variations in exceedance for mixed-mode buildings (Borgeson & Brager, 2011)
Country and climate: California, United States of America. A representative set of 6 (out of 16) climate zones of California have been studied.
Methodology: The authors bring to light (in 2007) that despite the advancements in comfort models and exceedance metrics, there is no consensus on application of these models (and associated metrics) to mixed-mode buildings. The authors attempt to study the exceedance metrics through simulation and evaluation of variety of exceedance metrics. The simulation outcomes are subject to sensitivity and uncertainty analysis. The study models Kirsch Center (Northern California), a two-storey building of academic use spread over 2,000 m^{2} area. The paper demonstrates modelling adaptive comfort models from ASHRAE, EN 15251, NPR-CR 1752 and PMV-PPD model (ISO 7730). These comfort models evaluate performance under natural ventilated, mixed mode and conditioned cases. Of note in this paper is the modelling of natural ventilation.
Tools: EnergyPlus
Passive measures and impact: The authors highlight that climate and conditioning strategies aren't the only factors impacting thermal comfort. They acknowledge minimizing gains before adopting a cooling strategy as an effective approach. They go on to identify geometry, orientation, shading, massing, glazing, and insulation as strategies that support low-energy cooling. With respect to internal gains, the authors note that regardless of comfort evaluation method, internal gains have a significant impact on exceedance.
Relevant findings: Ventilation rates have been modelled using both scheduled infiltration rates and a more complex AirFlow Network model built into EnergyPlus. A sensitivity analysis of four-fold increase in pressure coefficients led to a less than 1% change in exceedance across all climates in California. The study concluded that with respect to computational cost, AirFlow Network calculations do not provide advantage over the simplified approach of using scheduled infiltration rates as proxy for window operation. The authors have noted that the Air-flow network model is a bulk air-flow model. For this study, windows have been modelled as 'open' with infiltration rate of five air changes per hour between 12 and 25 ^{O}C and set to 0.2 air changes per hour for other times. The authors noted that wind-driven ventilation can dramatically exceed five air changes per hour, however, five air changes per hour has been chosen as an appropriate proxy for suboptimal/average conditions. The authors consider outside conditions conducive to natural ventilation if temperatures are within the 15 - 27 ^{O}C (60 – 80 ^{O}F) range while the relative humidity is less than 70%. Figure 3 includes a key map of California with its climate zones and the bar chart outlines the comfort performance of these climates. 'Temperate' indicates conduciveness of climate for natural ventilation.

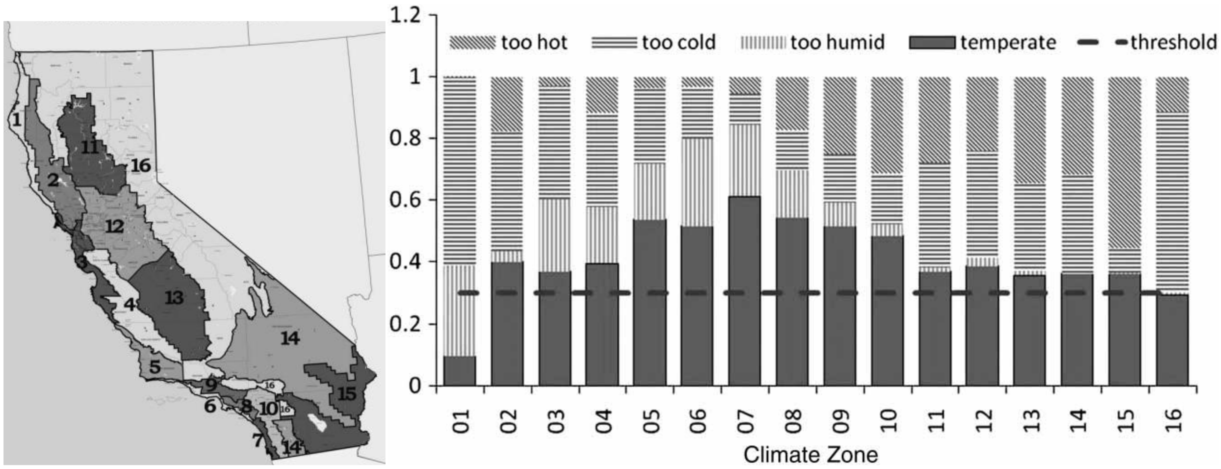


Figure 3 Performance of climates

Energy Efficient Building Envelope & Ventilation Strategies for Multi-storey Residential Buildings in India (Jaboyedoff et al., 2017)

Country and climate: India, Composite (Indore), Hot-Dry (Rajkot), Warm-Humid (Chennai).

Methodology: The study evaluates indoor temperatures for three case studies of multi-family high-rise residential buildings in Indore, Rajkot and Chennai using energy simulation tools. It further employs a combination of recommended strategies to improve comfort performance.

The study focuses on simulation of critical spaces instead of modelling whole building. For residences, bedrooms have been identified as critical spaces as these are most used and have maximum occupancy in evenings and at night. These spaces have been modelled and simulations report peak operative temperature inside flats on a typical summer day. This simulation is conducted for an intermediate and top floor case. The simulation assumes naturally ventilated dwelling units and models window operation based on temperature differential.

Tools: EnergyPlus (DesignBuilder)

Passive measures and impact: The simulations identify insulated envelope, movable external shades and operable windows (50% openable) as key measures. In addition, a low energy ventilation strategy by inducing downdraft has been utilized as well. Climate specific strategies and their impact is outlined in Table 1.

Table 1 Comparative analyses of comfort metrics and strategies evaluated for high-rise residential apartment case studies spanning three climate zones.

	Indore (Composite)	**Rajkot (Hot-Dry)**	**Chennai (Warm-Humid)**
Pre-recommendations	230mm brick wall plastered both sides (2 W/m^2-^{o}K) 6mm clear glass (5.8 W/m^2-^{o}K, 0.81 - SHGC) WWR: 29 – 43% Roof 3.7 W/m^2-^{o}K	230mm fly ash brick wall plastered both sides (1.9 W/m^2-^{o}K) 6mm clear glass (5.8 W/m^2-^{o}K, 0.81 - SHGC) WWR: 15% Roof 3.7 W/m^2-^{o}K	230mm AAC block wall plastered both sides (0.7 W/m^2-^{o}K) 6mm clear glass (5.8 W/m^2-^{o}K, 0.81 - SHGC) WWR: 20% Roof 3.7 W/m^2-^{o}K
Indoor operative temperature	**Intermediate Floor** Coolest bedroom: 34 ^{o}C Hottest bedroom: 38.4 ^{o}C Differential: 4.4 ^{o}C **Top Floor** Coolest bedroom: 37.9 ^{o}C Hottest bedroom: 40.4 ^{o}C	**Intermediate Floor** South facing room: 34.7^{o}C West facing room: 38.3^{o}C Differential: > 3.5^{o}C is **Top Floor** South facing room: 38^{o}C West facing room: 41^{o}C	**Windward Side**: 37.8 ^{o}C **Leeward Side**: 38.2 ^{o}C **Differential**: 0.4 ^{o}C (Case study in Chennai has a Sky Deck covering the roof. Simulations

	Differential: 2.5 °C	Differential: 3°C	evaluate leeward & windward sides)
Post-recommendations	Reduce WWR (20-30%) External movable shading on windows 200mm AAC block wall 100mm XPS roof insulation	External movable shading (or opaque window shutters with 20% daylight glazing) Casement windows 40mm Polyurethane foam (PUF) roof insulation Assisted ventilation via central shaft	Shaded windows with external movable shades Replacing sliding windows with casement windows
Indoor operative temperature	Peak: 33 °C (Differential of 7.4 °C)	**Peak reduction** Intermediate floor: 4°C Intermediate floor with assisted ventilation: 4°C + 1-2°C Top floor with assisted ventilation: 4-5°C Top floor with assisted ventilation and PUF insulation: 4-5°C + ~3°C	External movable shades lead to a differential of 4°C for windward and 4.2°C for leeward apartments. Fixed shading reduces temperatures by 1.5°C.
Remarks	The recommendations have the potential to reduce the cooling demand to a third.	Bedrooms facing north and south are coolest in summer. Highest heat gains occur through the glazed windows. Number of hours in a year with operative temperature less than 30°C can be improved from 25% to 72%. Wall insulation is best suited where diurnal range is high.	External movable shades have prominent impact. Number of hours operative temperature stays below 30°C improves from 65% to 95% for windward apartments and 40% to 74% for leeward apartments. Casement windows provide better control by offering more openable area.

Relevant findings: The study confirms reduction potential of 4 – 7 °C in indoor operative temperatures after incorporating recommended strategies. The thrust is on reducing heat gains through envelope and improving natural ventilation to improve thermal comfort. The study also points towards incorporation of RETV like metrics in bye-laws for implementation in new building stock.

In addition to providing insights into performance, the findings also point towards time-efficient modelling strategy of focusing on critical spaces, setting simplified temperature differential-based window operation algorithms and evaluating metrics related to peak operative temperature and percentage of hours beyond a threshold temperature.

Evaluating building design for thermal comfort with single rating parameter- hot-dry region of India (Agrawal & Singh, 2015)

Country and climate: India, Hot-dry climate

Methodology: The study presents a novel approach of evaluating building performance by computing Difference in Uncomfortable Hours Outside vs Inside (DUHOI). The study recognizes the need for using Thermal Comfort based rating tool that also responds to the climatic context. The response to climate is by way of normalization across different climate zones. The premise for 'Normalization' attempts to account for diversity of climate. The study evaluates comfort using the Tropical Summer Index for both indoor and outdoors. Indoor performance is evaluated for 5 case-studies. The case studies include traditional as well as contemporary forms of architecture. Traditional building forms include courtyards, deep recesses, heavy thermal mass, shaded verandas and other passive design measures.

The methodology includes simplifications for facilitating analyses. The computation of TSI uses Air speed, Air temperature and Humidity parameters. While hourly air temperature and humidity are obtained from simulation outputs for all habitable spaces, the air-flows are computed as per guidance in SP41 due to simulation constraints. Further window operation schedule has been simplified based on understanding of common practices. Window operation schedules assume windows to be closed during winter nights and summer afternoons.

Tools: EnergyPlus (Design Builder)

Passive measures and impact: The outcomes highlight that traditional havelis outperform contemporary building in owing to heavy thermal mass and courtyard arrangement, shading of habitable spaces using semi open verandas.

Relevant findings: Traditional architecture may hold the key for thermally comfortable and efficient design. Haveli architecture also closely resembles cluster of low-rise developments. The use of TSI as thermal comfort index and simplifications in modelling can potentially advise standard development methodology.

The operative temperatures corresponding to 'neutral' thermal sensation votes (+1, 0, -1) for different air velocity were determined using the trend line equation. For air velocity up to 0.2 m/s, the mean operative temperatures thus calculated for NV and MM buildings were 28.04°C and 26.93°C, respectively and considered as reference points for drawing curves between indoor air velocities and offset in temperature. For the elevated air velocity of 1.5 m/s, the offset increase in operative temperature for NV and MM buildings were reported to be 4.78°C and 4.24°C, respectively. Thus, the maximum comfort temperature obtained for NV and MM buildings were 32.78°C and 31.24°C, respectively (Sansaniwal et al., 2020).

Influence of building design and control parameters on the potential of mixed-mode buildings in India (Gokarakonda et al., 2019)

Country and climate: India. (Warm-humid) Visakhapatnam, Hot-dry (Surat), and Bhopal (Composite)

Scope and methodology: The study assesses the role of building design and control parameters in mixed mode buildings. The study performs uncertainty and sensitivity analysis for office buildings across three climate zones in India. Analyses and simulations are performed for a hypothetical 3 storey model with three-zones on each floor. The model uses Monte-Carlo based global Sensitivity Analysis to generate input cases for simulating various envelope (material and design) characteristics and control strategies. Further for uncertainty and sensitivity analyses Standardised Regression Coefficient and Morris elementary effects method are used. The mixed-mode control strategy uses a temperature set-point (varies between 22.5 and 28.5^{O}C) during cooling and a combination of vent opening factor and indoor-outdoor temperature differential during natural ventilation operation. The outcomes from simulation record the annual cooling energy consumption, thermal comfort conditions and hours of natural ventilation available. It must be noted that night-time ventilation or window operation during night-time has been ignored as it is not a widely adopted strategy in office spaces.

Tools: SimLAB, EnergyPlus, jEPlus, R, and MATLAB

Passive measures and impact: The outcomes indicate that a maximum of 10% of occupied hours are amenable for natural ventilation in Warm-humid and Hot-Dry climates. This improves slightly for composite hours.

The study identifies cooling setpoint has a positive correlation with natural potential, i.e. hours natural ventilation is effective. The number of hours natural ventilation is effective is also accentuated by thermal mass. Internal gains, window SHGC, openable area are the other influential parameters.

The study identifies cooling setpoint temperature, building size, window solar heat gain coefficient, and surface properties of exterior surfaces as influential parameters.

The incidence of higher values for Annual Cooling Energy Intensity (ACEI) is higher in the warm and humid climate followed by the hot and dry and composite climates, as these two latter climates have cold winter and lean seasons.

The frequency of occurrence of the peak ACEI values is lower in the warm and humid climate zone compared with the other two.

Relevant findings: It is critical to note that the literature review conducted for the study acknowledges that urban canyons and heat islands impact micro-climatic environments. These impacts can be seen in the urban wind speeds. Further, the review quotes published research to highlight impact and intensity of UHI effects (approximately 0.8 – 10^{O}C rise). This has impact on natural ventilation modelling. The study indicates extrapolating weather data from meteorological stations to suit site-specific conditions and generating accurate wind pressure coefficients are crucial. The study concludes

3.2 Analyses of passive strategies and their impact on thermal comfort

The literature review sheds light on not only the impact of passive strategies, but also on comfort (thermal and visual) requirements and evaluation criteria, tools used for evaluation, applicable codes and standards, behavioral aspects, and even housing programs. Along with thermal comfort impact of these strategies, these other factors will also shape the thermal comfort standard.

Some research studies attempt at addressing known gaps such as; performance of modern materials vis-à-vis traditional materials, complexity in modeling passive design strategies, accommodating behavioral aspects, control strategy for window operation, plethora of adaptive models, quantification of micro-climate, etc. The solutions to some of these challenges, especially with respect to design standard development lies in constraint relaxation.

Owing to diversity in climatic context, scope and research objectives, the studies conclude different approaches for meeting thermal comfort through passive design. Key strategies identified across different studies identify external moveable shades and operable windows, surface properties of exterior surfaces, etc.

The following sections show various passive strategies. Each strategy is presented with a brief description, its applicability in the climate zones of India, and impact on thermal comfort satisfaction. Where the impact of passive strategies on thermal comfort satisfaction are not available, their impact on heat gains or losses into the building from the surroundings or heating/cooling demand or energy consumption are being considered as proxy for thermal comfort satisfaction.

3.2.1 Building envelope design and geometry – Building form and massing/zoning

Brief description

Building form factor impacts the heat gains and losses through the building envelope to the surroundings, typically, relative to its volume. This is typically expressed as surface area – to – volume ratio (S/V or SVR) and form factor.

Remarks - Applicability in various climate zones of India and in various building typologies

Typically, most studies on S/V are from cold climates where energy consumption for space heating has to be minimized (Araji, 2019; Lim & Kim, 2018; Lylykangas, 2009; NHBC Foundation, 2016). In general, a low value of S/V is preferred to minimize heat loss from the buildings. The same principle can also be applied to minimize heat gains in to air-conditioned buildings in hot climates (Abu-Ghazalah et al., 2007). Furthermore, position of buffer spaces, such as staircases, in certain building typologies impact the hours of thermal comfort satisfaction, which can be included as an additional design strategy for massing/zoning studies (Pathirana et al., 2019). However, in unconditioned buildings, it is also important to lose accumulated heat effectively, e.g., through night ventilation, and optimize the depth of the building for maximizing the floor area via daylight and natural ventilation (CLEAR, n.d.). S/V is also minimized in multifamily buildings, where the number of external surfaces is less than single family buildings. Therefore, although this is an important strategy, S/V/form factor should be optimized in relation with other passive strategies, such as maximizing daylighting, natural ventilation, and night ventilation (Pathirana et al., 2019).

Metrics that could be considered for the standard development

- S/V or SVR = Surface (external) area of building envelope/volume (CLEAR, n.d.);

- Form Factor = Total heat loss area of walls, roofs, floors and openings (m^2)/Habitable floor area of all storeys (m^2) (NHBC Foundation, 2016)

Impact on thermal comfort satisfaction (heating/cooling demand or energy consumption)
For the same floor area, building with an optimized form factor could save as much as 136% of space heating energy demand (NHBC Foundation, 2016).

Impact on incremental cost (₹ (very low) - ₹₹₹₹₹ (very high), nil)
The cost impact from an affordable housing perspective may be marginal to no cost, to even marginally lower. While on the one hand the cost may be lower owing to compact form for homes in cold climates, it may be marginally higher for warm-humid climates that require higher ceilings. Overall impact is rated at Nil – Low (- ₹₹)

3.2.2 Building envelope design and geometry – Orientation

Brief description
Orientation of the building and of its external surfaces influences the amount of solar heat gains and losses in the building. Orientation is characterized by the angle the normal (outward facing) to these surfaces describes with respect to North. Furthermore, in naturally ventilated buildings, windows should be located on the facades facing the windward direction to maximise the potential for natural ventilation and night ventilation (Albatayneh et al., 2018). For horizontal surfaces (roof and shades), the pitch, i.e. the angle described by the horizontal surface with the ground plane, is critical as well. In addition to these two factors that impact thermal comfort satisfaction, orientation of the building is also strongly influenced based on other functional and design considerations. The solar azimuth and solar altitude are key metrics.

Remarks - Applicability in various climate zones of India and in various building typologies
Optimizing the orientation of the building for heat gains and losses, as well as for natural ventilation is an important design consideration for any building, irrespective of climate and building typology.

Metrics that could be considered for the standard development
- Solar azimuth angle of the longer wall in rectangular buildings
- Solar altitude angle of pitched roof
- Predominant wind direction, angle described with the openings, and wind velocity

Impact on thermal comfort satisfaction (heating/cooling demand or energy consumption)
Depending on the local variations in warm and humid climates, optimized orientation can improve thermal comfort by natural ventilation by up to 56% (Haase & Amato, 2009). However, for various zoning typologies and wall-to-window ratios, significant differences in the potential to improve thermal comfort are observed for different orientations, minimizing the impact of orientation than other factors (M. Al-Tamimi et al., 2011; Pathirana et al., 2019).

Impact on incremental cost (₹ (very low) - ₹₹₹₹₹ (very high), nil)
Nil

3.2.3 Building envelope design and geometry – Shading

Brief description
The principal role of shading elements is to protect fenestrations and walls from direct solar radiation, while their secondary role is to protect them from diffused and reflected radiation and thus, protecting the space from unwanted solar heat gains that can have negative impact on thermal comfort. This is a widely adopted passive strategy and often considered a low-hanging fruit that can be easily integrated into the building design, and typically, fixed shading devices are used in affordable housing projects (Bhikhoo et al., 2017; Charde & Gupta, 2013; Chen et al., 2018; Gou

et al., 2018; Hashemi & Khatami, 2017; Li et al., 2021; Mahar et al., 2020; Rincón et al., 2019; Rivera & H., 2019; Zune et al., 2020)

Remarks - Applicability in various climate zones of India and in various building typologies
Optimizing shading design is important for any building, irrespective of climate and building typology.

Metrics that could be considered for the standard development
Projection factor and SGHC adjustment factors are key metrics that may be used to evaluate effectiveness of shading. For different orientations, provide

- horizontal and vertical shadow angles for vertical and horizontal shading devices, respectively (or)
- length of the projection of horizontal and vertical shading devices

Impact on thermal comfort satisfaction (heating/cooling demand or energy consumption)
Shading alone could improve comfort percentage (percentage of hours when thermal comfort is achieved) by up to 28%, subject to other conditions, such as the room orientation, and number of external walls (Li et al., 2021). Furthermore, effective shading can reduce the risk of overheating in peak summer conditions by up to 52% (Hashemi & Khatami, 2017).

Impact on incremental cost (₹ (very low) - ₹₹₹₹₹ (very high), nil)
₹ (very low)

3.2.4 Building envelope design and geometry – Window area, U-Value, Solar Heat Gain Coefficient (SHGC), and visual light transmittance (VLT)

Brief description
The area of window significantly influences the amount of heat gains through solar radiation, daylighting, and the potential for natural ventilation. However, the requirement of area of window for both these aspects contradict each other, i.e., while a large window opening area maximizes the potential for daylighting and natural ventilation, at the same time, it increases the amount of (unwanted) solar radiation in the space (M. Al-Tamimi et al., 2011; Pathirana et al., 2019). In typical buildings, Window (area) – to – Wall (area) ratio (WWR) provides a convenient measure for comparison and optimization of window area that is required to meet the minimum requirements for daylighting and natural ventilation while minimizing unwanted solar radiation in the space. In addition to the area of window, its overall heat transmission value (U-Value) and solar heat gain coefficient (SHGC) influences the heat gain through windows. Lower U-Value and SHGC helps in minimizing conductive and radiative heat transfer into the space. Visual Light Transmittance (VLT) is a measure of the amount of daylight that passes through the glazing of a window. A window with a higher VLT transmits more visible light and leads to a reduction of the need for artificial lighting. In all cases good day lighting, VLT should be guaranteed. Care must be taken, though, not to produce glare inside the internal spaces. Optimising the balance between window U-Value, solar heat gain coefficient and visual light transmittance is therefore, important to minimize heat gains and maximize daylighting in the space.

Remarks - Applicability in various climate zones of India and in various building typologies
Optimizing WWR, U-Value, SHGC and VLT is important for any building, irrespective of climate and building typology.

Metrics that could be considered for the standard development

- Window – to – Wall Ratio for various climate zones
- U-Value of window
- SHGC of window
- VLT of glazing

- Minimum level of natural ventilation
- Minimum level of daylighting

Impact on thermal comfort satisfaction (heating/cooling demand or energy consumption)

Increasing the WWR beyond a threshold leads to marginal improvement in daylighting and significant decrease in thermal comfort satisfaction. Therefore, the influence of varying WWR on thermal comfort satisfaction is much higher than the potential for daylighting and natural ventilation (M. Al-Tamimi et al., 2011; Pathirana et al., 2019).

Impact on incremental cost *(₹ (very low) - ₹₹₹₹₹ (very high), nil)*

With respect to affordable housing, window wall ratio and shading are typically optimized. There, may be additional cost in integrating insulated glazing or relatively high-performance glazing. Overall, impact is rated as Low to High (₹ - ₹₹₹₹)

3.2.5 Building envelope construction – Thermal physical properties of external walls

Brief description

'Heavy-weight' or 'mass' materials, such as concrete, brick and stone, have the ability to absorb, store, and release heat to the surroundings. Characterization of 'Heavy-weight' or 'mass' is determined by fundamental thermophysical properties - conductivity, density, and specific heat capacity. These are used to derive other thermal properties such as diffusivity, mass, and inertia.

Thermally insulating materials impede the flow of heat from inside to outside or vice versa. Thermal insulation is derived from conductivity. Typically, heat insulating materials are characterised by low conductivity and density.

The external wall in a building determines two factors that influence internal temperature conditions. These are thermal lag and decrement factor. Thermal lag is the time difference between the occurrence of peak outdoor and indoor air temperatures during the day. Decrement factor is the ratio of the amount of peak-to-peak of indoor and outdoor air temperatures.

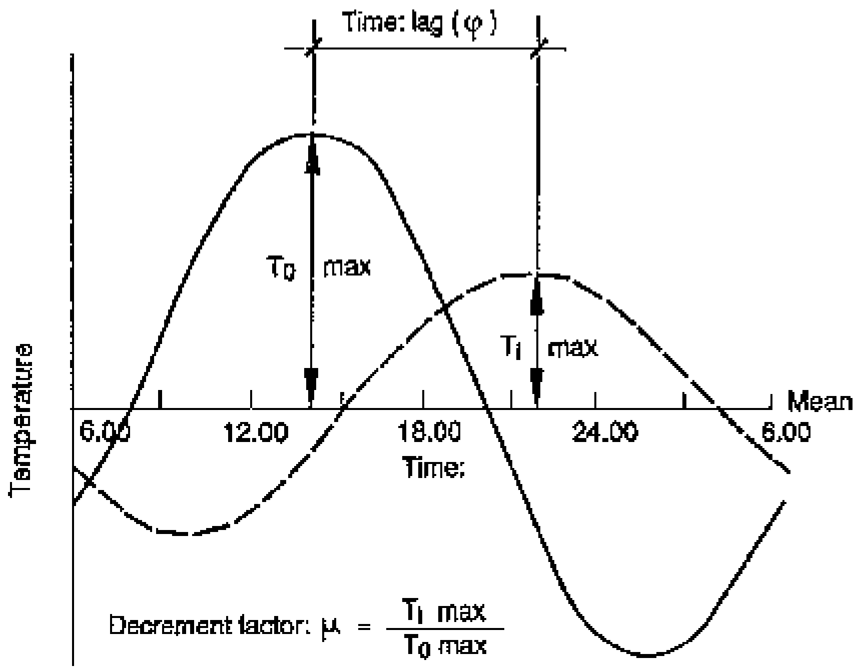


Figure 4 Thermal lag and decrement factor. Source: (Gut & Ackernecht, 1993)

Remarks - Applicability in various climate zones of India and in various building typologies

Climates which experience high diurnal range can benefit from both high thermal mass and high decrement factor. In these climates, it is advantageous to impede the heat flow by using the envelope as a heat sink. With the passage of the day, this heat sink can reject stored heat to the environment outside. For climates that have a lower diurnal range, heavy thermal mass is not desirable.

In addition to the thermo-physical properties of the building materials and wall configuration, thermal lag may be accentuated by natural ventilation in space. Passive cooling through natural ventilation occurs when the outdoor air temperature is lesser than the indoor air temperature and the accumulated heat in walls is removed through enhanced convective heat transfer between indoor wall surface, which is at a higher temperature than the outdoor air (Oropeza-Perez & Østergaard, 2014).

Metrics that could be considered for the standard development

Critical parameters from the list below, or a combination of these could be considered:

- Thermal lag/inertia
- Decrement factor
- Thermal diffusivity
- Thermal mass
- Thermal insulation and its placement
- Prescriptive constructions

Impact on thermal comfort satisfaction (heating/cooling demand or energy consumption)

A wall configuration of a typical 230mm brick wall has a time lag of approximately 6 hours and a decrement factor of 0.157, and an addition of 50 mm extruded polystyrene insulation on the outside and inside results in a time and decrement factor of approximately 12 hours and 0.009 and 8.4 hours and 0.016, respectively; while a monolithic 150mm cellular concrete and dense concrete walls result in a time lag and decrement factor of 4.8 and 0.1 and 2.5 and 0.5, respectively (Balaji et al., 2013). Compared to modern conventional wall and roof construction of plastered 230mm thick burnt brick wall and 150mm RCC roof, traditional wall and roof construction of 450mm thick wall with rubble masonry and mud mortar and composite roof with wooden plank, stone slab and 300mm thick compacted mud could potentially decrease the interior temperature by up to 7^{O}K (Shastry et al., 2014). Thermal mass, when combined with other passive strategies, such as cross ventilation, ground coupled heat exchange, etc. could potentially decrease discomfort hours by up to 95%. However, the potential to decrease discomfort hours considerably decreases when the diurnal variation is low (Calcerano & Cecchini, 2014).

Impact on incremental cost (₹ (very low) - ₹₹₹₹₹ (very high), nil)

Given that the predominant typical construction in Indian buildings is burnt brick, most of the other wall configurations entail incremental costs. Therefore, the impact on incremental costs can be rated as low to medium (₹ - ₹₹₹ (low-medium)).

3.2.6 Building envelope design and geometry – Natural ventilation through windows

Brief description

Natural ventilation enhances thermal comfort satisfaction by removing heat from the building. An increase in air velocity by 0.15 m/s compensates a temperature increase of 1 °C at a relative humidity of 75%. Perceived temperature difference of up to 2 °C may occur when air movement is increased by 0.8 - 1.6 m/s.

Remarks - Applicability in various climate zones of India and in various building typologies

In climates with minimal diurnal variation, such as warm humid or hot humid climates, natural ventilation enhances thermal comfort satisfaction as it passes over the human body. In climates with significant diurnal variation, such as hot and dry climate, night-flush ventilation cools down the building by removing excess heat accumulated in the building's thermal mass during the day. Cross ventilation provides substantial benefits over single sided ventilation (Omrani et al., 2017).

Impact on thermal comfort satisfaction (heating/cooling demand or energy consumption)

Natural ventilation in combination with correct thermal mass and ventilation schedule ensures high levels of thermal comfort, e.g., up to 70% of the occupied time, and save significant amount of energy by eliminating or limiting the use of mechanical ventilation (Omrani et al., 2017). Using natural ventilation for cooling purposes in warm climates, such as in Mexican residential sector could potentially mitigate CO_2 equivalent emissions of 2.89 Mt CO_2eq per year (Oropeza-Perez & Østergaard, 2014).

Impact on incremental cost (₹ (very low) - ₹₹₹₹₹ (very high), nil)

Typically, natural ventilation through windows does not entail incremental costs.

3.2.7 Building envelope design and geometry –wind tower

Brief description

Wind towers or wind catchers are wind scopes above the building envelope orientated in a direction to catch the prevailing winds. They capture the prevailing winds and funnel them into the building interior. Size of the wind catcher can influence the effectiveness. Traditionally, locations with predominant unidirectional wind are designed as one or two directional wind towers. Locations with no predominant wind direction are designed as four or eight directional wind catchers to be able to catch wind flowing from all directions. Wind catchers are also combined with evaporative cooling and double up as passive cooling systems in the form of Passive Down-draught Evaporative Cooling systems (PDEC) (Jomehzadeh et al., 2017).

Remarks - Applicability in various climate zones of India and in various building typologies

Wind towers can be predominantly found in hot-arid climates (Jomehzadeh et al., 2017). However, their usage has also been reported in hot humid regions in India (Shanthi Priya et al., 2012).

Impact on thermal comfort satisfaction (heating/cooling demand or energy consumption)

The use of wind towers, especially in combination with evaporative cooling has the potential to meet thermal comfort by natural means throughout the year (in school buildings) (Saif et al., 2021). Temperatures could be brought down by approximately 7°C by incorporating wind towers in design (Obeidat et al., 2021). Furthermore, several improvements in design of the wind towers could aid in their effective integration into modern buildings (Dehghani-sanij et al., 2015; Nejat et al., 2016).

Impact on incremental cost (₹ (very low) - ₹₹₹₹₹ (very high), nil)

Construction and maintenance of wind towers, especially those with integrated evaporative medium entails incremental costs, which can be considered in the range of low – high (₹₹ - ₹₹₹₹).

4 Literature Review: Modeling passive strategies

This section details out modeling procedures for passive strategies especially in EnergyPlus. The review draws references from methodology adopted in modeling these strategies from peer reviewed journals and also EnergyPlus documentation. The section closes with a selection of passive strategies that may be modeled for development of the Design Standard for thermal comfort.

4.1.1 Modelling natural ventilation

Natural ventilation is modeled by controlling window operation to allow airflow in the buildings when it is pleasant outside. Window operation is complex to model as it is a function of user behavior, which in turn is affected by climate, cultural contexts, indoor air quality, security, menace of insects, etc.(Bhikhoo et al., 2017; Faheem et al., 2022; Yang et al., 2022). In a recently conducted study, window opening behavior has been analyzed in residential buildings during the transitional season in China's Xi'an. From cases studies of four residential buildings, the indoor and outdoor environments and window opening states have been measured. The outcomes indicate that indoor temperature and CO_2 concentration, outdoor temperature, and relative humidity are key decision criteria that shape window opening behavior. The study further establishes positive correlation of window opening probability with temperature and negative correlation of window opening probability with indoor CO_2 concentration outdoor relative humidity (Yang et al., 2022). Another study conducted for residential buildings in Beijing for the period between April and May has similar outcomes (Jian et al., 2011). However, similar studies in Indian context for residential buildings are limited. Faheem *et al.*, stress on the need to study the window opening behavior over long-term for application in energy simulation tools to accurately predict the indoor environment(Faheem et al., 2022). While identifying appropriate window operation behavior requires field studies and statistical analyses, studies in the past have relaxed constraints to model window operation based on common knowledge of user behavior. These studies typically use a set-point (temperature/humidity) and ventilation schedule-based approach.

The Input Output Reference – EnergyPlus 9.5 outlines some control strategies to model rule-based window operation. EnergyPlus modulates window opening through five fields: **(1)** minimum venting open factor, **(2)** indoor and outdoor temperature difference lower limit for maximum venting open factor, **(3)** indoor and outdoor enthalpy difference lower limit for maximum venting open factor, **(4)** indoor and outdoor enthalpy difference upper limit for minimum venting open factor, and **(5)** venting availability schedule name (US DOE, n.d.). The linear relationship between vent (or window) opening multiplier with temperature or enthalpy is outlined in Figure 5.

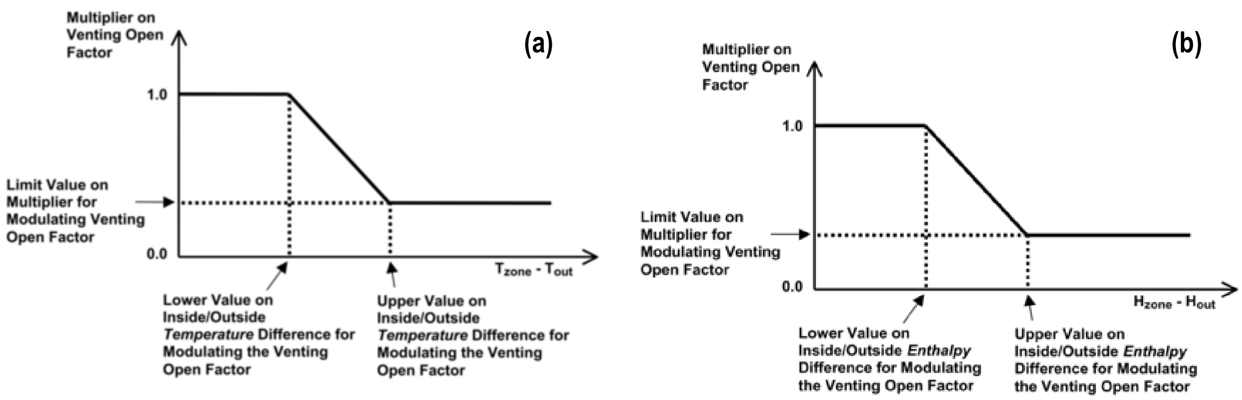


*Figure 5 Linear modulation of vent opening factor based on **(a)** temperature or **(b)** enthalpy differential between indoor and outdoor environment. Source: Input-Output Reference – EnergyPlus 9.5 (Accessed in June 30, 2022)*

All these 5 factors are not simultaneously at play and the choice of 'ventilation control mode' at zone-level for natural ventilation control decides the applicable fields. EnergyPlus defines ventilation control modes as **(1)** No Vent, **(2)** Temperature, **(3)** Enthalpy, **(4)** Constant, **(5)** ASHRAE55Adaptive and **(6)** CEN15251Adaptive. 'No Vent' ignores the 'Venting Availability' schedule and models the zone's openable windows and doors are closed at all times independent of indoor or outdoor conditions, while 'Constant' ignores the indoor-outdoor condition and models windows and doors as open whenever the 'Venting Availability' schedule allows venting. The 'Temperature' and 'Enthalpy' mode operate based on the conditions outlined in Table 2. The modes for adaptive standards use neutral temperature (as defined by the respective adaptive model) and 'Venting Availability' schedule to allow venting.

Table 2 Control algorithm for 'Temperature' and 'Enthalpy' ventilation control modes uses 3-conditional arguments for allowing window operation for venting.

Temperature	Enthalpy
$\boldsymbol{T_{zone} > T_{out}}$	$H_{zone} > H_{\boldsymbol{out}}$
and	**and**
$\boldsymbol{T_{zone} > T_{set}}$	$T_{zone} > T_{\boldsymbol{set}}$
and	**and**
Venting Availability Schedule allows venting	Venting Availability Schedule allows venting
$\boldsymbol{T_{zone}}$: Zone air temperature at time-step *'t-1'* $\boldsymbol{T_{out}}$: Outdoor air temperature at time-step *'t* $\boldsymbol{T_{set}}$: Zone air temperature set-point at time-step *'t'* as per *Vent Temperature Schedule*	H_{zone}: Specific enthalpy of zone at time-step *'t-1'* H_{out}: Specific enthalpy of outdoor air at time-step *'t'*

The EnergyPlus Engineering Reference also documents hybrid ventilation control. This high-level 'control construct' is relevant for mixed-mode operation. This 'hybrid ventilation control' availability manager ensures natural ventilation and HVAC system operation don't occur simultaneously and facilitates evaluation of strategies to maximize natural ventilation to limit colling/heating load. The 'hybrid ventilation control' construct identifies seven control logic options. These control options are: **(1)** Temperature Control, **(2)** Enthalpy Control, **(3)** Dew-Point Control, **(4)** Operative Temperature Control with 80 Percent Acceptability Limits, **(5)** Operative Temperature Control with 90 Percent Acceptability Limits, **(6)** CO_2 Control, and **(7)** Outdoor Ventilation Air Control. With reference to the Design Standard development strategies 1, 2, 4 and 5 are relevant. As the name suggests, strategies 4 and 5 allow natural ventilation when zone air operative temperature is within the respective acceptability limits. Strategies 1 and 2 define upper and lower limits of Outdoor temperature and enthalpy respectively. If the ambient conditions are within these defined conditions the logic shifts to evaluate meeting temperature setpoint/s. Fulfilment of all conditions implies natural ventilation operation (Department of Energy, 2022).

Several studies have modeling natural ventilation have been conducted. A summary of few studies outlining the impact of natural ventilation and the description of the adopted control logic are outlined here.

A study (S. B. Gross & Hu, 2011) showed that this algorithm can maintain the thermal comfort for a mid-rise student dormitory for about 99% of the cooling season. The natural ventilation control algorithm was used by many researchers in the past (May-Ostendorp et al., 2011; Spindler & Norford, 2009) and it was proved that model-based strategies can be used to predict and control a variety of parameters for window control operation based on outdoor temperature, wind speed, indoor temperature and building characteristics to ensure proper natural ventilation.

Another study (S. Gross, 2011) introduced a control algorithm to determine the most appropriate window position for the operable window based on the predicted zone operative temperatures and ventilation rates. As an example, if, opening the window will result in the zone temperature dropping below the acceptable limit, the controller will reduce the window opening area to stay in the threshold limit. A flowchart for the control logic is defined below in Figure 6.This control logic works upon the minimum ventilation mode and change the window opening positions based on the ambient temperature, and zone operative temperature.

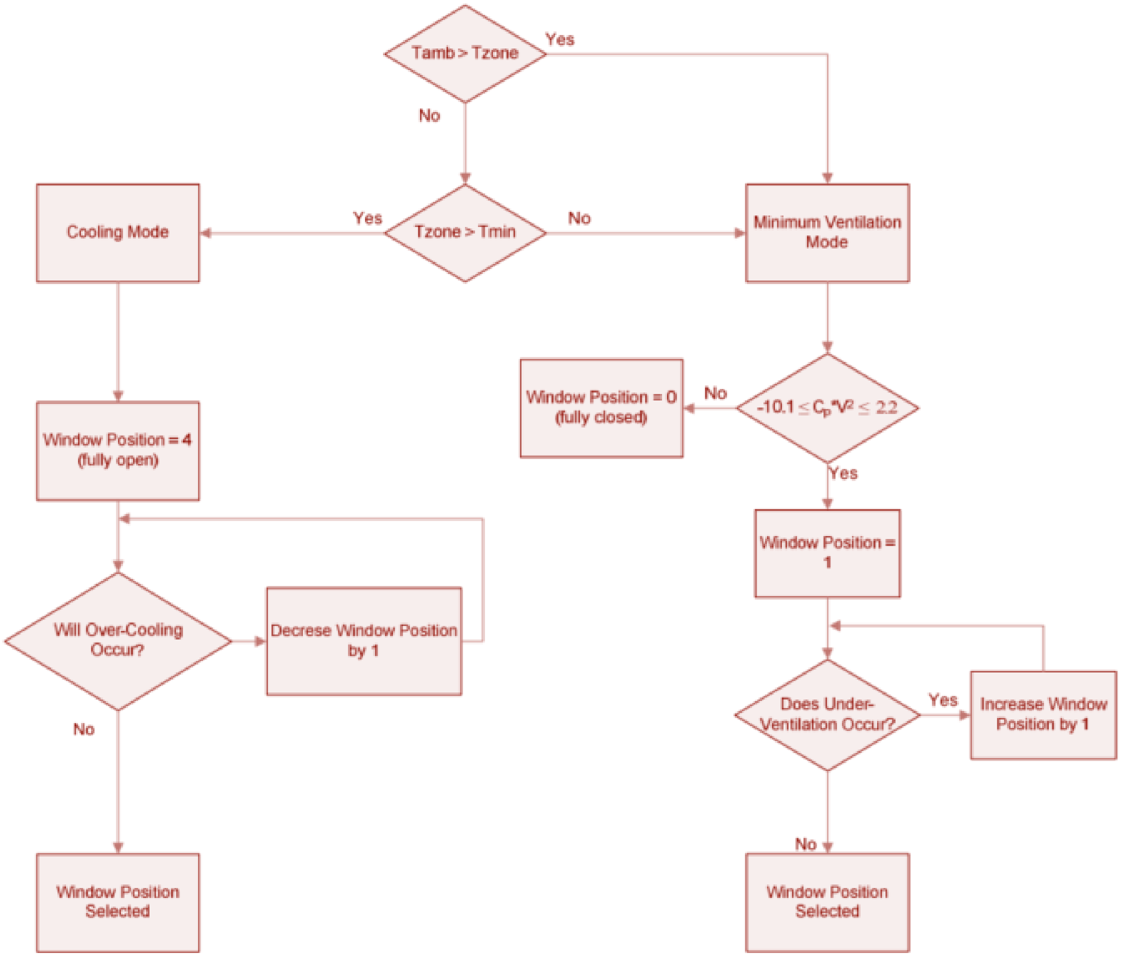


Figure 6: Model-based control logic flowchart. Source: (S. Gross, 2011)

Several studies (Dutton & Shao, 2010; Haldi & Robinson, 2008) published of window intervention are based on the presumption that the main driver of occupant window intervention if occupant discomfort. A study (Rijal et al., 2008) proposed a method of implementing occupant window opening behavior in a building simulation model on the basis that occupants only interact with their windows when they are thermally uncomfortable (defined as +/- 2°C either side of the adaptive comfort temperature). The simulation results are comparable with field observations and show that window opening is effective for cooling by controlling the internal and external heat gains in summer and by increasing indoor air movement. Thus, window opening is useful to mitigate summer overheating.

A study by Mirakhorli models natural ventilation in mixed-mode operation for a residential building in San Antonio to study the effectiveness of natural ventilation. The model operates openings in a building using rule-based controllers which take outdoor temperature (T_{out}), indoor temperature (T_{zone}), indoor set-points (T_{set}) and ambient temperature thresholds (upper and lower) as inputs. Figure 7 presents the rule-based control integrated in the model for enabling natural ventilation. The outcomes indicate that there is a potential to offset 20% AC electricity consumption (Mirakhorli, 2017).

If:

$T_{zone} > T_{out}$ and $T_{zone} > T_{set}$

and

$T_{out} > upper\ threshold$

and

$T_{out} < lower\ threshold$

Then:

Natural Ventilation is Enabled

Otherwise:

Natural Ventilation is Disabled

Figure 7 Rule-based control logic for enabling natural ventilation. Source: (Mirakhorli, 2017)

Wang and Chen. explored four control strategies with rules based on indoor comfort, described by ASHARE Adaptive Model, and temperature and humidity - both indoors and outdoors. The control strategies have been simulated and compared for a small office building in Philadelphia. The model considers a baseline model and an enhanced case (additional thermal mass) as well. The models include night venting. The outcomes report comfortable hours as per ASHRAE adaptive comfort model, hours relative humidity exceeds 80% and number of hours ventilation is available. The outcomes for this particular use case include best suited control strategy along with increased thermal mass. The best suited strategy responds to both temperature and humidity (Wang & Chen, 2013).

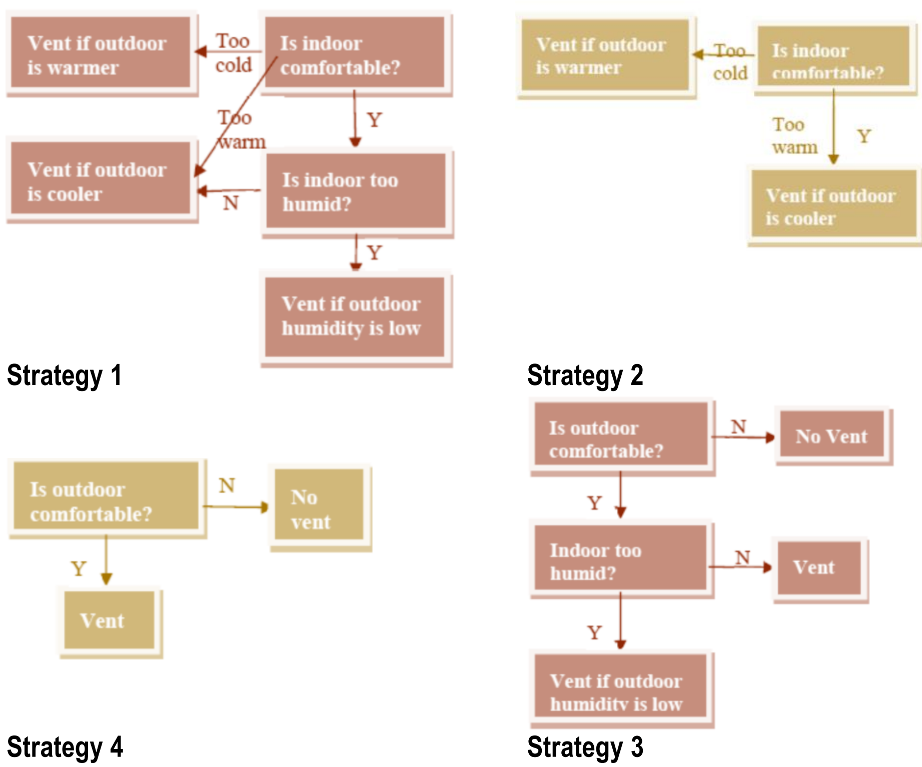


Figure 8: Control strategies developed for natural ventilation based on combinations of indoor comfort and conditions (both indoor and outdoor). Source:(Wang & Chen, 2013)

There is one dataset compiled for 'Natural ventilation potential from weather analysis and building simulation' which includes the properties of the building materials, airflow network opening setting, the natural ventilation controls through use of energy management system. The dataset also includes the user behaviors regarding the living and bedroom occupancy schedules. This dataset can help to perform an extended analysis of the information on behavioral with details of the EnergyPlus model (Sakiyama et al., 2021).

4.1.2 Modelling for Ceiling Fans

In naturally ventilated spaces, ceiling fans enhance comfort by supplementing air movement. Ceiling fan reduces the perceived temperature, by assisting cooling by evaporation through skin (Jain & Shorey, 2015). Early studies (R. Zhang et al., 2013; Y. Zhang et al., 2010)show that the air flow induced by a ceiling fan with a velocity between 0.5 to 1.0 m/s compensated for 2.8-3.3 °C temperature change of indoor air temperature.

As per the study conducted by (Manu et al., 2014) it can be concluded that the ceiling fan is one of the most significant behavioral adaptation mechanisms for thermal comfort. Studies have shown that a reduction in thermal discomfort at 32-40 °C reported at air velocity >2.5 m/s in India. It is concluded that with using ceiling fan, the set point can be increased by 2 °C (Pandey et al., 2018). The special publication issued by BIS, while outlining limits to thermal comfort, observes that increasing air motion from 0.5 to 1.5 m/s is equivalent to decreasing air temperature by 3°C (SP 41 (1987): Handbook on Functional Requirements of Buildings (Other than Industrial Buildings), 1987).

There have been suggested workarounds for modeling the effect of ceiling fan. Brendon Levitt proposes one solution as part of video tutorial series for Zero Energy Buildings course at UC Berkeley. Module VT5.10 "Modeling Ceiling Fans in EnergyPlus" outlines a method involving defining a ceiling fan operation schedule to account for energy use and, tied to this, another schedule that updates the set-point higher by 2°C (Levitt, n.d.). Other workarounds involve modeling dummy systems where cooling coils are sized to zero and only fan-power is input (Prasad & Jones, 2001).

Based on the literature, this study takes the effect of ceiling fan into account by increasing the upper limit of thermal comfort temperature by 2°C when the fan control is switched ON.

4.1.3 Modelling for Evaporative Cooling

Evaporative cooling is an active measure to increase the thermal comfort in an affordable way. The studies reveal (Chiesa et al., 2017; Mohamed et al., 2021) that discomfort hours can be reduced by direct evaporative cooling for hot & dry and composite climates. These studies model evaporative cooling to output the zone operative temperature and degree discomfort hours.

Akbarpoor *et al.* introduced an evaporative cooling system with the use of dome roof from which the required ACH has been supplied with help of direct evaporative cooling system. The evaporative cooling system provided thermal comfort as per adaptive thermal comfort standard at much lower rate of cooling demand and the system could save the electric energy consumption by about 30 W-h/m^3 (Mirzazade Akbarpoor et al., 2022). A study (Tewari et al., 2019) predicts the thermal performance of office building using direct evaporative cooling system for thermal comfort during the summer season of Indian composite climate. An EnergyPlus model has been developed and it has been concluded that approximately 42% of the thermal discomfort hours could be avoided with the use of evaporative cooling in the summer season.

The Engineering Reference for EnergyPlus includes description of direct, indirect, two-stage evaporative coolers along with description of inputs (*Evaporative Coolers*, n.d.). From affordable housing perspective Direct Evaporative Cooler is of note. Among others, the `EvaporativeCooler:Direct:CelDekPad` object requires inputs for **(1)** Availability Schedule Name, **(2)** Direct Pad Area, **(3)** Direct Pad Depth, **(4)** Recirculating Water Pump Power Consumption, **(5)** Inlet/Outlet node names, and reference to **(6)** Water Supply Storage Tank Name.

Based on the literature, the evaporative cooling system has been modelled in the EnergyPlus during the summer season to evaluate the thermal comfort and calculate the discomfort hours.

4.1.4 Modelling for Passive Strategies

There are several passive technologies those can be used in natural ventilation to increase the thermal comfort in the building. An extensive review of the passive strategies has been done and some of the passive techniques that can be modelled in EnergyPlus have been listed down based on the research paper and applicability in naturally ventilated buildings. Some of the passive strategies have been discussed below:

Cool Roof: Cool roof and natural ventilation increase thermal comfort up to 16% according to a study done in a hot & dry climate of Haiti (Borge-Diez et al., 2013). Another study (Kolokotroni et al., 2018) created a simulation model of naturally ventilated building in EnergyPlus to evaluate the effect of the cool roof on the thermal comfort and building load. It has been found that the average monthly reduction in roof temperature is 5 to 7 °C and 0.6 to 1.6 °C reduction in internal air temperature which leads to a greater number of thermally comfortable hours. A generic case study of commercial building (Lapisa et al., 2013) modelled with number of parameters considered for evaluating the impact on energy demand and thermal comfort. The study showed that the combination of cool roof with skylight with high thermal mass of the building can be an adequate passive cooling solution in summer with a 99.8% drop in degree-hours above the discomfort temperature in summer.

Thermal Mass: The coupling of thermal mass and natural ventilation is important to passive building design.(Zhou et al., 2008) discussed the effect of thermal mass on indoor air temperature of different configurations including lightweight and heavy structures with and without insulation. Based on this study, a simple tool is developed to estimate the indoor air temperature for certain external and internal thermal mass. An experimental analysis (Kuczyński & Staszczuk, 2020) has been carried out to evaluate the effect of thermal mass into thermal comfort and the total of 67% cooling load reduction was achieved while using thermal mass.

Cool roof and thermal mass are modeled by modifying material properties in EnergyPlus. For modeling these measures, the material object in EnergyPlus has provision for inputting thermos-physical characters; **(1)** Roughness, **(2)** Thickness, **(3)** Conductivity, **(4)** Density, **(5)** Specific heat, **(6)** Thermal Absorptance, **(7)** Solar Absorptance, and **(8)** Visible Absorptance.

Trombe wall: Trombe wall is a passive solar device designed for thermal storage and delivery (*Trombe Walls*, n.d.). Dhahri *et al.* explore the thermal behavior of a Trombe Wall placed in a fenestrated room in the semi-arid context of Tunisia. CFD simulations have been used to evaluate comfort as per ASHRAE (55-2013). Results indicate that Trombe Wall alone does not assure satisfactory comfort level. Simulations on a cold day confirmed higher internal temperature compared to the external environment. The difference in temperature observed is 6.45°C (Dhahri et al., 2021).

EnergyPlus does not include a Trombe wall object. EnergyPlus models a Trombe wall as a very narrow zone coupled to the desired surface via an interzone. The interzone is typically modeled 18-150mm wide, with no window. The Trombe zone is a single or double pane glazing. The interior layer is typically a mass wall with absorptive surface, i.e. surface characteristics having very high absorptivity and very low emissivity. For modeling Trombe Wall, it is critical to **(1)** set the Solar Distribution field in Building object to '`FullInteriorAndExterior`', and **(2)** set the Trombe Zone object to 'TrombeWall' (*Trombe Walls*, n.d.).

While the application of Trombe Walls can be a source of undesirable heating gains, some studies reveal that coupled with high thermal mass, wall screening and night ventilation can lead to stable temperatures and meet acceptable levels of thermal comfort (Ghrab-Morcos et al., 1993).

Earth-air-heat exchanger: The earth air tunnel heat exchanger system can provide sufficient heating and cooling in naturally ventilated buildings (Kaushik et al., 2013). A report published by IBPSA-India (Mathur et al., 2016) introduces the modelling of earth air tunnel in EnergyPlus including the effect of change of various parameters on the performance of earth air tunnel heat exchangers. Lee and Strand have integrated earth tube system into EnergyPlus program. The evaluation of earth air tube with respect to pipe radius, pipe length, air flow rate and pipe depth parameters reveals that pipe length and pipe depth affect the overall cooling rate and pipe radius and air flow rate mainly affect earth tube inlet temperature (Lee & Strand, 2006).

Simple earth tubes are modeled in EnergyPlus using a schedule and through the specification of minimum, maximum, and delta temperatures. The schedule controls actual airflow rate through the earth tube by the temperature difference between the inside and outside environment and the wind speed. The required input fields to simulate the earth tube include **(1)** the average soil surface temperature, **(2)** the amplitude of soil surface temperature, and **(3)** the phase constant of soil surface temperature. These fields should be calculated in advance by using a separate stand-alone program (CalcSoilSurfTemp) and should be input into earth tube. A weather file input is critical to model earth tube.(*ZoneEarthtube*, n.d.)

Based on the above studies, Table 3 shows a comprehensive list of passive design strategies and low-energy comfort systems, mapped to respective climate zones, that can potentially enhance thermal comfort:

Table 3 Potential strategies to be included in the development of design standard

Measures	Composite	Cold	Warm-Humid	Temperate	Hot & Dry
Building Orientation					
Cavity walls					
Light shelves					
Thermal Mass					
Green Roof / Terrace Gardens					
Buffer spaces on east & west facades					
Cool Roofs, High-reflective paint surfaces					
Geothermal cooling/heating					
Reduced Solar Access					
Light colored external surfaces					
Reduced solar access					
Roof insulation					
Solar heat collector-based ventilation/ thermal system					
Direct solar gain in rooms					
Air lock to prevent heat loss					
Direct Evaporative Cooler					
Indirect Evaporative Cooler					

5 Modeling methodology

Based on the detailed review and collective knowledge of previously conducted research and experience a modeling methodology for the development of standard has been developed. A 5-step process has been outlined for development of design standard in Figure 9. A detailed description is outlined in following sub-sections.

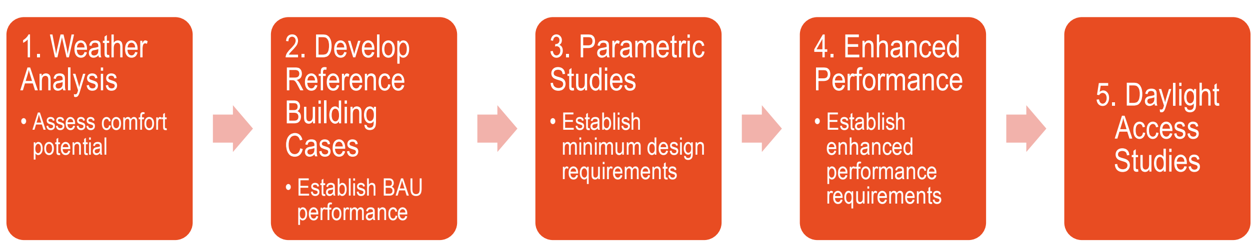


Figure 9 Overview of methodology for developing the design standard.

5.1 Weather analyses

Weather analyses for representative cities across 5 climates will be conducted. The identified cities are,

- Bengaluru (Temperate),
- Ahmedabad (Hot-dry),
- Kolkata ((Warm-humid),
- New Delhi (Composite), and,
- Srinagar (Cold)

The representative cities for India chosen based on research conducted (Bhatnagar et al., 2018). Figure 10 identifies the cities.

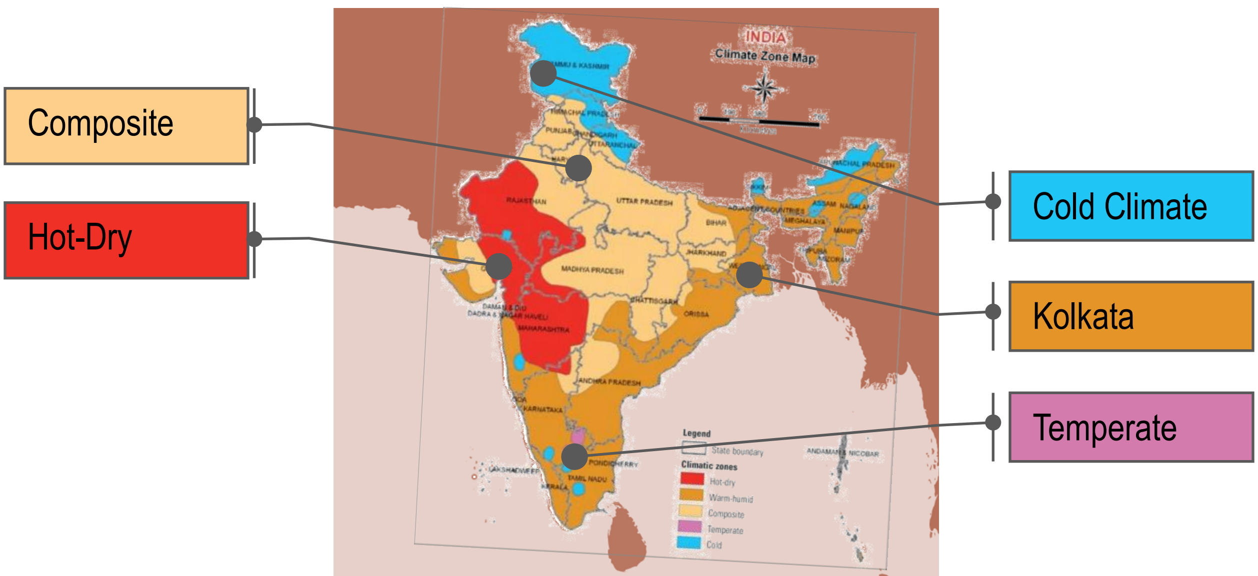


Figure 10 Representative cities considered for weather analyses and standard development

Weather analyses has been conducted for these cities as per adaptive comfort model defined in IMAC-Residential (IMAC-R). The adaptive comfort model for IMAC-R proposes a regression-based equation developed after compiling 2,179 responses from nationally representative field studies across 294 households. The neutral temperature and acceptability limits considering 30-day outdoor running mean temperature are identified by IMAC-R with the following equations(Rawal et al., 2022):

$$T_{neut} = 0.42\ (T_{out\ 30dRM}) + 17.60$$

$$for\ 90\%\ acceptability\ temperature\ range\ is\ T_{neut} \pm 2.15\ \ ^{o}C$$

$$for\ 80\%\ acceptability\ temperature\ range\ is\ T_{neut} \pm 3.60\ \ ^{o}C$$

Based on the IMAC-R equation, weather files for representative cities have been evaluated to identify comfort potential for respective climates. Evaluating comfort potential of cities is expected to facilitate thermal comfort performance across climates.

Weather analyses based on 80% acceptability reveals that outdoor conditions are most uncomfortable in Cold climates. Interestingly, discomfort in Temperate climate exceeds that of Warm-humid climate. This is due to ambient conditions in Temperate climate being relatively colder. It is important to note that the reported discomfort is for ambient conditions and for the purpose of comparative analysis only.

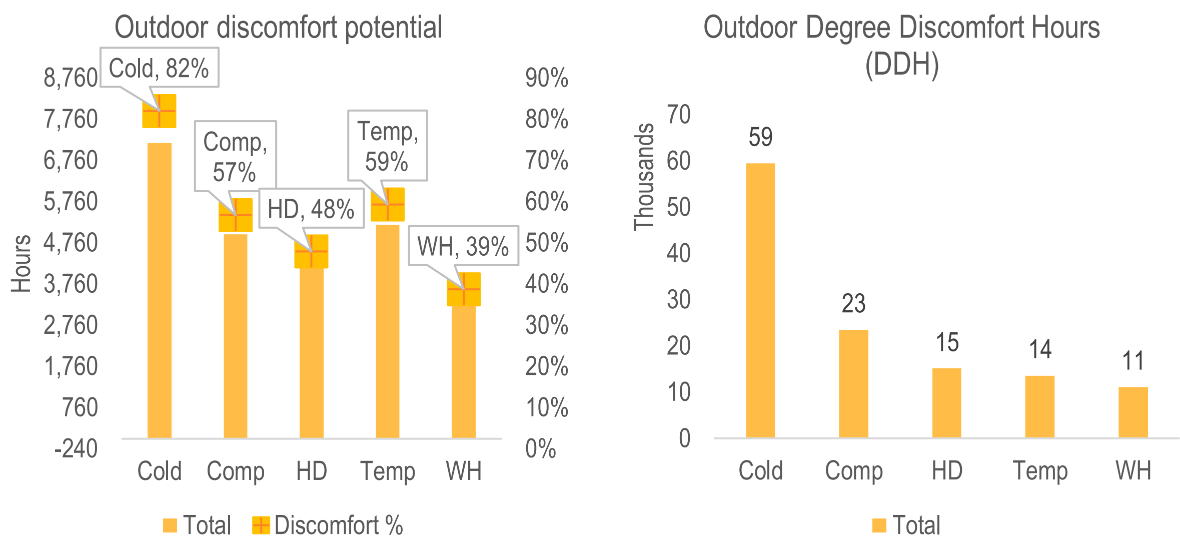


Figure 11 Outdoor discomfort, with respect to 80% acceptability defined by IMAC-R, is highest in Cold climate

The analyses is expected to assess dry-bulb temperature, wet-bulb temperature (or humidity), radiation (direct and diffused) data and wind speed and direction for thermally acceptable periods during the year. Computations regarding 30-day running mean temperatures, 80% acceptability limits and humidity on an hourly basis will facilitate development of schedules for ceiling fan and window operation. (Borgeson & Brager, 2011) consider outside conditions conducive to natural ventilation if temperatures are within the 15 - 27 ^{O}C at relative humidity is less than 70%. The same may be used to define window operation schedules.

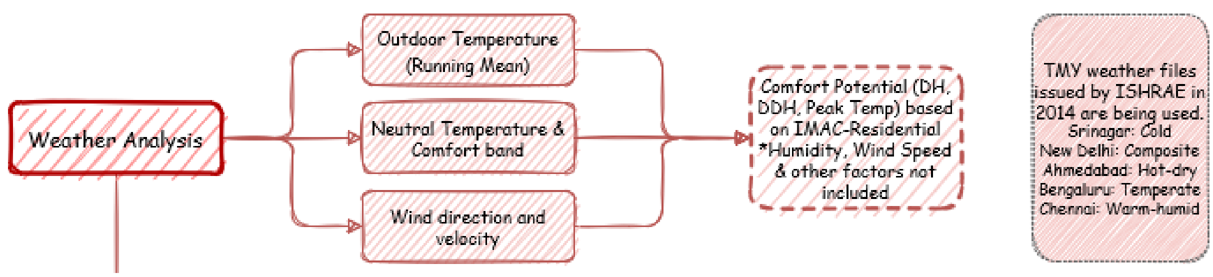


Figure 12 Weather analyses will facilitate development of schedules for ceiling fan and window operation.

5.2 Development of reference building cases

Typical building characteristics identified from detailed research will be used to develop models for each building typology. Each typology will be modeled within a cluster context and also accommodate adjacencies (top floor, sandwiched, etc.) and orientations. Other critical details such as demography, and schedules for occupancy, activity, equipment and window operation will be integrated. The simulations will be performed for all orientations and averaged out. Hourly and peak load profiles for simulations will be compiled. These outputs will be used to compute annual and peak-day metrics. Annual metrics include Degree-hours (DH) and Degree Discomfort Hours (DDH) and peak-day metrics include peak internal temperature, thermal lag and decrement factor. Based on simulation outcomes performance of least thermally comfortable will be compiled for analyses. These outcomes will define 'Business As Usual' (BAU) performance for all typologies across all climates. The analyses in the next step

(Parametric Studies) will attempt at reducing the thermal discomfort of these reference cases by 50% by modeling improvement measures. Since the shape characteristics are not being parametrized, optimal wall to floor area ratios will be compared across typologies now.

Since rooms or 'zones' in residential homes are typically not sealed from each other, the reference cases will be modeled as single-zone. Instead of a computationally expensive Airflow Network model, the simulation will assess Natural ventilation potential by modeling a dummy system integrated with economizer. The fan-power of the system will ensure minimum ventilation as defined by minimum infiltration rates and shall be variable to accommodate exhaust and ceiling fan effect.

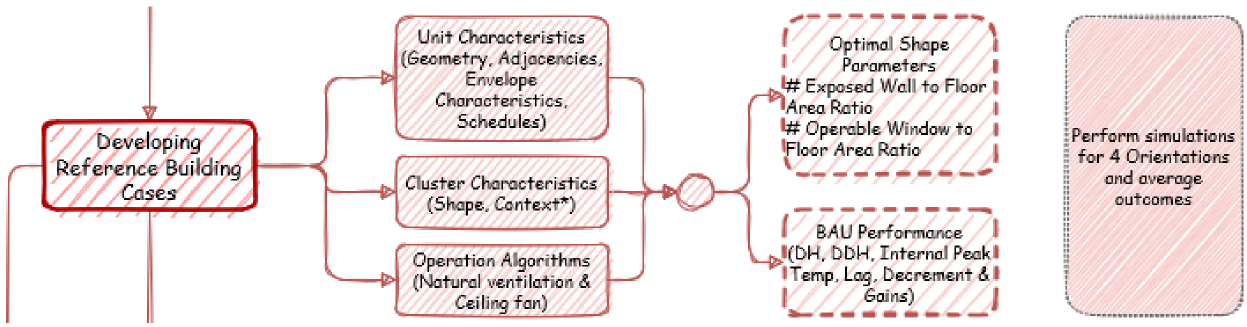


Figure 13 Reference building cases will be developed to outline baseline performance for thermal comfort.

5.3 Parametric studies for deriving Minimum Performance Requirements

After the reference building cases yield performance outcomes, in terms of thermal comfort and cost, a series of parametric evaluations will be performed. Parametric evaluations in terms of Window-to-Wall Ratio (WWR), construction assemblies, shading, etc. will be performed. These parametric evaluations will include passive design strategies such as heavy mass walls, cavity walls, cool roof, etc, For each case, incremental cost will be recorded as well. These measures will be characterized on cost basis as high, medium and low/no cost. It is expected that best performance achieved by low/no cost features will define the Minimum Performance Requirements (MPRs). At this stage, minimum performance bundles, as design and material specifications, may also be identified with each climate. The development of performance bundles may require integration with the Replicable Housing Designs being developed for thermally comfortable homes.

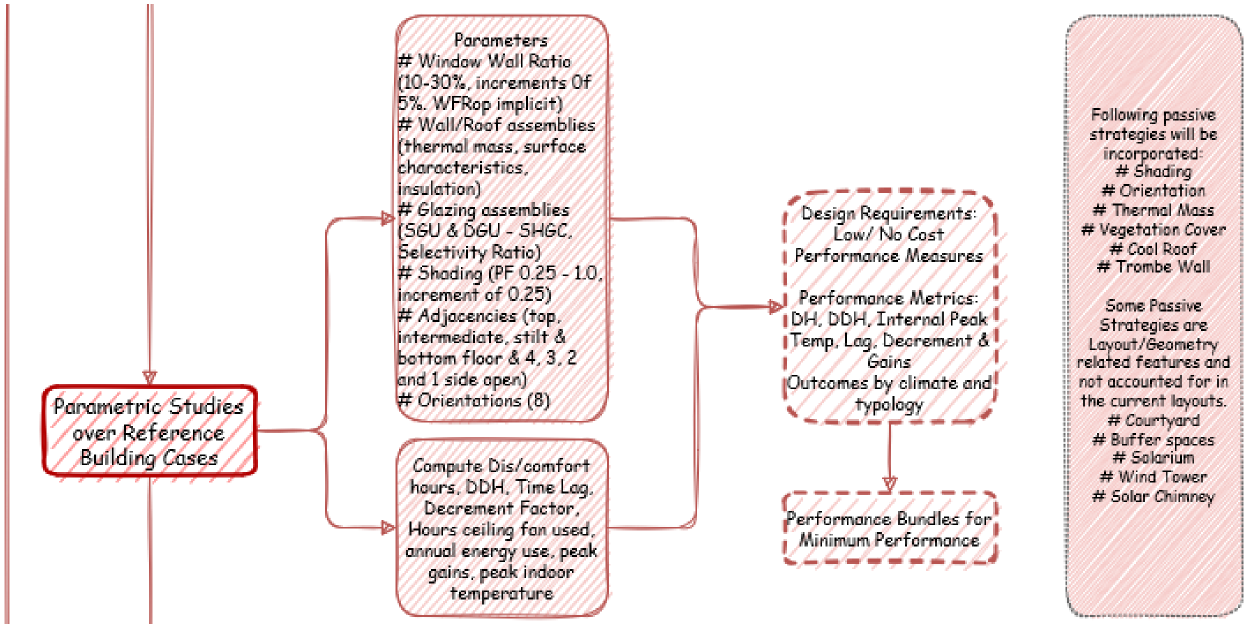


Figure 14 Parametric studies over reference building cases is expected to yield Minimum Performance Requirements (MPRs). Low-cost measures are a key strategy to derive MPRs.

5.4 Enhanced performance measures: Additional cost and low energy comfort systems

While the low-cost strategies will outline Minimum Performance Requirements, the high to medium cost measures will be accommodated as Enhanced Performance Requirements (EPRs). In addition, integration of low-energy cooling/heating measures may also be integrated for further improving thermal comfort. This provides for a graded approach similar to ECBC wherein projects may be bracketed as; Comfortable (meeting MPRs), Comfortable + (meeting EPRs) and Comfortable ++ (EPRs integrated with low energy cooling/heating).

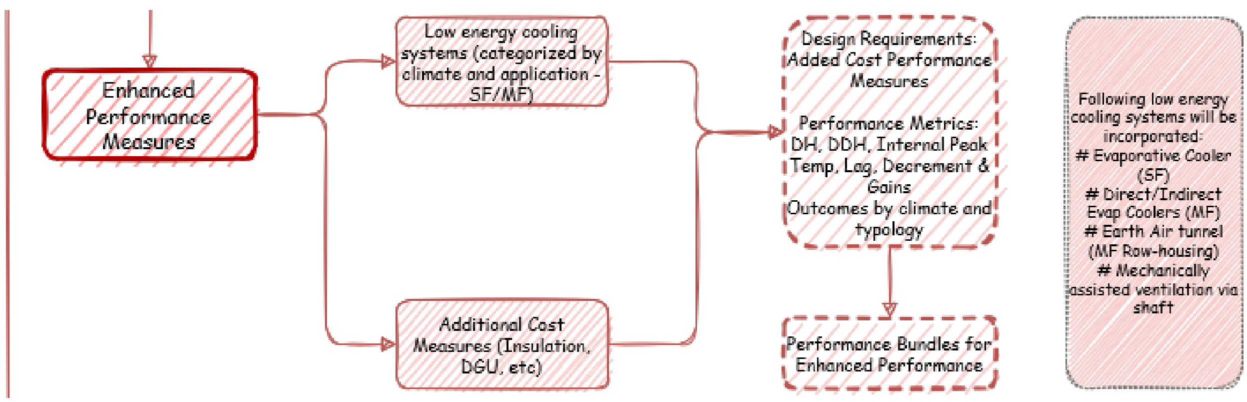


Figure 15 Enhanced performance measures will improve thermal comfort with the use of additional cost measures and low energy comfort systems

5.5 Simulation studies for integrating visual comfort

Visual comfort is a function of window opening and shading. Thermal comfort and minimum ventilation requirements override both the aspects of opening size and shading. However, daylight access studies will be conducted to incorporate minimum daylight access requirements. The Draft TOD policy outlined in Delhi MPD 2021 stipulates a minimum sunshine access period of 2 hours in at least one habitable room on the shortest winter day (Draft Policy for

Tranist Oriented Development in Delhi, 2019). The policy highlights the need for both adequate daylight and ventilation. For reference, minimum number of sunshine hours will be reviewed from (Li et al., 2021)

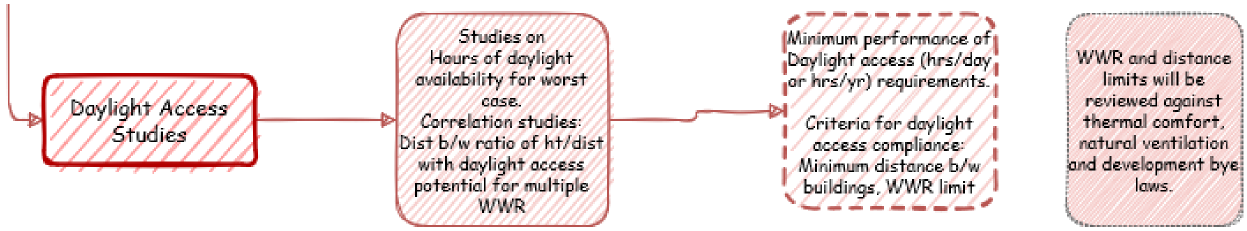


Figure 16 Daylight simulations will identify minimum requirements of daylight access.

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