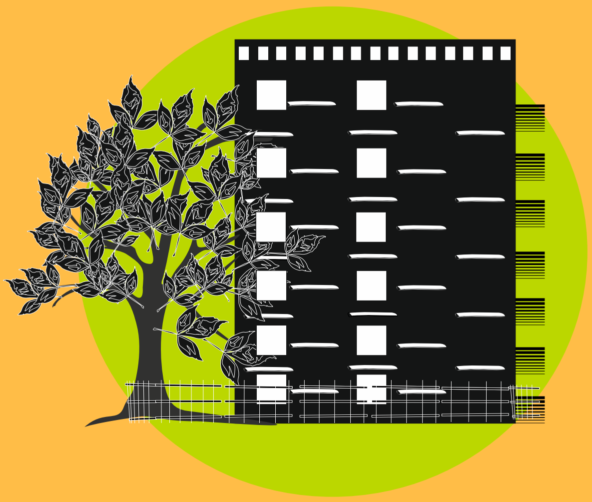

REPORT ON BEST PRACTICES & GAP ANALYSIS: STANDARDS & CODES

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

eds environmental design solutions

Wuppertal Institut

hunnarshālā FOUNDATION

Environmental Design Solutions Private Limited

Wuppertal Institute for Climate, Environment and Energy GmbH

Hunnarshala Foundation for Building Technology and Innovations

Quality control log

Date	Version	Revision Description	Prepared by	Approved by
October 18, 2021	0		Lakshmi, Nidhi Vaibhav and Piyush	Gurneet
January 10, 2022	1	Response to comments. Updated Section 2: Key Outcomes to include Gaps and Best Practices Included information on Building Codes and Standards from EU Included reference of Thermal Comfort Indices and Metrics. Member States and Brazil Included references in APA style	Piyush	Gurneet

Disclaimer

This report is prepared by Consortium of Environmental Design Solutions Private Limited [EDS], Wuppertal Institute for Climate, Environment and Energy GmbH and Hunnarshala Foundation for Building Technology and Innovation (referred to as Consortium Partners from here on) for the Ministry of Housing Affairs (MoHUA) and the Deutsche Gesellschaft fur Internationale Zusammenarbeit (GIZ) GmbH. This report is part of the *"Development of Thermal Comfort Action Plan 2050 and Thermal Comfort Performance based Design Standard cum Guidelines for Affordable Housing in India. [REF: 8338 0638]"* project under the *Climate Smart Buildings Program* funded by GIZ India.

This report has been prepared for the purpose set out in Terms of Engagement between EDS and GIZ, and is solely for the use of MoHUA and GIZ. Information contained in this report is current as at the date of the report, and may not reflect any event or circumstances which occur after the date of the report. This report is an outcome of the best efforts and technical judgement of the consortium members. The Consortium Partners do not accept any duty, liability, or responsibility to any person or entity in relation to this Report.

Contents

Abbreviations

AHP	Affordable Housing in Partnership
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BEE	Bureau of Energy Efficiency
BLC-N / BLC-E	Beneficiary-led construction or enhancement
BIS	Bureau of Indian Standards
CLSS	Credit Linked Subsidy Scheme
DDH	Degree Discomfort Hours
ENS	Eco Niwas Samhita
EWS	Economically Weaker Section
GRIHA	Green Rating for Integrated Habitat Assessment
IMAC	India Model for Adaptive Comfort
IGBC	Indian Green Building Council
ISHRAE	Indian Society of Heating, Refrigerating and Air Conditioning Engineers
LIG	Low-Income Group
MoHUA	Ministry of Housing and Urban Affairs
MIG	Middle-Income Group
NBC	National Building Code
NV	Natural Ventilation
PMAY-U	Pradhan Mantri Awas Yojana (Urban)
PMV	Predictive Mean Vote
PPD	Predicted Percentage of Dissatisfied
SET	Standard Effective Temperature
SHGC	Solar Heat Gain Coefficient
TIC	Indoor Conventional Temperature
VLT	Visual Light Transmittance
WFR	Window to Floor area Ratio
WWR	Window Wall Ratio

1 Review of standards, codes and rating systems

An extensive review of residential envelope performance, occupant thermal comfort, daylight performance, low-cost and low embodied energy materials and other sustainability indicators has been undertaken to identify relevant standards and codes that can potentially inform the Standard being developed for Thermal Comfort performance of Affordable Housing. Based on this extensive review, Standards, codes and rating systems from across the world and from India have been shortlisted for assessment of global best practices and gaps in Indian context.

1.1 Standards, codes and rating systems applicable in the Indian context

In the Indian context Standards and codes issued by the Bureau of Indian Standards, and Ministry of Power have been reviewed. These include, Special Publication 41 (SP41), National Building Code (NBC) of India 2016 and EcoNIWAS Samhita (ENS). In addition, Residential Building energy Label developed by the Ministry of Power has been referenced as well. In the private sector domain organizations like The Energy Resources Institute (TERI) and Confederation of Indian Industries (CII) have developed rating systems to push the real estate market towards energy efficiency, thermal comfort and overall sustainability. Some of these rating systems are tailored for Affordable Housing.

1.1.1 Special Publication 41: Handbook on functional requirements of buildings (other than Industrial buildings)

This handbook provides detailed information on climatology, heat insulation, ventilation and lighting in non-industrial buildings which would be helpful in the planning and functional design of buildings as applicable to Indian conditions. This handbook in turn takes reference from many contributing Indian Standards. Some of the standards have been listed below.

Table 1 Key standards that went into the development of SP41

Code	Title	Context for Utilization
IS: 7662 (Part 1) -1974	Recommendations for orientation of buildings: Part 1 - Non-industrial buildings	To recommend choice of orientation subject to favorable
IS: 3362 - 1977	Code of practice for natural ventilation of residential buildings (first revision)	To recommend design of glazing for lighting and ventilation.
IS: 3792 - 1978	Guide for heat insulation of non-industrial Buildings	To determine minimum thermal performance requirements
IS 2440 - 1975	Guide for daylighting of buildings (second revision)	General principles and methods of daylighting of dwellings, offices and hospitals, and recommendation on minimum illumination values.

SP41 is organized into 4 Parts: Climatology, Heat Insulation, Ventilation and Lighting. The following sub-sections outline information related to thermal comfort, natural ventilation, envelope performance and daylighting.

Part 1: Climatology

Indices of thermal comfort (Clause2.3)

The handbook defines 2 indices of thermal comfort, Effective Temperature and Tropical Summer Index (TSI). The TSI is defined as the temperature of calm air, at 50%relative humidity which imparts the same thermal sensation as the given environment. TSI can be expressed in simplified equation form as,

$$TSI = {}^{1}/_{3}\, t_w + {}^{3}/_{4}\, t_g - 2\sqrt{V}$$

where, t_w is wet bulb temperature in ^{O}C, t_g is globe temperature in ^{O}C and *V* is air speed in m/sec.

Amongst the environmental factors, globe temperature and air temperature are found to have the highest and next best correlation with thermal sensation.

Limits of thermal comfort (Clause 4.2)

For summer comfort condition, precise control of indoor temperature is not necessary. It has also been observed that increasing air motion from 0.5 to 1.5 m/s gives same comfort condition as created by decreasing the air temperature by 3°C.

Part 2: Heat Insulation

Selection of shading devices (Clause 8.3)

The handbook outlines thermal performance of different shading devices. This facilitates selection of cost-effective and energy performance-oriented shading devices for unconditioned building. The standard outlines requirements for hot dry and hot humid climate. The shade factor of windows with shading device in these climate types should be less than 0.5. The handbook indicates that landscaping element like trees, creepers, etc, provide sufficient protection against solar heat by way of shading walls and roof. Internal shading like curtains and plastic paints are effective means as well for protection.

Note: Shade factor is defined as the ratio between instantaneous heat gain through the shading device to the instantaneous heat gain through 3.0 mm plain glass sheet.

Table 2 Thermal performance of different shading devices

Description of Shading Device	U-value	Shade Factor
Plain glass sheet (3.0 mm thick)	5.23	1.00
Plain glass + wire mesh outside	5.00	0.65
Painted glass	5.22	0.35 (white paint) – 045 (green paint)
Heat absorbing glass	4.65	0.45
Plain glass sheet + venetian blind inside	3.72	0.35 (light colour) – 0.40 (dark colour)
Plain glass sheet + curtain inside	3.14	0.35 (light colour) – 0.40 (dark colour)
Plain glass sheet	5.23	0.14 (100% shaded) – 0.56 (60% shaded)
Note: *Shade factor is defined as the ratio between instantaneous heat gain through the shading device to the instantaneous heat gain through 3.0 mm plain glass sheet.*		

Selection of building components (Clause 8.4)

The handbook outlines thermal performance standard for both conditioned and un-conditioned buildings. The performance standards include maximum U-values, Thermal Performance Index (TPI), Thermal Time Constant (T) and Thermal Damping (D) by climate type for exposed wall and roof surfaces. The handbook provides certain thermal performance requirements for building components in three principal climatic zones (hot dry, hot humid and warm humid) of the country.

Table 3 Thermal performance standards for exposed wall and roof across climate types

Building Component	Hot-Dry and Hot-Humid Zones				Warm-Humid Zone			
	U (max)	TPI (max)	T (min)	D (min)	U (max)	TPI (max)	T (min)	D (min)
	(W/m^2K)		(h)		(W/m^2K)		(h)	
Roof	2.33	100	20	75	2.33	125	20	75
Exposed Wall	2.56	125	16	60	2.91	175	16	60
Note: Thermal Time Constant (T) is the ratio of heat stored to thermal transmittance of the structure expressed in hours. Thermal Damping (D) is expressed as temperature differential as percentage of ambient temperature. It is reflective of thermal resistance of materials used in the envelope assembly.								

TPI is a metric indicative of total heat gain through the building section both by steady and periodic part. TPI is a function of outside surface temperature. For an unconditioned building, TPI is provided by the following equation,

$$TPI = {}^{(T_{is} - 30) \times 100}/_{8}$$

where, TPI is expressed in percent (%) and T_{is} is peak inside surface temperature.

The TPI can also facilitate calculation of Peak Surface Temperature (in deg C) and Peak Heat Gain (in W/m^2). Computation equations are provided below.

$$Peak\ Surface\ Temperature = 30 + 0.08 \times TPI$$

$$Peak\ Heat\ Gain = 0.46 \times TPI$$

The handbook provides TPI values for a range of typical construction assemblies (wall, roof and sloped roof) for Hot-Dry region considering typical summer design day with a fixed surface absorption coefficient (α = 0.7). The handbook also provides correction factors for same assemblies in different climate zones by orientation.

Based on TPI, SP 41 outlines a broad classification for rating heat gain performance in unconditioned and conditioned buildings. The classification ranges from A to E, with A being the best and E being the poorest.

Table 4 Performance levels (A to E) defined for unconditioned and air-conditioned buildings on the basis of Thermal Performance Index.

Thermal Performance Index				Class	Quality of Performance
Unconditioned		Air-Conditioned			
	<=75		<=50	A	Good
>75	<=125	>50	<=100	B	Fair
>125	<=175	>100	<=150	C	Poor
>175	<=225	>150	<=200	D	Very Poor
>225		>200		E	Extremely Poor

Building Index (Clause 9.1)

SP41 concludes that that thermal behaviour of a building can be judged by the total peak heat flow resulting on account of individual heat flows. Based on this finding, the handbook defines 'Building Index' as ratio of total maximum heat gain averaged over entire surface area of the building envelope to the acceptable limit of heat gain for achieving comfortable conditions indoors. SP41 sets a threshold of 46 W/m2 as acceptable limit of heat gain. The handbook also indicates that given fan operation, Building Index of 50 can provide comfortable conditions.

Table 5 Limits of Building Index (BI) corresponding to air temperature and comfort conditions

Building Index	Indoor Air Temperature (in ^{O}C)	Comfort Conditions with Fan
0-50	32	Comfortable
51-100	32-36	Slightly Warm
101-150	36-40	Hot

Building characteristics for various climates (Clause 7)

SP41 recommends envelope characteristics for Hot-Dry, Hot-Humid, Warm-Humid and Cold climates. Some relevant recommendations are outlined in Table 6.

Table 6 Recommendations on design and material characteristics by climate type.

<table>
<tr><th></th><th>Hot-Dry</th><th>Hot-Humid</th><th>Warm-Humid</th><th>Cold</th></tr>
<tr><td>External Walls</td><td colspan="2"># Constructed of bricks or similar locally available materials.
Thickness of external wall should not be less than 22.5 cm.
Cavity walls, hollow block, etc, can also be used. The empty air space can be filled with loose insulating materials to improve the thermal performance.</td><td># 11.25 cm brick or equivalent. Light weight concrete blocks, panels and hollow blocks of 10 cm.</td><td># 11.25 cm brick with 2.5 cm of insulation on the inner side.</td></tr>
<tr><td>Roof (Flat/Sloping)</td><td colspan="2"># 10 cm RCC
or reinforced brick cement (RBC) over which 7.5 cm thick mud phuska or cinder or any other equivalent insulating material is laid waterproofed with 7.5 cm of lime concrete or 5.9 cm of brick tiles or with 2 layers of tarfelt.</td><td># Lightweight roof with AC sheet or precast flat roof. Protection against heavy rainfall.</td><td># Asbestos cement or GI sheets backed by false ceiling of wood, 2.5 cm wood-wool board or equivalent material.</td></tr>
<tr><td>Glazing</td><td colspan="2"># 15-20% of floor area to be utilized as fenestration for adequate ventilation and daylighting.
Shutters, if used, that can be tightly closed during summer days or winter nights.
External shading (external louvers, sun-breakers, etc.) and Internal shading like curtains to protect against direct sun.
Heat resistant glasses, double and painted glasses to avoid excessive solar heat penetration.</td><td># 15-20% of floor area to be utilized as fenestration for adequate ventilation and daylighting.
Windows located on walls in the direction of available wind.
Windows longer in the horizontal direction and having low sill height are preferred.
Good arrangement of cross ventilation is essential.</td><td># Up to 25% of floor area to be utilized as fenestration.
Longer axis facing N-S for solar heat gains.
Double glazing to avoid heat losses.</td></tr>
<tr><td>Special Needs</td><td># Outdoor sleeping areas for summer nights are essential.</td><td># Outdoor sleeping areas for summer nights are essential.</td><td># Building axis preferably along E-W or NE-SW axis to</td><td># Protect wall and roof surfaces</td></tr>
</table>

	# Cooling building by spraying water on roofs, white painted reflective surfaces and shading. # Use of ceiling fans is desirable. # Desert coolers, may be used in summer. # Unit type room heaters may be required during winter months.	# White painted reflective surfaces and shading. # Use of ceiling fans is desirable. # Desert coolers are not suitable in these areas.	reduce solar heat gains by walls and improve wind movement. # Good rain-water drainage is essential. # Desert coolers are not suitable in these areas.	against heavy rain and snowfall. # Use vapour barrier to protect insulation against condensation. # Artificial heating is essential during winter. # Ceiling fans may be used during summer.

Part 3: Ventilation

SP41 recognizes ventilation for meeting health and comfort requirements. For meeting health requirements, the focus is on replacing indoor air by fresh outdoor air to maintain certain levels of CO_2 and oxygen in air. This needs to be met under all climatic conditions. For comfort, ventilation aids heat loss from the body and prevents discomfort due to moist skin. Ventilation also removes excess heat and cools the indoor space when the indoor temperature exceeds outdoor temperature. This is known as comfort ventilation.

Clause 3.4

In hot-arid regions, outdoor temperatures exceed indoor temperatures, therefore, windows are generally kept closed and only minimum ventilation is provided for control of odours or removal of products of combustion.

In hot humid and warm humid regions, the design intent is to provide free passage of air to keep the indoor temperatures as near as possible to those in the shade outside. Therefore, buildings are oriented to face the direction of prevailing winds. Windows and other openings windward and leeward sides are kept open to facilitate cross ventilation.

For cooling dominated climates, in summer months, wind action alone does not provide sufficient relief. Adequate number of circulating fans are required to provide necessary air movement.

In the winter of cold regions, windows are kept shut and minimum ventilation for control of odours or removal of products of combustion is achieved by stack action or infiltration. For non-industrial buildings, stack effect may be neglected, except in cold climates.

Minimum standards of ventilation (Clause 4)

SP41 outlines minimum ventilation requirements based on maintenance of required oxygen, carbon dioxide levels in indoor air and control of body odours when no products of combustion or other contaminants are present in air.

Table 7 Ventilation requirements for space types in dwelling units expressed as Air changes per hour.

Space type	Air changes per hour
Bed Rooms/Living Rooms	3-6
Bath/Toilets	6-12
Kitchen (Domestic)	3-6

Limits of comfort and heat tolerance (Clause 4.3.1)

In terms of effective temperature, SP41 identifies the upper limit of comfort as 27.5^{O}C for every day work. At relatively elevated temperatures, air movement can also provide the necessary conditions for comfort. SP41 indicates minimum desirable wind speed for achieving thermal comfort at different temperatures and relative humidity. However, these are applicable to sedentary work in offices and other places without any noticeable sources of heat gain. Even in relatively warmer conditions, where work is of lighter intensity (such as in godowns) higher temperatures can be tolerated without much discomfort.

Table 8 Thermal comfort at different temperatures and relative humidity for sedentary work in offices without any noticeable sources of heat gain.

Dry Bulb Temperature	Relative Humidity						
	30%	40%	50%	60%	70%	80%	90%
	Wind Speed (in m/sec)						
28	*	*	*	*	*	*	*
29	*	*	*	*	*	0.06	0.19
30	*	*	*	0.06	0.24	0.53	0.85
31	*	0.06	0.24	0.53	1.04	1.47	2.10
32	0.20	0.46	0.94	1.59	2.26	3.04	+
33	0.77	1.36	2.12	3.00	+	+	+
34	1.85	2.72	+	+	+	+	+
35	3.20	+	+	+	+	+	+

Table 9 Thermal comfort at different temperatures and relative humidity in relatively warmer conditions, where work is of lighter intensity

Dry Bulb Temperature	Relative Humidity						
	30%	40%	50%	60%	70%	80%	90%
	Wind Speed (in m/sec)						
28	*	*	*	*	*	*	*
29	*	*	*	*	*	*	*
30	*	*	*	*	*	*	*
31	*	*	*	*	*	0.06	0.23
32	*	*	*	0.09	0.29	0.60	0.94
33	*	0.04	0.24	0.60	1.04	1.85	2.10
34	0.15	0.46	0.94	1.60	2.26	3.05	+
35	0.68	1.36	2.10	3.05	+	+	+
36	1.72	2.70	+	+	+	+	+

Design guidelines for comfort ventilation (Clause: 5.3.1)

- For taking advantage of natural outdoor air flow, the building need not necessarily be oriented perpendicular to the prevailing outdoor wind. The building may be oriented at anywhere between 0” and 30” without losing beneficial aspects of the breeze.
- Openings in the façade should be prioritized on the windward side at a low level and the outlets should be arranged on the leeward side.
- Keeping the sill height of the opening at 85% of the critical height (say head level) ensures maximum air movement at the critical height.
- Greatest flow per unit area of openings is obtained by using inlet and outlet openings of nearly equal areas at the same level.

- For a total area of openings (inlet and outlet) of 20-30% of floor area, the average indoor wind velocity is around 30% of outdoor velocity.
- Air motion in a shielded building is less than that in an unobstructed building. To minimize shielding effect, the distances between two rows should be 8 times the height for semi-detached houses and 10 times height for long row houses.

Part 4: Lighting

SP 41 provides reference for recommended illumination levels in lux and daylight factor for residential use. In addition, the handbook provides a graphical method to determine daylight factor for given fenestration ratio (defined as percentage of floor area).

Table 10 Illumination and daylight requirements by use/space type

Space type	Illumination (Lux)	Daylight Factor (percent)
Kitchen	200	2.5
Bathroom	100	
Stairs	100	
Living Room		0.625
Homework/sustained reading	300	
Reading casual	150	
Study Room		1.9
Circulation		0.313
Note: *Wherever applicable, Illumination and Daylight Factor values must be ensured at horizontal work plane, room centre and other specific locations.* *1% DF=80 lux*		

1.1.2 National Building Code

The Indian National Building Code defines three thermal comfort indices for our climate: Standard effective temperature (SET), Tropical summer index (TSI), and adaptive thermal comfort. Indoor design conditions as per adaptive thermal comfort are recommended for naturally ventilated buildings, mixed-mode buildings, and air-conditioned buildings. NBC recognize people's thermal comfort needs depend on their past and present context and these needs vary with the outdoor environmental conditions of their location.

The NBC uses the Indoor Operative Temperature as metric to evaluate the Thermal Comfort with 90% acceptability limit. The equations are outlined below.

- For naturally ventilated buildings:

  Indoor operative temperature = (0.54 x outdoor running mean temperature) + 12.83

  The 90 percent acceptability range for the India specific adaptive models for naturally ventilated buildings is ±2.38°C.

- For mixed-mode buildings:

  Indoor operative temperature = (0.28 x outdoor running mean temperature) + 17.87

  The 90 percent acceptability range for the India specific adaptive models for mixed-mode buildings is ±3.46°C.

It must, however, be noted that the thermal comfort standards defined in NBC are not explicitly designed for residential buildings. The equations reference IMAC model which is based on field studies conducted in the office environment.

1.1.3 IS 8888 (Part 1): 1993, Requirements of Low-Income Housing – Guide

This standard provides guidelines for the planning and general building requirements of low-income where dwelling units have a maximum plinth area of 40 rn^2. The standard provides layout guidelines by plot-size and distinguishes these requirements for metros and non-metros. Other considerations on maximum ground coverage, Floor Space Index (FSI), etc. are prescribed as well. The standard also prescribes minimum spatial characteristics such as size of habitable room, heigh of spaces etc.

The guide addresses Lighting and Ventilation in low-income housing. The openings, windows and ventilators shall meet the following requirements:

- 1/10th of the floor area in Hot-Dry climate.
- 1/6th of the floor area for Wet-Hot climate.

Regarding incremental housing, this guide finds it necessary to provision for vertical and horizontal increment when finances of the low-income family allow. Based on findings from other studies, this guide advises integration of housing area with commercial and industrial land use renders to enable a self-supporting ecosystem for the residents. Finally, this Guide discourages plotted development since it would cost more in terms of land, except in the case of incremental housing and site and services schemes. Instead, recommendations have been made for row housing and group housing on cluster planning approach.

1.1.4 IS 13727: 1993, Requirements of Cluster Planning for Housing – Guide

At the outset, based on previous studies, this guide concludes having "rediscovered the virtues of low-rise, high-density development in the context of affordability and incremental growth. It further states "Cluster planning has proved to be a powerful urban design tool, yet number of conventional byelaw provisions such as set-back and coverage hinder efficient planning based on cluster concept. It has, therefore become necessary to devise guidelines that will permit imaginative cluster planning.".

This standard provides guidelines for the planning and building requirements of housing developed as clusters. The standard acknowledges, low-rise high-density developments (as opposed to plotted developments) and the need for incremental growth. Cluster approach has been accepted as an economic necessity and socially desirable. The standard also acknowledges bye-law provisions (for example, setbacks) hinder planning around the cluster concept. The standard prescribes clusters of 20 homes (and not more) to ensure proper maintenance, maintaining identity and countering encroachments. Few standard cluster designs outlined in the standard are shown in Figure 1.

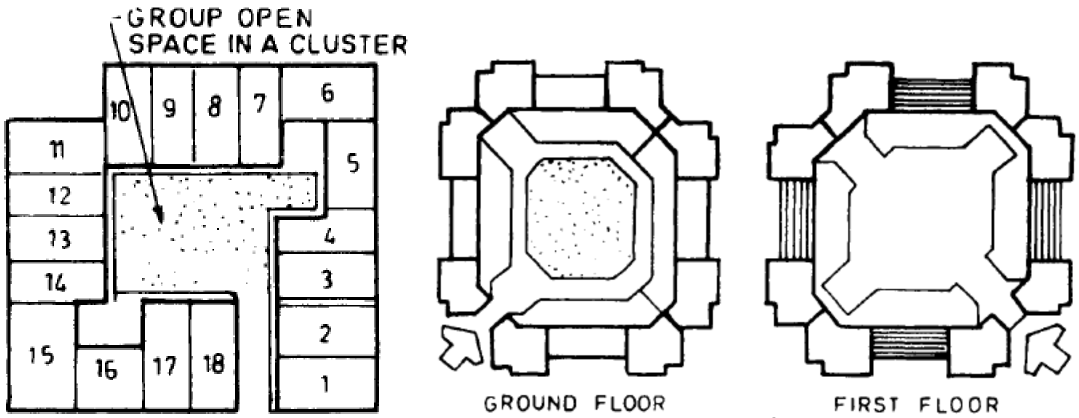

Figure 1 Cluster planning approach for developing low-income settlements. Source: IS 13727: 1993

A common theme among the cluster designs are courtyards/open spaces. The standard goes onto prescribe maximum courtyard dimensions, width and breadth 13 m. In addition to this, minimum plot-size, ground coverage and FSI have been prescribed for cluster developments. This includes prescription for slum resettlement as well.

1.1.5 EcoNIWAS Samhita (Part I: Building Envelope) & Code Compliance and Part-II (Electro-Mechanical and Renewable Energy Systems)

EcoNIWAS Samhita is a energy performance code for residential buildings in India. The code outlines compliance approach and requirements for design and its components (Envelope, Electro-Mechanical and Renewable Energy Systems)

EcoNIWAS Samhita (Part I)

EcoNIWAS Samhita (Part I) is a code intended to outline minimum performance standards for building envelope with respect to heat gain/loss, natural ventilation, and daylight potential. The code provides flexibility to meet minimum performance standards by varying envelope components. The code is applicable to residential buildings and residential component of mixed-use buildings developed on a minimum plot area of 500 m^2. The code allows states and municipal bodies to modify the applicability requirements to make the code more inclusive.

The code defines Residential buildings as "Any building in which sleeping accommodation is provided for normal residential purposes with or without cooking or dining or both facilities.". The code identifies 2 categories of residential dwellings,

1. one/two family private dwellings, occupied by members of one or two families and has a total sleeping accommodation for not more than 20 persons.
2. apartment houses, in which living quarters are provided for three or more families.

The code acknowledges the building envelope as central to maintaining thermal comfort, improving energy efficiency and reducing life cycle environmental impact. Key requirements for compliance with the code are outlined in this section.

Openable Window-to-Floor Area Ratio (WFR_{op}) is the operable window area described as a fraction of the carpet area. This metric is indicative of natural ventilation potential. The code adapts information from National Building Code of India 2016 to outline minimum requirement of window-to-floor area ratio (WFR_{op}).

Table 11 Minimum requirement of window-to-floor area ratio (WFR_{op}) by climate type.

Climate Zone	Climatic zone Minimum WFR_{op} (%)
Composite	12.50
Hot-Dry	10.00
Warm-Humid	16.66
Temperate	12.50
Cold	8.33

Visible Light Transmittance (VLT) is indicative of daylight potential. The code outlines minimum VLT requirements for window-to-wall ratio (WWR) ranges. These values have been adapted from NBC of India 2016.

Table 12 Minimum visible light transmittance (VLT) requirements

Window-to-wall ratio (WWR)	Minimum VLT
0–0.30	0.27
0.31–0.40	0.20
0.41–0.50	0.16
0.51–0.60	0.13
0.61–0.70	0.11

The code advises that the design/material specifications maintain,

1. WWR not exceeding 0.40
2. WWR ≤ 0.15, and
3. VLT meeting or exceeding 0.4

Envelope transmittance limits

The code requires meeting Residential Envelope Transmittance Value (RETV). A mathematical equation with climate, orientation and surface specific coefficients and constant values. RETV is indicative of envelope gains and accounts for thermal characteristics and design. However, it does not account for the roof surface and for the Cold climate. For roof surfaces, the code has defined a maximum thermal transmittance value of 1.2 W/m^2K for roof for all climates. For Composite, Hot-Dry, Warm-Humid, and Temperate climates, the code specifies a maximum RETV of 15 W/m^2, with a view to improve this to 12 W/m^2 in the near future.

Since RETV aims at limiting heat gain, it has limited applicability for the Cold climate. To plug heat losses, the code prescribes maximum maximum thermal transmittance value of 1.8 W/m^2K for all envelope surfaces except roof.

Guidelines for design

The code refers the NBC of India 2016 to outline design guidelines for Natural Ventilation. Guidelines include configuration of openable windows to maximize cross-ventilation. The code also provides information on Roof Gardens and reflective roof surfaces.

EcoNIWAS Samhita Code Compliance and (Part II)

EcoNIWAS Samhita Code Compliance and (Part II) provides a prescriptive and point based compliance approach for compliance. For both modes of compliance, mandatory requirements must be met with. It specifically addresses Affordable Housing and characterizes the low-income residential typologies (Table 13).

Table 13 Affordable Housing typologies and respective area limits

Typology	Area Range (Carpet Area)
Lower Income Group – A	28 – 40 m^2
Lower Income Group – B	41 – 60 m^2
Note: *Dwelling units with carpet area exceeding 60 m2 are not considered as Affordable.* *The code provides flexibility to adopt latest definition as changed time to time by Ministry of Housing & Urban Affairs and respective states.*	

With respect to Mandatory Requirements, Section 4.1 requires compliance with EcoNIWAS Part 1. Prescriptive requirements in Section 5.1 include:

1. Openable Window-to-Floor area ratio, Visible Light Transmittance (VLT) as per requirements stated in EcoNIWAS Part 1.
2. Maximum RETV of 12 W/m^2 for Composite, Hot-Dry, Warm-Humid, and Temperate Climate.
3. Thermal transmittance of building envelope (except Roof) for cold climate shall comply with the maximum U value of 1.3 W/m^2K.
4. Thermal transmittance of roof shall not exceed 1.2 W/m^2K.

For showcasing compliance via the points-based approach, in the Affordable Housing project category must meet 70 points or more in addition to meeting the mandatory requirements. The points criteria for building envelope and components is outlined below.

- For compliance with thermal transmittance of roof surface, a minimum of 3 points and a maximum of 7 points can be achieved.

Table 14 Points available for meeting thermal transmittance requirements.

	3 Points		4 Points		5 Points		6 Points		7 Points
U-Value (Roof)	≤ 1.20	≥ 0.97	≤ 0.97	≥ 0.74	≤ 0.74	≥ 0.51	≤ 0.51	≥ 0.28	≤ 0.28

- For compliance with RETV requirements in Composite, Hot-Dry, Warm-Humid, and Temperate Climate, a minimum of 44 and a maximum of 80 points can be achieved.

Table 15 Points available for meeting RETV requirements.

	44 Points	50 Points	80 Points
RETV	15	12	≤6
Note: For 12 <= RETV <15, Points = 74 - (2 X RETV) For 6 <= RETV <12, Points = 110 - (5 X RETV)			

- For compliance with thermal transmittance requirements for envelope surfaces (except roof) in Cold climate, a minimum of 44 and a maximum of 80 points can be achieved.

Table 16 Points available for meeting U-value requirements for envelope surfaces (except roof) in Cold climate.

	44 Points	50 Points	80 Points
U-value	1.80 W/m²K	1.32 W/m²K	≤0.36
Note: For 1.32 <= U-value <1.80, Points = 66.5 - (12.5 X U-value) For 0.36 <= RETV <1.32, Points = 91.25 - (31.25 X U-value)			

Overall, for the Building Envelope category, a minimum of 47 and a maximum of 87 points may be accomplished.

1.1.6 SVAGRIHA

SVAGRIHA is a guidance cum rating system developed by The Energy and Resources Institute (TERI) and Association for Development and Research of Sustainable Habitats (ADARSH). The pre-fix 'SVA' in 'SVAGRIHA' stands for Small, Versatile and Affordable. The SVAGRIHA rating system is designed for small developments with built up area up to 2,500 m². This rating system is applicable to stand alone buildings like residences, commercial offices, motels, dispensaries, schools etc. The focus of SVAGRIHA is to reduce environmental impact of small developments. The rating system has 14 criteria split into 5 broad sub-groups: architecture & energy, water & waste, materials, landscape and lifestyle. The criteria are a group of specific requirements to meet SVAGRIHA defined performance levels. SVAGRIHA defines performance levels from 1 Star (most environmental impact) to 5 Star (least environmental impact). Each criterion is characterized by points representative of performance. The range of points define Star Rating bands. The rating system mandates certain criteria within each sub-group as mandatory.

Criterion #2 "Adopt passive architectural design strategies" focuses on **passive design/low-energy strategies to reduce energy consumption while maintaining thermal comfort**. This criterion outlines few passive/low-energy design strategies by climates as well. The requirement is to,

a) integrate **at least 2 passive design measures** in the architectural design, and/or,
b) install low-energy cooling/heating systems.

Criterion #3 "Good Fenestration design for reducing direct heat gain and glare while maximising daylight penetration" is a passive design measure that can impact thermal comfort as well. **The criterion aims at reducing direct heat gain through openings while ensuring adequate and glare-free daylighting.** The criterion emphasizes on orientation of opening, opening size, shading and glazing material properties. The calculation procedure, to deem compliance with requirements is incremental. It optimizes façade design (window opening and orientation), improves window material, evaluates combined effect on heat gain, and finally, measures performance for daylight. The requirements are to,

a) **[Mandatory] limit window to wall ratio (WWR) to a maximum of 60%**,. This threshold is attributed to ECBC 2007.
b) reduce heat gain vis-à-vis a pre-defined Baseline case, and,
c) **[Mandatory] meet/exceed daylit area of 25% as per ECBC (2007)**.

For evaluating compliance, the web-based calculator uses some assumptions. For example, the base case fenestration uses **glass SHGC of 0.64 for non-north orientations** and **0.68 for north glass**. The direct heat gain through fenestration is computed as the product of Insolation, Window Area and SHGC. It appears that these calculations are conducted for the peak period.

The criterion also defines minimum insolation reduction (over base case) thresholds through fenestration for cooling dominated (or tropical) climate types. For heating dominated climates insolation is welcome, however, no minimum threshold for insolation has been mandated.

Table 17 Thresholds (in %) of minimum reduction in Insolation for the proposed case vis-à-vis the base case and corresponding points for cooling dominated climate types.

Points	Composite/Warm & Humid/Hot & Dry	Moderate*
1	30%	10%
2	45%	20%
3	60%	30%
* Moderate refers to Temperate climate.		

For evaluating daylight in dwellings, the rating system outlines daylight requirements for dwelling units by space. **These minimum performance thresholds for daylight have been adopted from SP 41**.

Table 18 Daylight factor requirements for dwelling unit by space type as referenced from SP41.

Living Area	Daylight Factor
Kitchen	2.5
Living Room	0.625
Study Room	1.9
Circulation	0.313

The rating also outlines daylight factor for combination of WWR and Visual Light Transmittance (VLT) percentage, however, these have been derived for 7 m deep floor plate which may not be relevant for Affordable Housing.

Table 19 Daylit area thresholds for minimum and incremental performance thresholds.

	Mandatory	1 point	2 points	3 points
Daylit Area (in % of total living area)	25%	50%	70%	90%

Criterion #5 "Design of building envelope to reduce overall heat gain" aims at lowering overall heat gain from building envelope through use of appropriate materials and design of external wall section. The criterion identifies External and Internal heat gain sources that are critical to maintain thermal efficiency of the building envelope. For evaluation, the criterion measures thermal efficiency in square feet per ton of refrigeration (SF/TR) or Thermal Load in Watts per unit area (W/m^2).

Table 20 Thermal gain thresholds for major cities across India

Climate Zone	City	< ft^2/TR (1 point)	> W/m^2 (1 point)	< ft^2/TR (2 points)	> W/m^2 (2 points)
Moderate	Bengaluru	275	**135**	325	**115**
Hot-Dry	Jodhpur	275	**135**	350	**110**
Composite	Allahabad	225	**165**	300	**125**
Composite	New Delhi	275	**135**	325	**115**
Composite	Chandigarh	275	**135**	350	**110**
Composite	Hyderabad	300	**125**	350	**110**
Warm-Humid	Chennai	275	**135**	350	**110**
Warm-Humid	Pune	300	**125**	375	**100**
Warm-Humid	Kolkata	300	**125**	375	**100**
Warm-Humid	Mumbai	325	**115**	400	**95**

Criterion 6 "Use of energy efficient appliances" requires installation of BEE Star labeled appliances for Air-conditioners, Fans and Geysers.

Table 21 Requirements of energy performance of equipment is outlined as 3 Star (of BEE Star Rating program) or better for AC, Celing fan and Storage Water Heater.

1 point	2 points	3 points
3 Star AC, Ceiling fan and Storage Water Heater	4 Star AC, Ceiling fan and Storage Water Heater	5 Star AC, Ceiling fan and Storage Water Heater

The rating system considers a VRV system as a 5 Star Rated AC.

Criterion 7 "Use of renewable energy on site" defines a requirement for meeting Hot Water requirement per dwelling unit. As per the rating system, hot water requirement per residence is defined as 100 litres/day. Meeting 50% of this requirement qualifies for 1 point, and meeting daily requirements of 75% and above qualifies for 2 points.

Criterion 11 "Reduce the embodied energy of building" focuses on replacing Ordinary Portland Cement (OPC) use in structure and masonry with Plain Pozzolana Cement (PPC) and reducing the embodied energy in structure by 5 and 10% for 1 and 2 points respectively. **Criterion 12** "Use of low-energy materials in interiors" outlines the following as low energy materials,

- Locally mined stones without mirror-finishes
- Bamboo/rubber wood products
- Particle board, MDF, HDF, agro-fiber based products
- Manufactured products with recycled content, etc.

The rating system allocates 1 point each for achieving 70% of flooring and 70% of internal partitions/paneling/false ceiling/in-built furniture/ doors & window-panels & frames, etc. as low energy materials.

Criterion #13 "Adoption of Green Lifestyle" specifies an optimal range of development density. For residential buildings, the rating system identifies a range of 12.5 – 50 m^2. In context of Affordable Housing, this range of development density may be considered sparse.

1.1.7 GRIHA for Affordable Housing

GRIHA for Affordable Housing is a point-based rating system. GRIHA AH identifies 30 criteria for appraisal on a 100-point system with issues aligned to Site Planning, Energy & Occupant Comfort, Water Saving, Waste Management, Sustainable Building Materials, Social Aspects and Bonus Points. The rating system has Mandatory, Partly Mandatory and Optional criteria. Based on the points achieved, the System provides a Rating from 1 to 5 Stars.

Eligibility requirements for GRIHA AH program mandate, Approval Letter (by State/Centre) confirming the development as per PMAY guidelines, conformance with development plan and local municipal authority's assurance of water supply as per estimated demand. Although the rating system does not explicitly state, but the performance requirements, fee structure and other aspects indicate that this rating system is designed for multi-family apartments.

Criterion 1 "Low Impact Design" stresses on integrating passive design strategies and natural site features to reduce energy consumption while maintaining thermal comfort. The criterion requirements include integrating **at least 2 passive design and low-impact site planning strategies (1-4 points)**, and **demonstrating use of active, low-energy cooling/heating systems in the building (2 points)**. The rating system provides a list of Passive Design Measures by climate type.

Table 22 Point structure for integrating Passive Design strategies.

Passive Strategies Adopted	2	3	4 or more
Points available	1	2	4

Criterion 2 "Design to Mitigate UHIE" requires area exposed to sky, except landscape, are either soft paved OR covered with high SRI coating (SRI > 0.5) OR shaded by vegetation, solar PV panels. If such areas constitute 25% of site area rating system provides 1 point. For meeting 50% of site area, the rating system provides 2 points.

Criterion 6 "Envelope Thermal Performance" outlines peak envelope gain and cooling load thresholds to guide design of envelope through use of thermally appropriate construction material, optimal fenestration design **to minimize heat gain and ensure thermal comfort**.

Table 23 Thresholds for peak envelope heat gain and cooling load by climate type.

Climate	Peak Envelope Heat Gain Factor (W/m^2) (2 points)	Peak Cooling Load Threshold (W/m2) (1-6 points)
Composite	55	210
Hot-Dry	50	270
Warm-Humid	40	350
Moderate	30	220

Table 24 Points available for reduction in cooling load over defined thresholds

% Reduction in cooling load	Points
3%	1
6%	2
9%	4
12%	6

Criterion #7 "Occupant Visual Comfort" outlines minimum daylit area requirements using the Useful Daylight Illuminance (UDI) metric which is an outcome of Climate-based Daylight Modeling (CBDM) approach. The UDI is computed based on ECBC 2017 calculation methodology. This is a mandatory requirement with minimum 25% area meeting the UDI requirements for at least 90% of daylight time.

Table 25 UDI requirement thresholds and corresponding points

Percentage of area meeting UDI requirements (for 90% of daylight time)	Points
25%	1 [Mandatory]
50%	2
75%	3
> = 90%	5

Criterion #18 "Reduction in Environmental Impact of Construction" identifies three strategies to reduce environmental impact of construction. These strategies include, (1) use waste material, OR (2) use of material with recycled content, OR (3) material with low embodied energy.

Table 26 The rating system identifies 3 strategies for reducing environmental impact of construction. Demonstrating achievement of any one requirement for any one strategy is sufficient to meet the desired points

	Strategy #1		Strategy #2		Strategy #3
Requirement 1	Minimum replacement of sand, aggregate or Ordinary Portland Cement (OPC) with any BIS recommended waste by weight of sand, aggregate or OPC respectively used in structural concrete.		Minimum utilization of recycled content in structural framework.		Minimum reduction in combined embodied energy of structure and walls over a baseline case. Baseline case is defined as RCC structure with burnt clay brick masonry.
Requirement 2	Composition of building blocks/bricks by any BIS recommended waste by volume, for 100% load bearing and non-load bearing masonry walls.		Minimum utilization of recycled content in infill panels.		
2 Points	R1:15%	R2: 40%	R1: 2.5%	R2: 40%	R1: 10%
4 Points	R1:25%				R1: 20%
6 Points					R1: 30%
Note: *Any one requirement is to be fulfilled to meet the desired points.*					

1.1.8 IGBC AH

The Green Affordable Housing Rating System is designed for multi-dwelling units. The rating system is applicable to housing projects where at least 70% dwelling units have maximum carpet area of 60 m^2. The rating system focuses on 6 major categories to ensure a high degree of sustainability with no/meagre additional cost to the developer or the occupant. The categories are identified below:

1. Site Measures
2. Water Conservation
3. Energy Conservation
4. Materials Conservation
5. Indoor Environmental Quality
6. Innovation & Design Process

The rating system has several requirements under each category. The requirements are categorized as Mandatory Requirements (MRs) and Credits. Each credit carries some points. The total number of points achieved determine the applicable rating. The various levels of rating are:

- Certified (38-44 points). Indicates the project has adopted known Best Practices.
- Silver (45-51 points): Indicates that the project has Outstanding Performance.
- Gold (52-59 points): Indicates that project is recognized for National Excellence.
- Platinum (60-75 points): Indicates that project is recognized for Global Leadership.

For a project to be eligible for rating, all mandatory requirements must be met, and the overall points tally must achieve at least 38 (of 75) points.

Site Measures Credit 6 "Heat Island Effect - Roof: 75%, 95%" requires **covering at least 50% [Mandatory – 0 points] of exposed roof surface areas with reflective materials** to reduce heat islands. Light colored chinamosaic/white tiles and reflective surface applications (white in color) are accepted measures. For achieving percentage of exposed roof area as reflective points are awarded (75% 1 point, 95% 2 points).

Energy Conservation Credit 1 "Energy Efficient Building Envelope" stresses on meeting envelope performance metrics to improve energy efficiency. Table 27 outlines maximum allowable conductance for wall roof and glazing assemblies for each climate zone, and Table 28 highlights maximum allowable Solar Heat Gain Co-efficient (SHGC) for all climate zones with respect to Window Wall Ratio (WWR) threshold of 20%. Meeting these requirements is anticipated to yield energy cost savings in the range of 20 - 30% (vis-à-vis conventional building).

Table 27 Maximum allowable conductance of wall, roof and glazing assemblies by climate type.

	Maximum 'U'-Value of the overall assembly (W/m^2K)		
Climate Zone	**Wall**	**Roof**	**Glazing**
Composite	2.5	1.2	5.7
Hot and Dry	2.5	1.2	5.7
Warm and Humid	2.5	1.8	5.7
Moderate	1.1	1.2	5.7
Cold	2.5	1.2	-

Table 28 Maximum allowable Solar Gain coefficients by climate types for

	Maximum SHGC Value	
Climate Zone	**WWR < 20%**	**WWR < 20%**
Composite	0.50	0.42
Hot and Dry	0.50	0.42
Warm and Humid	0.50	0.42
Moderate	0.60	0.48
Cold	0.80	0.80

Energy Conservation Credit 2 "Shading Elements for Building Openings" outlines requirements for shading. The credit provides option of 2 approaches. The first approach requires providing **shading with Projection Factor (PF) of 0.5 or better for at least 80% of external openings.** The second approach outlines design features such as extended louvers, punched windows, pergolas, horizontal and vertical landscaping, bamboo chick curtains/blinds, etc.

Energy Conservation Credit 3 "Efficient Lighting" outlines choice of measures for meeting prescribed lighting power densities. Of the 4 measures listed, at least 2 must be implemented to achieve the designated points. Further, only one measure is outlined for interior lighting in residential units. **This measure limits the lighting power density for the dwelling unit to 0.5 W/m^2 or lower**.

Energy Conservation Credit 4 "On-site Renewable Energy: 50%, 75% - Solar Water Heaters: 25%, 50%" requires installation of on-site renewable energy systems for common area lighting and/or solar water heating. Considering hot water requirement as 20 litres/person-day, a solar hot water system exceeding 25% will fetch 1 point and a system exceeding 50% will fetch 2 points.

Material Conservation Credit 3 "Use of local Materials: 50%, 75%, 95%" stresses use of locally available materials. The credit requires at least 50% materials (by cost, not including labor cost) should be extracted and manufactured within 400 kms of development. Meeting this requirement will earn 1 point. Exceeding requirements to meet 75% and 95% of material costs with locally available material will earn 2 and 3 points respectively.

Material Conservation Credit 4 "Material with Recycled content: 10%, 20%, 30%" encourages use of material with recycled content. For achieving 1 point, the credit requires meeting at least 10% of total material cost (exclusive of any labour component) is attributable as recycled component. This requirement can fetch 2 and 3 points if material cost of recycled components meets or exceeds 20 and 30% respectively. The rating system considers the following as materials with recycled content:

- Fly ash / AAC / CLC/ Phosphogypsum / red mud blocks
- Cement
- Composite wood
- Glass
- Steel
- Tiles
- FaLG (Fly ash + Lime + Gypsum)

Material Conservation Credit 5 "Appropriate Technologies: 25%, 50%, 75%, 95%" emphasizes on use of cost-effective yet functional alternative construction technologies. For compliance with this credit, at least 50% (2 points) of cost of structure should utilize alternative construction technologies. Additional performance thresholds for meeting 75% (3 points) and 95% (4 points) of costs are available as well. The rating system identifies the following as few alternative construction technologies:

- Monolithic Concrete Construction
- Precast Concrete Construction for Super structures
- Glass Fiber Reinforced Gypsum (GFRG) Panel Building System
- Use of Compressed Stabilized Earth Blocks, and
- Filler Slabs

Material Conservation Credit 6 "Alternate Construction Materials: 25%, 50%" encourages use of alternative construction materials that conserve natural resources. The credit requires that cost of alternative construction meets and exceeds 25% (1 point) or 50% (2 points) thresholds. The standard identifies the following as few of the Alternative Construction Materials:

- Innovative curing materials,
- Ground-granulated blast-furnace slag (GGBS or GGBFS) to minimise cement usage,
- Slag sand/artificial sand to replace natural sand, and others.

Indoor Environment Quality Credit 1 "Day Lighting: 75%, 95%" ensures adequate daylighting. The rating system provides 2 options to demonstrate compliance.

Option 1 is a Prescriptive approach that requires achieving a minimum glazing factor (GF) for all regularly occupied spaces. GF is calculated as per the equation below,

$$Glazing\ Factor = {(Window\ Area \times Visible\ Transmittance \times Constant \times 100)}/{Floor\ Area}$$

The constant values for windows on vertical and horizontal surface are 0.2 and 1.0 respectively. For windows where the obstruction angle exceeds 70° will not be considered for daylight calculations. The angle of obstruction is the angle subtended between the top of the window sill and the top of the obstruction.

Table 29 Glazing factor requirements for regularly occupied spaces in dwelling units.

Type of Regularly Occupied Space	Glazing Factor (GF)
Living/Bed Room	1
Multi-purpose Room	1
Kitchen	2
Note: *For other regularly occupied spaces which are not listed in the table above, a minimum glazing factor of 1 should be achieved.*	

For meeting the requirements of the credit, the design must showcase, by prescriptive approach, achieving 75% (1 point) or 95% (2 points) of total regularly occupied area as daylit.

Option 2 is a Measurement/Simulation-based approach that requires achieving minimum lux levels for all regularly occupied spaces. The measurement approach requires measurements to be taken at 2 feet 6 inches height at 9 am, 12 pm, and 3 pm, on a 10-foot square grid. The simulation approach requires modeling for daylight illuminance in clear sky condition on 21st September at 12 noon, at 2 feet 6 inches height. For both measurement and simulation approach, the credit requires meeting a minimum 0f 110 lux for 50% of regularly occupied spaces.

Indoor Environment Quality Credit 2 "Fresh air ventilation:50%, 75%" outlines requirements for openable area (window/door/ventilator) to exteriors for each space type.

Table 30 Openable area requirements are expressed as a function of total carpet area for Living Room, Kitchen and Bathroom

Space type	Net openable area as percentage of total carpet area [100 X Openable Area/Total Carpet Area]
Living Room	10%
Kitchen	8%
Bathrooms	4%

Spaces that meet the requirements in Table 30 are considered to meet Fresh Air Ventilation. 50% of spaces meeting the defined ventilation criteria fetch 1 point and 75% of spaces meeting the criteria fetch 2 points.

Indoor Environment Quality Credit 3 "Cross Ventilation: 50%, 75%" encourages cross ventilation in regularly occupied spaces including living room, bedroom, dining room, study room, kitchen. The credit requires openable doors/windows/ventilators on exterior surfaces in at least 2 orientations. An exception is provided to spaces with opening in only one orientation if there is a permanent opening to the adjoining room which meets the cross-ventilation criteria. The credit also requires that windows/ventilators are free from any obstruction within 2 m from outside surface. The rating system provides 1 or 2 points if the dwelling unit meets cross ventilation criteria in 50% or 75% regularly occupied spaces respectively.

Indoor Environment Quality Credit 4 "Exhaust Systems" ensures adequate ventilation in bathroom and kitchen spaces. The credit outlines airflow requirements for specified area thresholds by space type.

Table 31 Airflow requirements for bathroom and kitchen based on area

Space Type	Floor Area	Minimum Airflow
Bathroom	≤ 4.64 m^2 (50 ft^2)	50 cfm
Kitchen	≤ 9.3 m^2 (100 ft^2)	100 cfm

The credit provides 2 approaches to meet credit requirements. The first approach requires installation of mechanical exhaust systems meeting or exceeding the minimum airflow thresholds. An alternative approach allows provision of ventilators (with mesh to keep insects out) sized to meet the minimum air-flow requirements.

1.1.9 BEE Star Labeling Program

Star Rating of residential buildings is a building energy labeling program notified by the Ministry of Power. As per the schedule, the energy labeling requirements are applicable for all single and multiple dwelling units for residential purpose. The Star Rating is based on Energy Performance Index (EPI) calculation, i.e. Annual Energy consumption (in kWh) per unit built-up area (in m^2). Since the label applies to all residential buildings, the EPI thresholds represent Mixed-mode buildings which assume 25% area Air-conditioned (24 deg C set-point) and 75% area Naturally Ventilated (set-points as per IMAC).

Star Rating	Composite		Warm & Humid		Hot & Dry		Temperate	
	Low (<)	High (=<)	Low (<)	High (=<)	Low (<)	High (=<)	Low (<)	High (=<)
1 Star	52	60	58	64	55	67	28	31
2 Star	45	52	49	58	47	55	24	28
3 Star	37	45	39	49	38	47	21	24
4 Star	29	37	30	39	29	38	17	21
5 Star	29	-	30	-	29	-	17	-

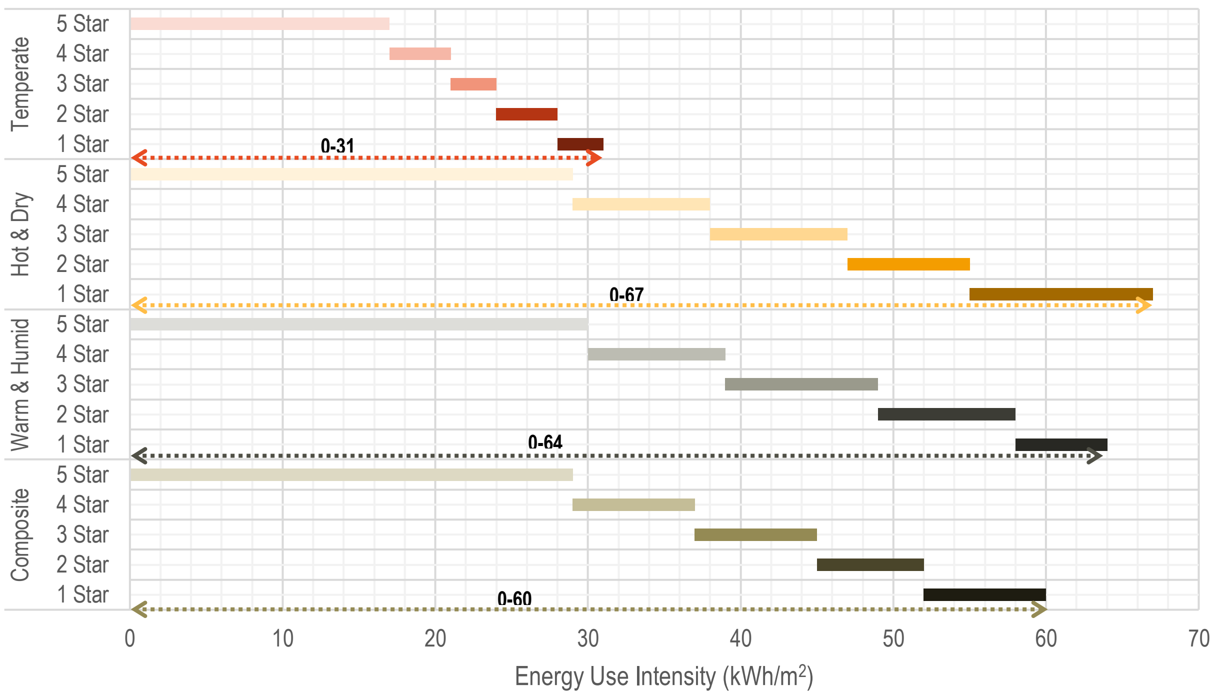

Figure 2 Range of EPI for respective Star Labels across climate zones.

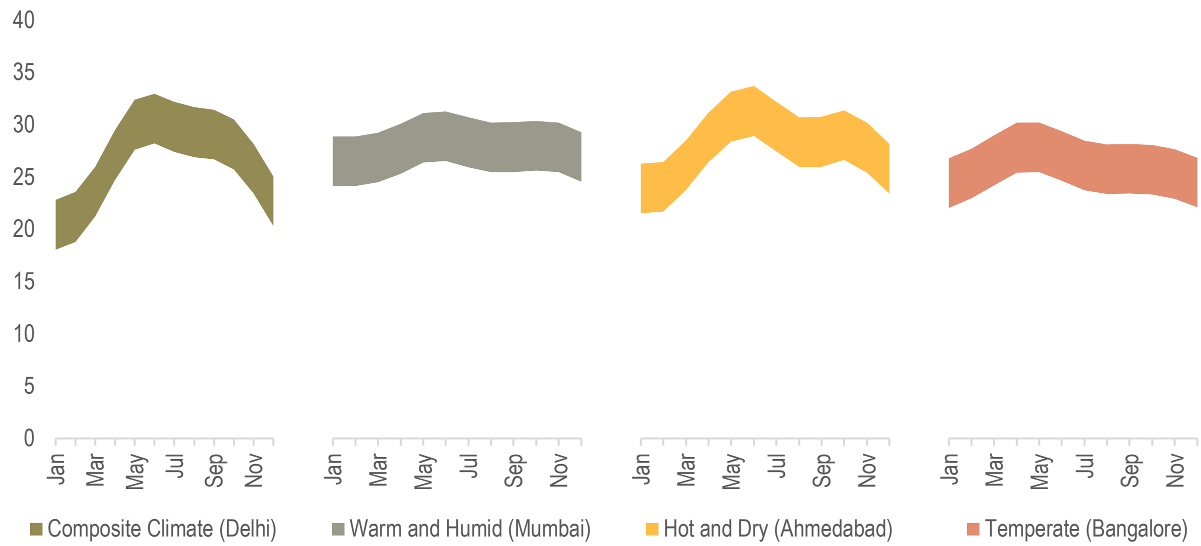

Figure 3 Comfort bands predicted for developing Star Label thresholds using IMAC for all Climate Zones.

1.1.10 ISHRAE Standard-10001 2019: ISHRAE Indoor Environmental Quality Standard

ISHRAE released the first ever Indian standard on indoor thermal environmental quality in 2016 which identifies thermal comfort, indoor air quality, visual comfort and acoustic comfort. This standard is applicable for both residential and non-residential buildings of either naturally ventilated, mixed-mode or air-conditioned buildings. The ISHRAE IEQ standard recognizes the impact of air velocity on thermal comfort acceptability and defines operative temperature as a function of air velocity.

1.2 Standards, codes and rating systems applicable in the International context

This section outlines internationally accepted Thermal Comfort Standards and other International Building Codes. An effort has been made to review standards and codes that are applicable to residential buildings and address tropical and sub-tropical climatic contexts similar to India.

1.2.1 Thermal comfort standards

This section outlines internationally recognized thermal comfort standards. The section also compares the heat balance and adaptive comfort models. This is especially critical in context of affordable housing in India where comfort systems for space raise affordability concerns in both first and operating costs. Finally, the section presents a comparative of popular thermal comfort standards for adaptive comfort in naturally ventilated buildings.

ASHRAE 55-2020: Thermal Environmental Conditions for Human Occupancy

It was first published in 1966 and primarily used in USA but it has become a well-known standard which is widely used for designing, commissioning, and testing of indoor environments. It offers two methods for determining acceptable thermal environments in occupied spaces: an analytical comfort zone method and an elevated air speed comfort zone method (Thermal Environmental Conditions for Human Occupancy, 2017). The standard has a separate method for determining acceptable thermal conditions in occupant controlled naturally conditioned spaces i.e. the adaptive model. The adaptive comfort model embedded within ASHRAE 55 is global in scope because the field study research data sourced from 160 different buildings located all over the world across four different continents (de Dear et al., 1997). This model also recognized the effect of increased airspeed on occupant thermal comfort particularly in naturally ventilated spaces. Therefore, this adaptive model is regarded as a global implementation of the adaptive thermal comfort (Carlucci et al., 2018).

EN 16798-1, 2019: 'Energy performance of buildings - Ventilation for buildings, Part 1

The standard defines indoor environmental input parameters for design and assessment of energy performance of buildings to address indoor air quality, thermal environment, lighting, and acoustics. It is the updated version of standard EN15251 (EN 15251, 2007) that is generally used for the design of residential and non-residential buildings. The European standard EN 15251 was firstly published in 2007 (Nicol & Humphreys, 2010)and included both the PMV/PPD model and the adaptive comfort method developed (McCartney & Fergus Nicol, 2002; Nicol & Pagliano, 2007). It has been renamed in 2015 as prEN-16798. In this standard, available range of outdoor running mean temperature of thermal zone extended from 15 to 30°C to 10 to 30°C. The predefined PMV and PPD calculations obtained through ASHRAE 55 and ISO7730 have been considered as the base for thermal criteria in EN16798-2019 (Sansaniwal et al., 2020). This standard has also considered the variations for occupant's thermal expectations obtained for NV and MM spaces, in addition to year-round prediction of indoor thermal comfort (EN 16798-1, 2019).

ISO 7730-2015: Ergonomics of the thermal environment

The ISO standards on thermal comfort were developed by the technical committee of physical environment ISO/TC/159 SC5 WG1 of which ISO7730 is the most notable that deals with analytical evaluation of thermal comfort. The standard presents methods for predicting the degree of general thermal sensation and thermal dissatisfaction of occupants exposed to moderate thermal conditions during the calculation of PMV and PPD and local thermal comfort criteria. The standard offers a method to estimate the air speed required to offset the thermal comfort range to compensate an increase in operative temperature (Kazanci et al., 2019). However, the theory of adaptive comfort is still not considered particularly in natural ventilated spaces (Sansaniwal et al., 2020).

Dutch ISSO 74-2014: Netherlands ISSO 74 thermal comfort regulatory document

This standard was established based on adaptive thermal comfort theory. It can be applied to both unconditioned, mixed-mode, and conditioned spaces. The ISSO algorithm for thermal neutrality was the same as that in the RP-884 project (de Dear et al., 1997). An "adapted running mean temperature" was used as the outdoor climate metric for this standard. The updated version of the standard used SCAT European comfort field study database to develop adaptive thermal comfort equation rather than ASHRAE RP-884, and the calculation method of outdoor reference temperature causing the adaptive thermal comfort equation to differ it from EN 16798 (de Dear et al., 2020).

Chinese GB/T 50785-2012: Evaluation standard for indoor thermal environment in civil buildings

The Chinese GB/T 50785 was issued in 2012 to provide an adaptive comfort model for the evaluation of the indoor thermal environment in free-running buildings at design and operational stages (GB/T 50785, 2012). This standard does not specifically mention the type of buildings where the comfort model can be applied, but it includes two methods for assessing free-running buildings: a graphical method and a calculation method (Carlucci et al., 2018). The graphical method is based on the adaptive comfort model appearing in ANSI/ASHRAE 55 (ASHRAE Standard 55, 2017). This Chinese standard bears a resemblance to the comfort zone of ASHRAE 55 but there is a distinct difference between the upper and lower acceptability limit thresholds.

Singapore Standard SS 554-2016: Code of practice for indoor air quality for air-conditioned buildings

Singapore standard code of practice was released in 2016 which applies to all air-conditioned buildings where air-conditioning is used intermittently or continuously (SS 554, 2016). It recommends the minimum ventilation rates for conditioned areas. Singapore government released a 'Thermal Comfort Guidelines and Policy' in 2012 to achieve comfortable, healthy and safe environment by reducing the consumption of electricity from air-conditioning which define that a temperature range of 23°C to 26°C is generally comfortable in Singapore when wearing summer clothes. It also defines local control measures to control indoor air temperature such as opening of windows, clothing sense to ensure personal comfort, and increase the air movement without using air-conditioning.

Malaysian Standard MS 1525-2007: Code of practice of energy efficiency and use of renewable energy for non-residential buildings

Malaysian standard MS 1525 provides the criteria and minimum standards for energy efficiency in the design of new buildings, retrofit of existing buildings and methods for determining compliance with these criteria and minimum standards. It defines passive strategies to increase the thermal comfort in naturally ventilated buildings with the use of ventilation strategies such as stack ventilation and cross ventilation. Further, department of Standards Malaysia, 2007 has published a guideline for a standard indoor environment design for Malaysian climate recommends indoor temperature to be in the range of 23°C – 26°C (Jamaludin et al., 2015).

Adaptive Models vs Heat Balance Methods

Traditionally, the main International Standards (ASHRAE Standard 55 & ISO 7730) have considered Fanger's equation, i.e. the heat balance approach for evaluating thermal comfort. The heat balance approach quantifies the heat exchanges between the human body and the physical environment. To correlate this heat exchange with thermal comfort, the thermal sensations are mapped onto a 7-point scale and expressed as Predicted Mean Vote (PMV) and/or Percentage People Dissatisfied (PPD). The thermal sensations on 7-point scale are recorded in climate-controlled chambers, which studies indicate do not account for climate adaptation or in other words, factors including exposure to external environment and psychological and cultural aspects (Ferrari & Zanotto, 2012). While several studies indicate that the PMV approach over or under-estimates comfort (compared to adaptive indices) it is well accepted in conditioned buildings.

Adaptive approach, on the hand, uses field Studies and statistical analysis on thermal sensation feedback. This approach indicates direct correlation between indoor comfort temperature and outdoor temperature. Since Adaptive Approach is statistical in nature, the derived equations have a higher degree of reliability in predictions when there are contextual similarities with field studies that derived the equations in the first place. (Ferrari & Zanotto, 2012). Studies indicate adaptation dynamics are equally effective in mixed mode and naturally ventilated buildings (Brager & Baker, 2009; Zhang et al., 2011), hence Adaptive Approach is suitable in both contexts. Finally, adaptive approach is better suited for warm conditions compared to harsh/cold climates (Ferrari & Zanotto, 2012). This is especially notable with respect to the Indian context.

A comparative analysis of Thermal Comfort Standards has been performed and presented (de Dear et al., 2020)

Table 32 Comparative analysis of thermal comfort standards.

	ASHRAE 55	EN 16798-1	ISO 7730	NBC	GB/T 50785	SS 553	ISHARE 100001
Revised in	2020	2019	2015	2016	2012	2016	2019
Standard is developed specifically for Residential application ***-1:*** *Specifically excludes residential buildings.* ***0:*** *Not specifically designed for residential buildings.* ***1:*** *Specifically designed for residential buildings.*	0	1	1	0	0	-1	0
Standard applies to Naturally Ventilated buildings. ***-1:*** *Does not account for natural ventilation* ***0:*** *Accounts for natural ventilation* ***1:*** *Accounts for natural ventilation & occupant-control (windows)*	1	0	-1	0	0	-1	0
Standard applies to Mixed-mode operation in buildings. ***-1:*** *Does not account for mixed-mode operation in buildings.* ***0:*** ***1:*** *Accounts for mixed-mode operation in buildings.*	-1	1	-1	1	1	-1	1
Standard applies to Air-conditioned buildings. ***-1:*** *Does not account for Air-conditioned buildings.* ***0:*** ***1:*** *Accounts for Air-conditioned buildings.*	1	1	1	1	1	1	1
Data Source. ***-1:*** *SCATs (Europe).* ***0:*** *RP-884 (Continental Representation)* ***1:*** *Field Studies in India.*	0	-1	0	1	0	0	0
Comfort Indices - PMV and PPD for Air-conditioned Buildings ***-1:*** *No* ***0:*** ***1:*** *Yes*	1	1	1	-1	1	-1	-1
PMV Limits	(0.5) 0.5	(0.7) 0.7	(0.7) 0.7	NA NA	(1.0) 1.0	NA NA	NA NA
PPD Limits	10%	15%	15%	NA	25%	NA	NA
Note (PMV/PPD Limits): (1) *The most lenient class/acceptability limit has been used to map PMV/PPD, except,* ***(a)*** *Category IV for EN 16798 has not been included as it is meant for short occupancy periods only, and* ***(b)*** *Category III of GB/T has no limits so Category II has been used for defining limits.* ***(2)*** *ISHRAE 10001 does not specify criteria for the overall thermal comfort index value.*							
Comfort Indices - Operative temperature (Adaptive Comfort) for Mixed-mode operation or naturally ventilated building.	10.0 33.5	10.0 30.0	? ?	15 34	18.0 30.0	? ?	? ?
Note: *Temperature range for Hot summer/cold winter, hot summer/warm winter, mild zone, for Category II of GB/T 50785 has been used.* ***'?'*** *indicates information not available.* ***'NA'*** *indicates metric/indicator Not Applicable.*							

1.2.2 A review of thermal comfort requirements in International building codes

A review of international building codes has been compiled to identify Thermal Comfort requirements and standards provisions for improving thermal performance in residential buildings. The international experiences are pre-dominantly from tropical climates that are similar to Indian context. Building Codes from Australia, Singapore, South Africa, Spain, Australia, EU Member States and Brazil have been reviewed.

Table 33 outlines Thermal comfort requirements across codes for naturally ventilated and air-conditioned buildings.

Table 33 Summary of thermal comfort in naturally ventilated and air-conditioned spaces requirements from codes/standards

Code/Standard	Thermal comfort requirements	
	Naturally ventilated spaces	**Air-Conditioned spaces**
Building Code of Australia (vol2), Australia	Thermal comfort requirements are not given explicitly, except for opening area requirements for natural ventilation, and provision of ceiling fans and evaporative coolers.	Predicted Mean Vote of the thermal perception of building occupants determined in accordance with ANSI/ASHRAE Standard 55.
Code for Environmental Sustainability of Buildings, Singapore	Option 1: Establish satisfactory natural ventilation design through ventilation simulation modelling or wind tunnel testing. **OR** Option 2: Design building layout with window openings facing north and south directions, and design living rooms and bedrooms with provision for cross ventilation.	Option 2 on the left. **OR** Provide energy efficient air-conditioners that are certified under the Singapore Energy Labelling Scheme.
SANS 204 Energy efficiency in buildings, South Africa	Thermal comfort requirements are not given explicitly, however, the following measures are provided: # Glazing requirements (U-value and SHGC) for naturally ventilated buildings. # Recommendation of appropriate R-values for roofs and ceilings in naturally ventilated spaces.	Recommended set point temperature in summer and winter of 24 and 20 °C, respectively.
Código Técnico de la Edificación (CTE), Spain		Recommended set point temperature in summer of between 25 and 27 °C, and 17 °C in winter.
2019 Building energy efficiency standards for residential and non-residential buildings, California, USA	The maximum distance from an operable window is a function of ceiling height, and the size of the openings should not be less than 4% of the floor area	
Norma Brasiliera ABNT NBR 15220-3, 2005 (Thermal performance in buildings. Part 3: Brazilian bioclimatic zones and building guidelines for low-cost houses)	The standard does not explicitly state that the requirements for either AC or NV residential dwellings. In scope, this standard is explicitly for Social housing up to 3 storeys high, and, based on climate zone mapping it acknowledges the requirement of Artificial heating	

	and cooling in 2 climate zones. From the nature of requirements and scope, it is interpreted that the standard primarily applies to non-air-conditioned buildings. The standard, by way of a strategy-climate matrix, mandates thermally passive conditioning strategies. The thermally passive conditioning strategies have been derived from bio-climatic charts for each of the 8 zones. The standard also outlines requirements for window openings (as fraction of floor area), thermal transmittance and thermal mass (as thermal lag).	
EU Member states: Belgium (Brussels Region), Denmark, France, Germany, Italy, Poland, Sweden and the UK (England and Wales)(Kontonasiou et al., 2015)	**#** Indoor air temperature is an indicator of thermal comfort in all eight member states. Temperature requirements/recommendations range between 16 °C (Poland, winter) and 28 °C (France, summer). Some countries (France and UK) also use operative temperatures to assess thermal comfort. **#** Requirements of Passive systems include solar shades and thermal mass (Italy only). French indicator "TIC" (Indoor Conventional Temperature) and the German "Sonneneintragskennwert" (Solar Transmittance Value) take several (passive) aspects into account. **#** Brussels, Denmark, France, Germany and the UK introduced a limit on overheating. Brussels (regulation, >25°C for 5%/year) and the UK (recommendation >28°C for 1%/year by the Chartered Institution of Building Services Engineers) **#** France, Germany, Poland and Sweden require minimum temperature limit in winter and Italy requires minimum (winter) and maximum (summer) temperature limits. A brief description of thermal comfort requirements and recommendations in EU member states has been provided below: **Brussels:** Recommendations from Bruxelles Environnement, maximum difference between internal and external temperature should be between 5°C and 7°C (in summer). **Denmark:** DS 474 outlines requirements for appropriate indoor temperatures. • Not more than 100 hours above 26°C; • Not more than 25 hours above 27°C. **France:** French indicator TIC (Indoor Conventional Temperature) expressed in °C is the maximum operative temperature ensuring comfort during the hot season while avoiding air conditioning systems. Comfort temperature levels in summer are defined through a reference indicator TIC_{ref} that should not be exceeded over more than 5 consecutive days. The TIC_{ref} is calculated by the method of Th-2012 BCE. The maximum comfort temperature is the same throughout the year when a mechanical system is used (28°C), while in the case of natural ventilation, different limit values are established according to the type of building and external temperature. **Germany:** In summertime, the EnEV requires a building to be in line with "Sonneneintragskennwert", an indicator for maximum solar gains, calculated	

	according to DIN 4108 -2. Maximum solar gains to avoid overheating for more than 10% of the time have to be checked for each room. **Italy:** Temperature limits are defined to limit energy wastage on account of cooling and heating. Cooling systems have to be limited to 26°C (with -2°C of tolerance) in summer and heating systems during have to be limited in each building unit to 20°C (with +2°C of tolerance) in winter. For all walls (excluding the ones facing north), the periodic thermal transmittance YIE must be lower than 0.12 $W/m^2 \cdot K$ or the surface thermal mass must be higher than 230 (kg/m^2). For all floors and roofs the periodic thermal transmittance YIE must be lower than 0.20 W/m2·K. External shades are mandatory provided window solar factor is not higher than 0.5. **Sweden:** Swedish building code requires minimum guarantee of satisfactory thermal comfort. The recommended minimal operative temperature for the average dwellings is 18°C, and 20°C for dwellings inhabited by older people. Among the different rooms of a dwelling, the operative temperature difference should not exceed 5°C. Additionally, surface (floor) temperature limits (18 - 26°C based on application) have been specified as well. Dwellings must be designed with a maximum average U-value of 0.4 W/m^2K regardless of the climate zone and the energy supply system. **UK (England and Wales):** Heating systems should be designed to be able to maintain a temperature of 18°C in sleeping rooms and 21°C in living rooms when the temperature outside is at the local design temperature. CIBSE recommends the following criteria for overheating: • Living areas: 1% annual occupied hours over operative temperature of 28°C. • Bedrooms: 1% annual occupied hours over operative temperature of 26°C. For non-air-conditioned dwellings, CIBSE specifies general indoor comfort temperatures. • Living areas should be at an operative (maximum) temperature of 25°C. • Bedrooms should be at an operative (maximum) temperature of 23°C, noting that sleep may be impaired above an operative temperature of 24°C. UK has a specified procedure Appendix P (Assessment of internal temperature in summer) of Standard Assessment Procedure for Energy Rating of Dwellings (SAP 2012) for designers to assess designs for internal temperatures in summers. The assessment takes into account solar gain (considering orientation, shading and glazing transmission), ventilation (considering window operation), thermal capacity and medium summer temperature for the dwelling location. In addition, 'Reducing overheating– a designer's guide', Energy Efficiency Best Practice in Housing, by the Energy Saving Trust (2005)a guide is available to designers as well.

Table 34 outlines provisions in codes for the thermal characteristics of envelope.

Table 34 Summary of requirements for thermal characteristics of building components across international codes.

Code/standard	Provisions/remarks

Building Code of Australia (vol2), Australia	The code prescribes minimum R-values for:
	• Roof assemblies and roof light, considering:
	  o Climate zone
	  o Direction of heat flow
	  o Surface solar absorptance
	  o Construction of the roof
	  o Area of roof light
	  o Thermal insulation
	  o Ventilation of roof space
	• External wall assemblies, considering:
	  o Climate zone
	  o Shading on the external wall
	  o Surface density of external wall and thermal insulation
	• Floor assemblies, considering
	  o Climate zone
	  o Suspended or slab-on-ground
	  o Insulation of slab edge
	The code prescribes aggregate values for conductance and solar heat gain coefficient of the glazing in each storey, considering:
	• Aggregate conductance, considering climate zone and:
	  o Area of each glazing element
	  o Total U-value of each window
	  o Total SHGC of each window
	  o Winter exposure factor each window
	  o Shading projection
	• Aggregate solar heat gain coefficient
	  o Area of each glazing element
	  o Total SHGC of each window
	  o Summer exposure factor each window
	  o Shading projection
	• Floor construction (direct contact with the ground/suspended floor)
	• Air movement (standard/high)
	The code prescribes minimum total ventilation opening area as a percentage of the floor area for each habitable room, considering climate zone and the provision of the following in the space:
	• Ceiling fan
	• Evaporative cooler
	• Either of the above
	The code prescribes maximum values for cooling, heating and total load limits

Code for Environmental Sustainability of Buildings, Singapore	A maximum permissible aggregate Residential Envelope Transmittance Value (RETV) of 25 W/m^2 is prescribed considering: • Window-to-wall ratio • Thermal transmittance of opaque wall (W/m^{2}K) • Thermal transmittance of fenestration (W/m^{2}K) • Correction factor for solar heat gain through fenestration

	• Shading coefficients of fenestration
SANS 204 Energy efficiency in buildings, South Africa	The code prescribes a minimum permissible CR-value (time constant) for external masonry walls based on the climate zone The code prescribes the maximum values for aggregate conductance and solar heat gain coefficient (SHGC) of the glazing in each storey for naturally ventilated buildings, considering: • Climate zone • Constants for conductance • Constants for SHGC • Net floor area Recommendations for shading are provided The code prescribes minimum R-values for roof assembly, considering: • Climate zone • Direction of heat flow Thermal and reflective insulation shall be provided where required The code prescribes maximum permissible SHGC and U-values for roof lights, considering • Area of the roof light The code prescribes maximum permissible values for infiltration
Código Técnico de la Edificación (CTE), Spain	The code prescribes maximum permissible U-values for wall, roof, floor and window assemblies based on the climate zone In addition to individual components, the code prescribed maximum permissible value for the building's global heat transfer coefficient 'K lim [W/m²K]' for private residential use, considering: • Climate zone • Building volume to floor area ratio (m^3/m^2) • The code prescribes limits for maximum solar gains/shading requirements • The code prescribes requirements for airtightness
2019 Building energy efficiency standards for residential and non-residential buildings, California, USA	The code prescribes maximum permissible U-values for wall and roof For thermal transmittance through transparent elements, the code prescribes a maximum permissible aggregate value considering their areas, U-values and SHGC (including shading)
Norma Brasiliera ABNT NBR 15220-3, 2005 (Thermal performance in buildings. Part 3: Brazilian bioclimatic zones and building guidelines for low-cost houses)	This standard has been prepared by the Brazilian Civil Construction Committee under the Commission of Thermal Performance Study of Buildings. The standard presents recommendations on the thermal performance of single-family dwellings also characterized as Social Housing in Brazil. The standard establishes 8 bioclimatic zones across Brazil and provides design guidelines and strategies for passive thermal conditioning. For each climate type, the standard outlines guidelines for (1) opening for ventilation and solar shading, (2) thermal properties of envelope (color, thermal mass, etc.), and (3) Passive Thermal Conditioning Strategies. Ventilation openings are defined as fraction of floor area in %, thermal properties of envelope are characterized by thermal transmittance, thermal delay and solar factor. Ranges of parameters • Ventilation opening: minimum 10% of floor area. • Thermal mass characterized qualitatively as Light, Light-reflective, Light-isolated and Heavy • Thermal transmittance: <= 3.6 W/m^2-°K

	• Thermal Delay: up to 6.5 hours Based on the city-bio-climatic zone-strategy matrix, the standard outlines and mandates implementation of strategies.

In summary, most standards prescribe the maximum permissible thermal transmittance values (U-values) or minimum permissible thermal resistance (R-values) for building components such as external walls, roof, floor, windows and roof lights. In South Africa, maximum permissible Time Constant is provided. Some codes require conditional inclusion of thermal and reflective insulation. In addition, for transparent/translucent components, such as windows and roof lights, maximum permissible values of solar heat gain coefficient (SHGC) and shading requirements are provided.

In some cases, in addition to meeting the thermal requirements for individual building components, an overall/global transmittance value for the entire building envelope is given. For example, in Singapore, an RETV value is prescribed which considers the heat transfer characteristics of all building components, but there are no requirements for individual building components. In Spain, a global K-value should be met in addition to the individual building components. In Australia and California, a maximum permissible aggregate value is prescribed for windows. In most of the global/aggregate calculation methods, the area of window is considered in calculation procedures.

Most standards provide typical and worst-case values of various building components and constructions for reference, as well as solved examples for calculation methodologies.

2 Key outcomes

This section presents analyses from the review of standards, codes and rating systems. While the review is comprehensive, it is limited to the learnings from the referred standards, codes and rating systems. This section outlines the key passive measures applicable in the Indian Context, discussion on key thermal comfort indices and metrics, and, finally, the gaps and best practices in regulations for residential buildings.

2.1.1 Passive measures outlined by rating systems relevant to the Indian context

GRIHA and SVAGRIHA identify comprehensive list of passive design strategies and low-energy comfort systems, mapped to respective climate zones, that can potentially enhance thermal comfort.

Table 35 Passive design measures classified by applicability in India's 5 Climate Zones

Measures	Composite	Cold	Warm-Humid	Temperate	Hot - Dry
Building Orientation					
Buffer spaces on east & west facades					
Ventilators					
Earth berms					
Thermal Mass					
Cross Ventilation					
Green Roof / Terrace Gardens					
Cool Roofs, High-reflective paint surfaces					
Geothermal cooling/heating					
Solar Chimney/Wind Tower					
Courtyards					

Light colored external surfaces					
Passive Evaporative Cooling Structures					
Reduced solar access					
Cavity walls					
Roof insulation					
Light shelves					
Trombe Walls					
Solarium					
Heat capturing wall panels					
Sun spaces					
Solar wall					
Solar heat collector-based ventilation/ thermal system					
Direct solar gain in rooms					
In-direct solar gain					

2.1.2 Thermal comfort indices and metrics

The relevant standards and codes identify the comfort criteria, and the metrics enable quantification of comfort. This section outlines relevant indices and respective metrics that can be utilized to evaluate comfort. A summary of indices, metrics, comfort criteria and definitions has been outlined in Table 36.

Predicted Mean Vote (PMV)

The predicted mean vote (PMV) has been developed by Povl Ole Fanger. It combines the physics of heat transfer with an empirical fit to sensation. The PMV denotes a thermal strain based on steady-state heat transfer between the body and the environment and quantifies this strain as thermal vote (on a 7-point scale for ASHRAE Standard 55 and 5-point scale for ISO 7730). PMV is the most widely used Thermal Comfort Index, especially in Air-conditioned buildings, that establishes a link between sweating, vaso-constriction, vaso-dilation, and thermal comfort vote (*Predicted Mean Vote*, 2020; *Thermal Comfort Models*, n.d.). PMV uses six variables: metabolism, clothing, indoor air temperature, indoor mean radiant temperature, indoor air velocity and indoor air humidity. PMV method has been the basis of the ISO 7730 and ASHRAE 55 standards.

In the Indian context, field studies conducted by Manu *et al.* indicate that the PMV overestimates demand for cooling (Manu et al., 2016). Another study by Cheung *et al.* concludes that the accuracy of PMV reduces with deviation from neutral conditions(Cheung et al., 2019). Again, in context of India, where warmer temperatures prevail this is of significance. Finally, PMV is difficult to comprehend and therefore uses PPD to express comfort. While PPD supports comprehension, it does not distinguish between heating and cooling discomfort (Salimi et al., 2021).

ASHRAE defines exceedance hours as "the number of occupied hours within a defined time period in which the environmental conditions in an occupied space are outside of the comfort zone.". With respect to PMV, the exceedance hours are the sum of all the hours when the absolute value of PMV is greater than 0.5. Exceedance hours can also be expressed as a fraction of occupied hours in percent (Thermal Environmental Conditions for Human Occupancy, 2017). PMV limits across other standards have been outlined in Figure 4.

	Predicted Mean Vote																						
Standards	>-1.0	-1.0	-0.9	-0.8	-0.7	-0.6	-0.5	-0.4	-0.3	-0.2	-0.1	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	<1.0
GB/T 50785	3	2	2	2	2	2	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	3
ISO 17772, EN 16798		4	4	4	3	3	2	2	2	1	1	1	1	1	2	2	2	3	3	4	4	4	
ISO 7730					3	3	2	2	2	1	1	1	1	1	2	2	2	3	3				
ASHRAE 55							A	A	A	A	A	A	A	A	A	A	A						
Legend			A: Acceptable				1: Category I				2: Category II				3: Category III				4: Category IV				

Figure 4 PMV limits across Standards. Source: (Khovalyg et al., 2020)

Operative Temperature (OT)

ASHRAE defines Operative Temperature as *"the uniform temperature of an imaginary black enclosure, and the air within it, in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual nonuniform environment"*.

Subject to limitations, and in combination with humidity, ASHRAE Standard 55 uses the Operative temperature to demonstrate range of comfort with the Graphical Method. The graphical method is based on 10% dissatisfaction threshold derived from PMV-PPD index.

ASHRAE states that for an occupant-controlled naturally conditioned space, the exceedance hours are the sum of hours when the operative temperature falls outside of the lower and upper boundaries of the comfort zone defined by the adaptive comfort model. For typical applications, 80% acceptability limit is considered (ASHRAE Standard 55, 2017). Other adaptive comfort models in the National Building Code (2016) En 16798 also outline allowable Indoor Operative Temperature. Figure 5 includes information in Indoor operative Temperature limits from other standards and codes.

	Indoor Operative Temperature in °C (Naturally Ventilated Buildings)																								
Adaptive Comfort Models	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
GB/T 50785									A	A	A	A	A	A	A	A	A	A	A	A	A				
ISO 17772, EN 16798	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A				
ISO 7730	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A							
ASHRAE 55 (80% Acceptability)	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
NBC 2016						A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Legend	A: Acceptable																								

Note:

1. Thresholds for both summer and winter season have been considered.

2. Thresholds for residential application used wherever applicable

3. Some values have been rounded up/down to nearest integer.

4. For ISO 17772, EN 16798 comfort range has been considered only till Category III.

5. Comfort range for NBC 2016 has been referenced from IMAC model for Naturally Ventilated Buildings (Manu et al., 2016).

Figure 5 Indoor operative temperature limits adapted from (Khovalyg et al., 2020)

Standard Effective Temperature (SET)

(Thermal Environmental Conditions for Human Occupancy, 2017)

The SET is a temperature metric that incorporates all 6 physical factors of thermal comfort. SET also incorporates physiological factors like skin temperature and skin wettedness. LEED uses SET to define 'Liveable temperatures' to demonstrate compliance with the Passive Survivability pilot credit. Liveable temperatures per the credit are between 12.2 °C (54 °F) and 30 °C (86 °F) For single and multi-family residential buildings during a one-week period occurring over the summertime peak, the building may not exceed 30 °C (86 °F) SET for more than 102 °C (216 °F) SET hours. During the wintertime peak, the building may not drop below 12.2 °C (54 °F) SET for more than 102 °C (216 °F) SET hours throughout a one-week period (Overbey, 2016).

Tropical Summer Index (TSI)

The Tropical Summer Index (TSI) is defined as the "temperature of calm air, at 50 percent relative humidity which imparts the same thermal sensation as the given environment". The TSI has been statistically determined for thermal sensation response of 24 students at the Central Building Research Institute, Roorkee in hot-dry and warm-humid conditions over 3 consecutive years. The TSI accounts for wet-bulb temperature, globe temperature and air speed. The environmental conditions within which TSI has been established account for a wide range of air velocity (0 - 2.5 m/s) (SP 41 (1987): Handbook on Functional Requirements of Buildings (Other than Industrial Buildings), 1987). This range of velocity can accommodate impact of ceiling fans. TSI (in °C) within 19 and 34 °C is considered within the comfortable range (National Building Code of India, 2016).

Table 36 Thermal comfort indices and applicable metrics

		Metrics		
Thermal Comfort Index	Units	Peak Exceedance	Exceedance Hours	Exceedance Degree Hours Criteria
PMV	unitless	Max/Min PMV of discomfort.	A PMV value outside of ±0.50 is considered uncomfortable. For 80% acceptability, this may be extended to ±0.84.	Not Applicable
Operative Temperature (OT) Indoor OT is an outcome of equation based adaptive comfort models in ASHRAE, EN and NBC	°C	Max and Min indoor OT recorded.	A value of indoor OT outside comfort band (established for each hour) is considered uncomfortable.	The deviation in Indoor OT for the respective exceedance hour cumulated over the period of a year.
Standard Effective Temperature (SET)	°C	Max and Min SET recorded.	A value of SET outside comfort band (established for each hour) is considered uncomfortable. SET Comfort band as/LEED ranges between 12.2 – 30 °C.	The deviation in SET for the respective exceedance hour cumulated over the period of a year.
Tropical Summer Index (TSI)	°C	Max and Min TSI recorded.	A value of TSI outside comfort band (established for each hour) is considered uncomfortable. TSI Comfort band as/NBC ranges between 19 – 34 °C.	The deviation in TSI for the respective exceedance hour cumulated over the period of a year.
Definitions				

<u>Peak Exceedance:</u> Peak discomfort experienced. Peak exceedance in context of indices outlined above can be expressed in PMV, PPD and temperature.
<u>Exceedance Hours:</u> Number of hours, the comfort criteria are **exceeded. Alternatively, the balance hours may be reported as Comfortable Hours. Exceedance Hours can be explained as percentage of total occupied hours.**
<u>Exceedance degree hours:</u> Severity of discomfort can be cumulated hourly over time. Exceedance degree hours is the summation of deviation from thresholds of comfort band at each occupied hour.

2.1.3 Best practices and gaps

This section presents the best practices and gaps from a review of building standards and codes across the globe.

From the extensive review conducted, there does not appear to be a precedent for a Thermal Comfort Design Standard. There are, however, several instances of standards or codes developed for improving energy performance of buildings. Therefore, most codes/standards stress on thermal performance of the envelope and natural ventilation for meeting comfort conditions. (Kontonasiou et al., 2015) While this research does not document, Thermal Comfort Design Standard, it does point to standards that are developed on the premise of achieving thermal comfort in buildings and consequently meeting energy efficiency goals. Best practices and gaps from standards across the world touch upon some of these aspects.

Best Practices

- Few building regulations across the reviewed states underline the co-benefits of thermal comfort. Denmark and Sweden are two states that acknowledge co-benefits of thermal comfort. The Brazilian Standard (ABNT NBR15220-3) for Thermal Performance is rooted in thermal comfort. The requirements of the standard are based on Bio-climatic zones. The requirements are derived from plotting the climate on psychrometric charts. These requirements are further translated into design guidelines.
  Figure 6 shows the adaptive bio-climatic chart for zone 8. Zone 8 can utilize design strategies outlined for K,J, I and F (see Table 37).

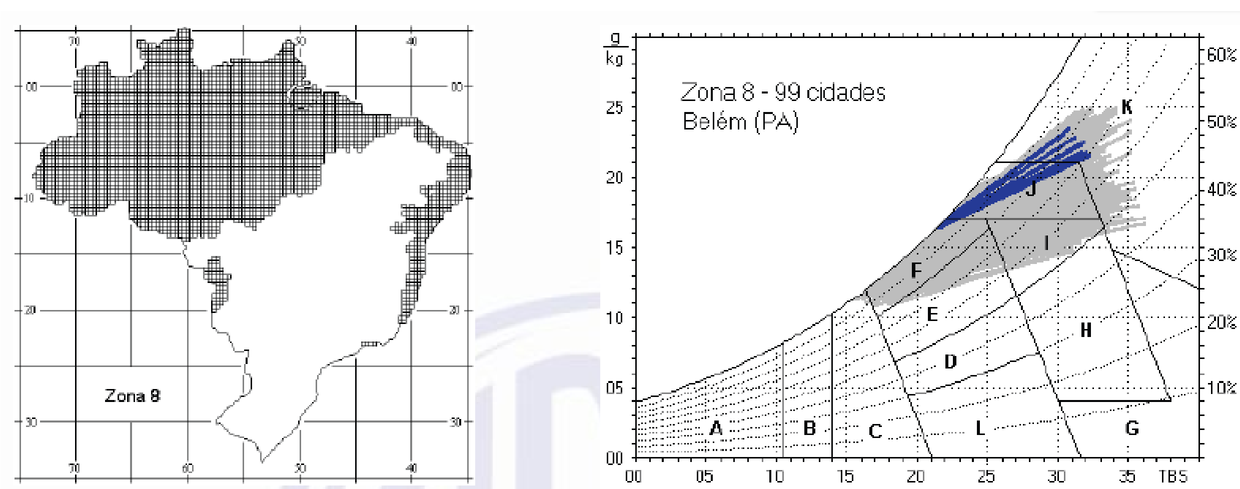

Figure 6 Zone map (Zone 8) and corresponding Adapted Bio-climatic chart.

Table 37 Design strategies for respective bio-climatic zones

Bio-climatic Zone	Strategy
A: Artificial heating zone (heating)	Artificial heating will be necessary to alleviate thermal discomfort from cold.
B: Building solar heating zone	The shape, orientation of the building, orientation and color of the surfaces, etc., should be optimized to maximize incidence of solar radiation to naturally heat during the cold period.
C: Thermal mass zone for heating	Heavy (mass) walls can help maintain the building's interior heated.
D: Thermal comfort zone (low humidity)	Characterizes thermal comfort zone (at low humidity).
E: Thermal comfort zone	Characterizes thermal comfort zone.
F: Dehumidification zone (air renewal)	Renewal of indoor air with outdoor air through ventilation can aid in dehumidifying internal environments and promoting thermal comfort.
G + H: Evaporative Cooling Zone	In hot and dry regions, evaporation of water can provide comfort during hot summer months. Use of vegetation and proximity to water sources can also provide effective cooling.
H + I: Thermal mass cooling zone	More pleasant indoor temperatures can also be achieved using thermal mass to store heat during the day and naturally reject it outdoors during night.
I + J: Ventilation zone	Mindfully integrating pre-dominant natural wind flow patterns in context with surroundings, placement of windows can aid in integrating cross ventilation.
K: Artificial Cooling Zone	Artificial cooling will be necessary to alleviate thermal discomfort from heat.
L: Air humidification zone	Characterized by low relative humidity and air temperatures in the range of 21°C to 30°C, humidifying strategies including vegetation are helpful in maintaining thermal comfort.

- Denmark has regulations for functional requirements and methods of specification, verification and monitoring of the thermal indoor climate. These are described in the DS 474 Danish Code for Indoor Thermal Climate, as well as in the International DS/EN ISO 7730.
- French Energy Code127 requires guaranteed comfort temperatures by use of heating or cooling systems. The code requires all accommodation within a residential building to be heated with provision for hot water, under the conditions laid down by the Construction Code, Article R 111-20.
- In Italy, control devices for indoor temperatures in single rooms or zones are mandatory in the case of new or modified thermal systems.
- Italy has regional and local regulations that outline minimum percentage of window surface for which shades have to be provided
- Swedish building code requires minimum guarantee of satisfactory thermal comfort.
- Regulations in UK differentiate between comfort requirements in sleeping and living rooms.
- EN 15251 recognizes the impact of humidity on comfort and provides recommended design criteria for humidity in occupied spaces ranging between 20 and 70%for each performance category (I to IV). Germany also recommends minimum and maximum indoor relative humidity ranges from 30 to 70%. Swedish and Polish codes also address humidity but from a health perspective.
- Germany has regulations that require the lessor to guarantee an indoor temperature of at least 19 ^{o}C in winter. There are no requirements for maintaining comfort in summer.
- EnEV in Germany requires space-by space computation of maximum solar gains.
- Finally, while most regulations are limited to thermal transmittance some codes look at thermal inertia of opaque elements as well. For example,

a. Italy utilizes periodic thermal transmittance (YIE) that accounts for thermal transmittance and decrement factor.
b. The Handbook of Functional Performance of Buildings in India specifies the Thermal Time Constant and Thermal Damping values in addition to thermal transmittance. Thermal time constant is representative of Time Lag and Thermal Damping is indicative of decrement factor.
c. SANS 204 for Energy efficiency in buildings South Africa utilizes a CR value to outline envelope performance. CR value is a product of thermal capacity of wall and its thermal resistance. CR value is expressed in hours.

Gaps

- As in the case of new buildings, compliance checks are only done on structural analysis and energy performance aspects, while no indoor air quality or thermal comfort verification procedures have been identified.
- Even though, increased thermal comfort is often the main driver for refurbishment in Europe, thermal comfort is rarely captured by national and/or European legislations.
- In Europe, passive systems to avoid overheating are common in southern climates, but minimum requirements are mainly limited to solar shades. Additional measures, such as the management of glazing areas of the building envelope, dynamic external shading, consideration of solar gains and the use of building mass, natural and night-time ventilation strategies, etc. are not governed by regulation.

3 References

ASHRAE Standard 55, Thermal Environmental Conditions for Human Occupancy 66 (2017).

Thermal environmental conditions for human occupancy, 7 ANSI/ASHRAE Standard - 55 14 (2017).

Brager, G., & Baker, L. (2009). Occupant satisfaction in mixed-mode buildings. *Building Research and Information*, *37*(4), 369–380. https://doi.org/10.1080/09613210902899785

Carlucci, S., Bai, L., de Dear, R., & Yang, L. (2018). Review of adaptive thermal comfort models in built environmental regulatory documents. *Building and Environment*, *137*, 73–89. https://doi.org/10.1016/j.buildenv.2018.03.053

Cheung, T., Schiavon, S., Parkinson, T., Li, P., & Brager, G. (2019). Analysis of the accuracy on PMV – PPD model using the ASHRAE Global Thermal Comfort Database II. *Building and Environment*, *153*(February), 205–217. https://doi.org/10.1016/j.buildenv.2019.01.055

de Dear, R., Brager, G., & Cooper, D. (1997). ASHRAE RP-884: Developing an adaptive model of thermal comfort and preference. *ASHRAE Transactions*, *March*, 1–18.

de Dear, R., Xiong, J., Kim, J., & Cao, B. (2020). A review of adaptive thermal comfort research since 1998. *Energy and Buildings*, *214*, 109893. https://doi.org/10.1016/j.enbuild.2020.109893

EN 15251, Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics (2007).

EN 16798-1, Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics (2019).

Ferrari, S., & Zanotto, V. (2012). Adaptive comfort: Analysis and application of the main indices. *Building and Environment*, *49*(1), 25–32. https://doi.org/10.1016/j.buildenv.2011.08.022

Jamaludin, N., Mohammed, N. I., Khamidi, M. F., & Wahab, S. N. A. (2015). Thermal Comfort of Residential Building in Malaysia at Different Micro-climates. *Procedia - Social and Behavioral Sciences*, *170*, 613–623. https://doi.org/10.1016/j.sbspro.2015.01.063

Kazanci, O. B., Coakley, D., Olesen, B. W., Kazanci, O. B., & Olesen, B. W. (2019, June). *A Review of Adaptive Thermal Comfort Implementation in International Thermal Comfort Standards*. https://orbit.dtu.dk/en/publications/a-review-of-adaptive-thermal-comfort-implementation-in-internatio/fingerprints/

Khovalyg, D., Kazanci, O. B., Halvorsen, H., Gundlach, I., Bahnfleth, W. P., Toftum, J., & Olesen, B. W. (2020). Critical review of standards for indoor thermal environment and air quality. *Energy and Buildings*, *213*, 109819. https://doi.org/10.1016/j.enbuild.2020.109819

Kontonasiou, E., Mariottini, F., & Atanasiu, B. (2015). Analysis of residential building regulations. In *Buildings Performance Institute Europe*.

Manu, S., Shukla, Y., Rawal, R., Thomas, L. E., & de Dear, R. (2016). Field studies of thermal comfort across multiple climate zones for the subcontinent: India Model for Adaptive Comfort (IMAC). *Building and Environment*, *98*(January), 55–70. https://doi.org/10.1016/j.buildenv.2015.12.019

McCartney, K. J., & Fergus Nicol, J. (2002). Developing an adaptive control algorithm for Europe. *Energy and Buildings*, *34*(6), 623–635. https://doi.org/10.1016/S0378-7788(02)00013-0

GB/T 50785, Evaluation standard for indoor thermal environment in civil buildings (2012).

National Building Code of India, Volume 2 (2016).

Nicol, F., & Humphreys, M. (2010). Derivation of the adaptive equations for thermal comfort in free-running buildings in European standard EN15251. *Building and Environment*, *45*(1), 11–17. https://doi.org/10.1016/j.buildenv.2008.12.013

Nicol, F., & Pagliano, L. (2007). Allowing for thermal comfort in free-running buildings in the new European Standard EN15251. *2nd PALENC Conference and 28th AIVC Conference on Building Low Energy Cooling and Advanced Ventilation Technologies in the 21st Century*, *2*(September), 708–711.

Overbey, D. (2016). *Standard Effective Temperature (SET) and Thermal Comfort*. Building Enclosure Online January 18, 2016. https://www.buildingenclosureonline.com/blogs/14-the-be-blog/post/85635-standard-effective-temperature-set-and-thermal-comfort

Predicted Mean Vote. (2020). Design Buildings, The Construction Wiki. https://www.designingbuildings.co.uk/wiki/Predicted_mean_vote

Salimi, S., Estrella Guillén, E., & Samuelson, H. (2021). Exceedance Degree-Hours: A new method for assessing long-term thermal conditions. *Indoor Air*, *31*(6), 2296–2311. https://doi.org/10.1111/ina.12855

Sansaniwal, S. K., Mathur, J., Garg, V., & Gupta, R. (2020). Review of studies on thermal comfort in Indian residential buildings. *Science and Technology for the Built Environment*, *26*(6), 727–748. https://doi.org/10.1080/23744731.2020.1724734

SP 41 (1987): Handbook on Functional Requirements of Buildings (Other than Industrial Buildings), (1987).

SS 554, Code of practice for indoor air quality for air-conditioned buildings (2016).

Thermal comfort models. (n.d.). Energy Systems Research Unit (ESRU), University of Strathclyde. Retrieved January 5, 2022, from http://www.esru.strath.ac.uk/Reference/concepts/thermal_comfort.htm

Zhang, H., Arens, E., & Pasut, W. (2011). Air temperature thresholds for indoor comfort and perceived air quality. *Building Research and Information*, *39*(2), 134–144. https://doi.org/10.1080/09613218.2011.552703