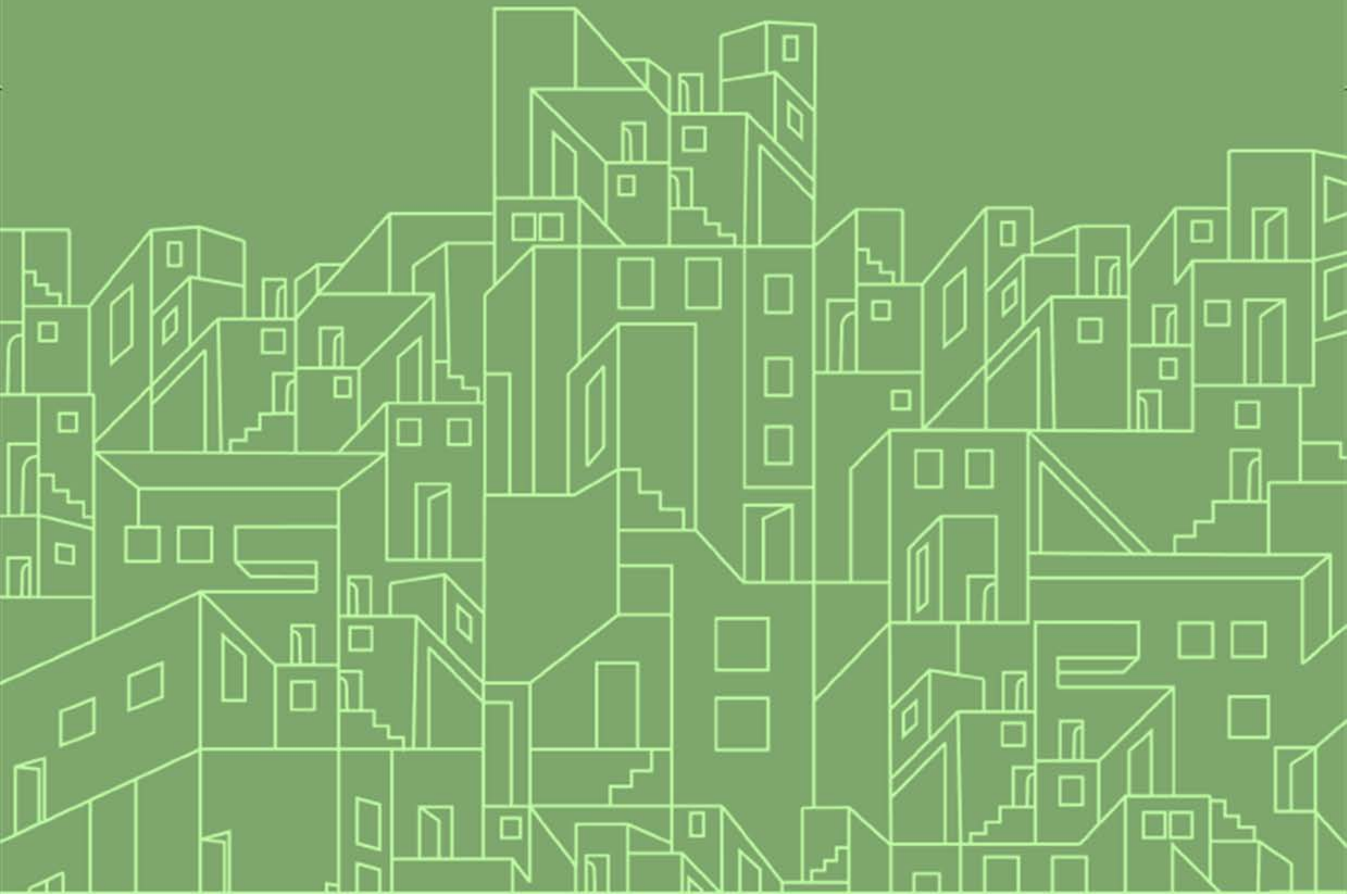
Innovative Construction Technologies & Thermal Comfort in Affordable Housing

HANDBOOK

July 2022



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RESILIENT, AFFORDABLE AND COMFORTABLE HOUSING THROUGH NATIONAL ACTION

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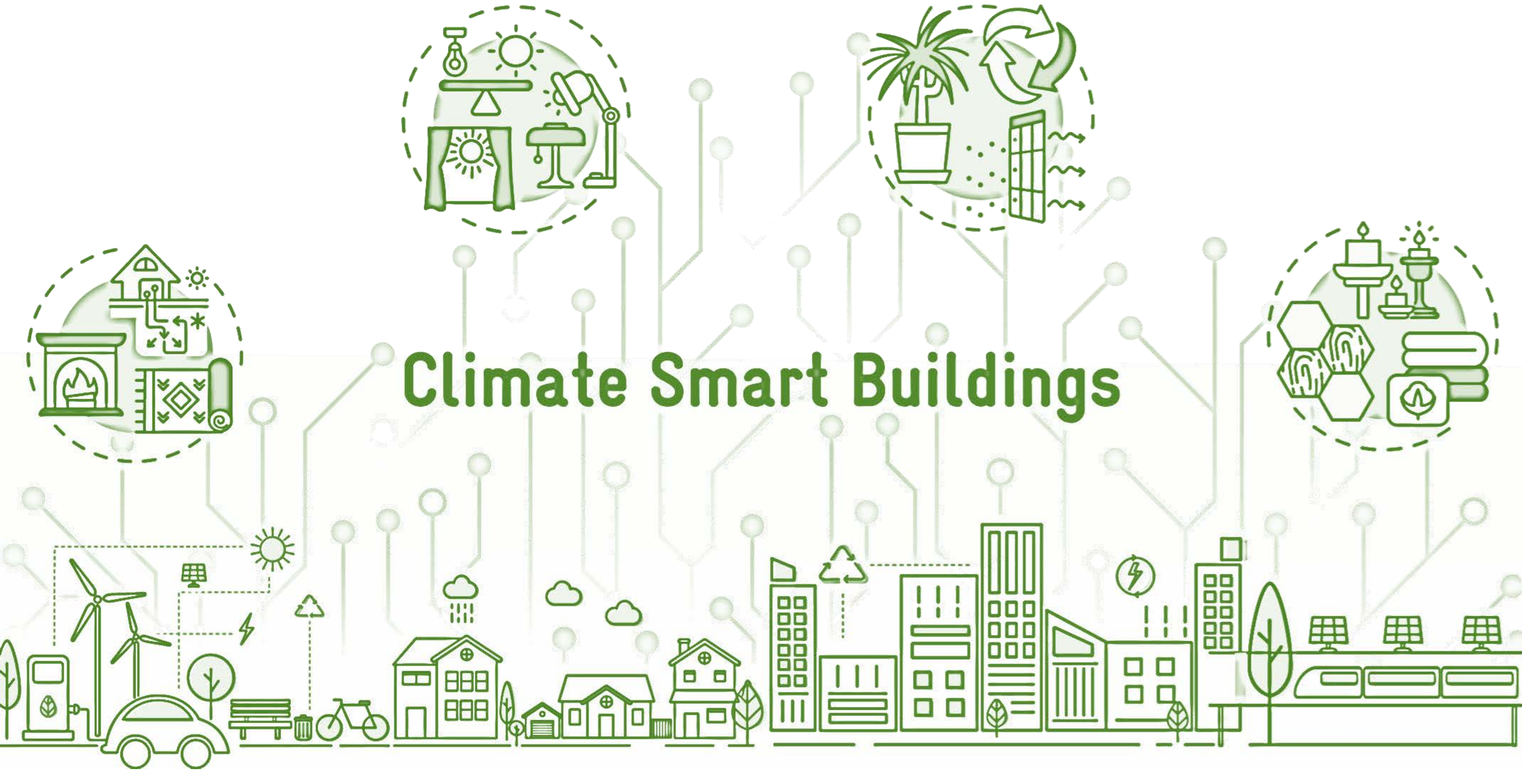

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Message

The reality of the increasing frequency and magnitude of climatic extremes necessitates a global concern. India, owing to its unique climatic forcing, is presently experiencing the reality of climatic extremes through an increased incidence of heatwaves. The high temperatures are often accompanied by unhealthy outdoor air quality and reduced access to electricity during peak demand hours. The studies on urban growth indicate an increase in the national urban population from ~380 million (in 2011) to ~600 million (in 2031). Consequently, the projections highlight a ~700% increase in residential energy consumption on a comparable timescale.

The challenge of protecting the population from the climatic extremes, while ensuring their well-being, and financial independence, can be helped resolved by providing access to thermally comfortable, low-energy, and cost-effective buildings. Providing such buildings coincides with the national visions of "housing for all", and "thermal comfort for all"; it also lies in line with the United Nation's Sustainable Development Goals 7, 9, 11, and 13.

Under the Indo-German technical cooperation, the Federal Republic of Germany and the Government of the Republic of India have been working towards the "Indo-German Energy Programme" (IGEN). The IGEN extends technical assistance and cooperation to the Climate Smart Buildings (CSB) programme, in line with the national visions and international goals.

I am pleased to highlight the preparation and delivery of training under Resilient, Affordable, and Comfortable Housing Through National Action (RACHNA) and this handbook on "Innovative Construction Technologies & Thermal Comfort in Affordable Housing". The handbook introduces the aspects of thermal comfort through a quantified understanding of the underlying physical phenomenon and practical interventions for thermal comfort and energy efficiency at low or no cost. This will add to the high-level understanding of the senior government officials at the levels of the urban local body level, state level, and central level and develop capacities for practitioners to develop and construct buildings that provide enhanced thermal comfort. These training programs and the resources materials, developed as a part of RACHNA, are also available through an online learning platform in the form of e-modules, offering a self-paced learning experience.

Indo-German collaboration for sustainable development in the building sector has tread a significant mile since 1988 when the Indian climatic zones for the first time were introduced by the Indo-German Cooperation in Scientific Research and Technological Development. Through these training programs and the development of this handbook, it is aimed to bring the knowledge on climate smart building designs for thermal comfort in affordable housing accessible to the masses and lead to sustainable development in India.

Dr. Winfried Damm

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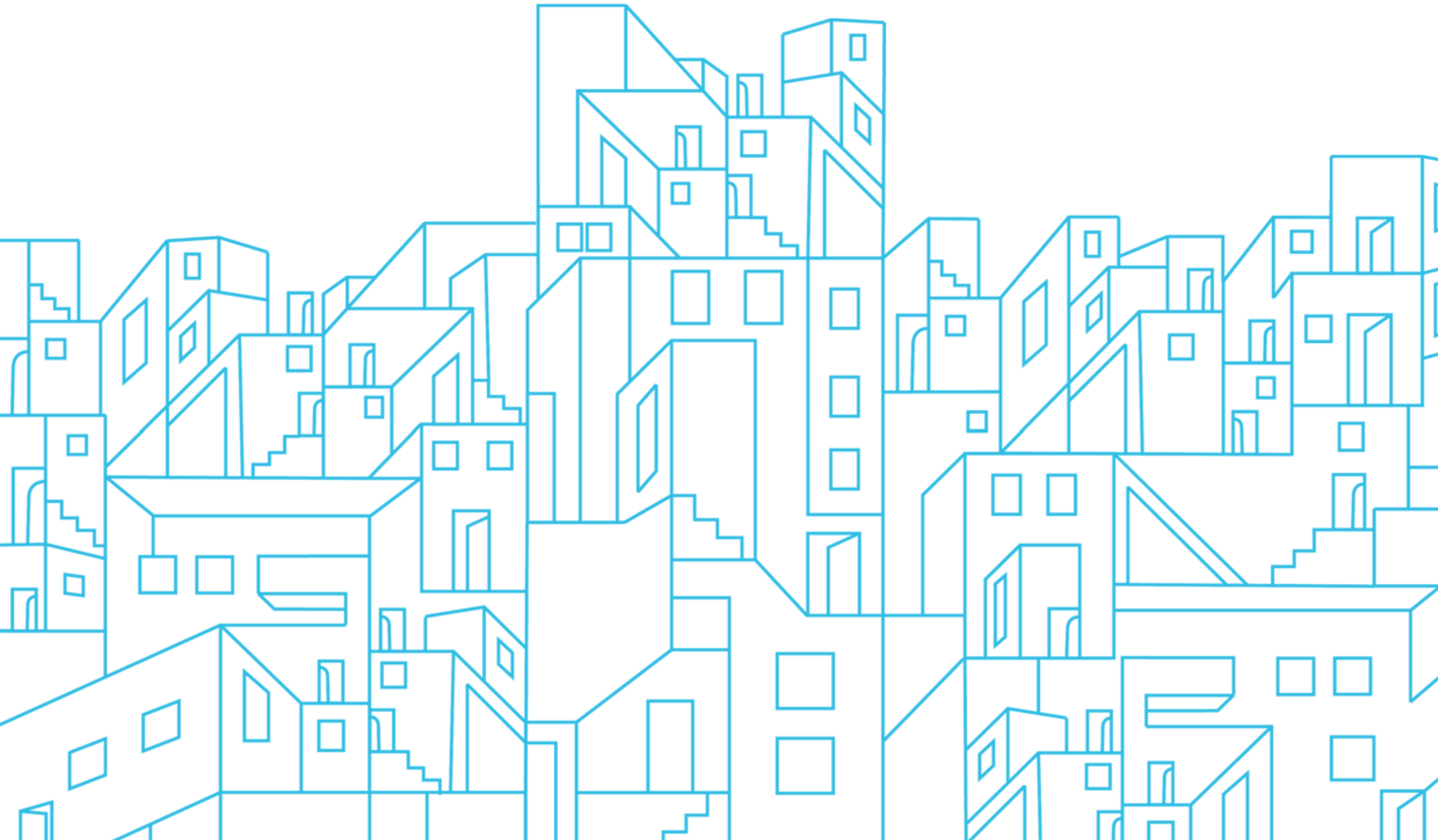
IMPORTANCE OF THERMAL COMFORT



1.1 Introduction

This chapter introduces the thermoregulation mechanisms of the human body to throw light on the concept of thermal comfort, thermal discomfort, and thermal stress. The narrative proceeds to scale up from thermal comfort at an individual level to an entire population. The interplay between provision of thermal comfort at the larger scale and multiple systems such as national economy, global climate change phenomenon, and approaching energy crisis are also presented in this chapter. Further, the chapter acquaints the readers with the provisions for thermal comfort in national codes of India. Finally, addressing the building scale, the chapter describes factors that affect thermal comfort of humans in indoor spaces.

1.1.1 Endothermic human body

Humans are a part of animal kingdom; based on the regulation mechanism for body temperature, the vertebrates of animal kingdom are further classified into endotherms and ectotherms. Endothermic animals, like mammals and birds generate heat within their bodies to sustain life. Opposite to that, ectotherms depend on external conditions for regulation of their internal temperatures.

Taxonomically, humans or homo sapiens belong to the primate order of the Mammalia class, making them an endothermic species. When the food consumed by endotherms is broken down to generate chemical energy for survival, heat is released as a by-product as shown in Figure 1. The generated metabolic heat maintains a constant core body temperature for survival. This thermoregulatory mechanism makes endotherms capable of existing in a wide range of outdoor temperatures. In case of humans, the core body temperature lies in a narrow range around 37° C (ASHRAE, 2021). To maintain the body core temperature during varying external temperatures, the human body is constantly acclimatizing itself to its external environmental conditions through exchange of heat between the body and surrounding environment. This exchange is facilitated by the largest organ of the human body- the skin. The thermal receptors in the body sense the microscopic heat exchange making us feel hot or cold. The same is termed as thermal sensation of human body.

While the core body temperature is required to be maintained for survival, the skin surface temperatures vary over different body parts. Normally, the skin surface

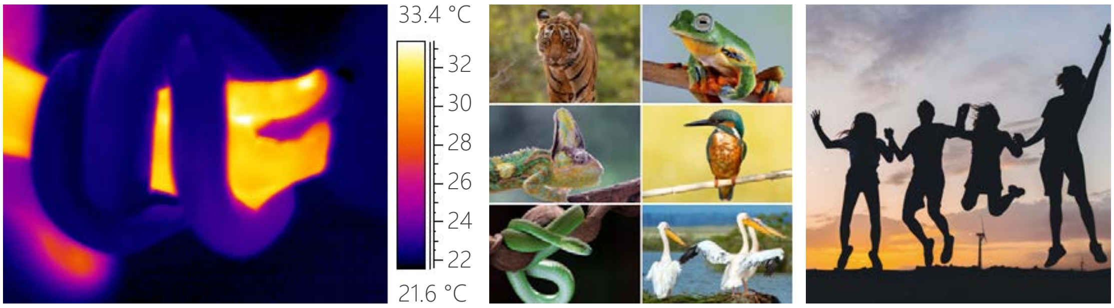


Figure 1: (Left)Thermal image of a snake wrapped on a human arm. (Right) Humans are a part of the animal kingdom

Source: https://en.wikipedia.org/wiki/Thermoregulation https://www.freepik.com/;https://www.freepik.com/free-photo/happy-friends-silhouettes-jumping-sunset_13870658.htm#query=youth&position=0&from_view=keyword

temperature of a human body is around 34°C. Both core body temperature and skin surface temperature are relevant in understanding thermal comfort.

1.1.2 Thermal range of human body

The heat generated from metabolism is distributed throughout the human body by blood. As a result, the core of human body houses maximum amount of heat due to concentration of blood vessels. As the blood flows away from the core, heat gets distributed. Hence, surface temperature of skin over a specific body part is a function of the temperature of the core and the distance of the skin surface from the core, as seen in Figure 2. Moreover, the skin surface temperature of the palms, feet and top of the skull at an ambient temperature of 20°C are lower than that at 30°C, but the core body temperature remains constant. It is noteworthy that the area of skin surface in direct contact with surrounding air and amount of heat present in the immediate air also determine the rate of local heat transfer.

In the absence of thermally comfortable environment, the human body may begin to experience elevated heart rates and loss of concentration. As shown in Figure 2, beyond this narrow range, medical conditions such as pyrexia and hypothermia may be induced (CIBSE, 2015). More severe effects of discomfort can result in thermal stress leading to sickness, vomiting and unconsciousness. Ultimately, it can result in sever cell damage and even death.

(ASHRAE, 2020) defines thermal comfort as "*that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation*." Minimizing the physiological efforts in maintaining the core temperature within desirable range contributes towards feeling thermally comfortable.

1.1.3 Maintaining thermal comfort

Variations in the indoor environment can be reduced through design and construction measures. Well planned residences account for the impacts of the outdoor climate on indoor environment through spatial design, thermal performance of construction materials, and building envelope design and performance. In addition, certain electrical/

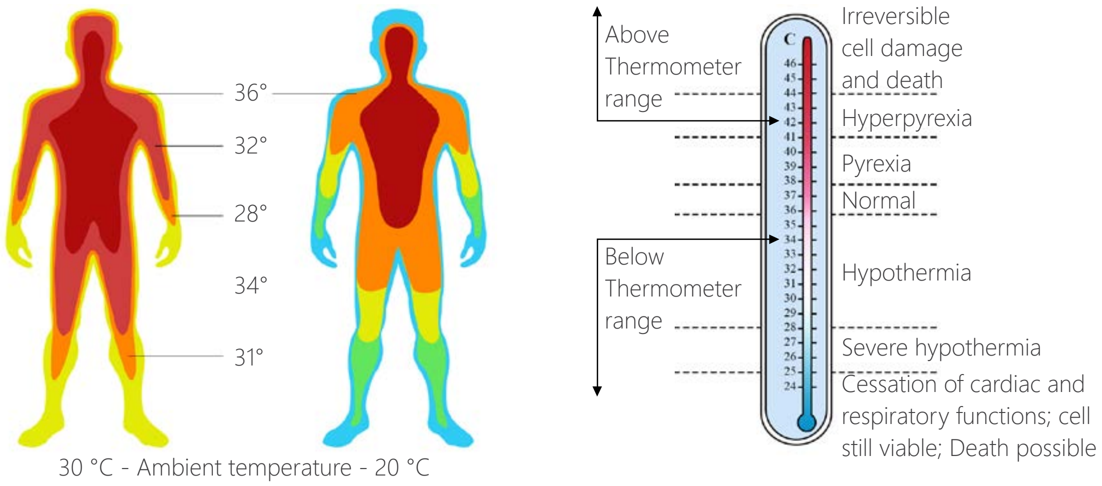


Figure 2: (Left) Skin surface temperatures of human body at various body parts in ambient temperature of 30°C vs 20°C; (Right) Comfort band of human body

Figure 3: Electro-mechanical ways to achieve thermal comfort.
Source: http://www.freepik.com;https://toppng.com/show_download/8026/electrical-ceiling-fa/larghttps://freepngig.com/png/50210-fan-heater-free-download-image

mechanical systems such as fans, humidifiers, air-conditioners, etc shown in Figure 3 can be used to further improve indoor thermal environment.

Conditioning indoor air through these systems affects the amount of heat and sometimes relative humidity in the space directly. Subsequently, it can help to alter the rate of heat transfer between human body and the surrounding environment in favour of the occupants' thermal comfort. Similarly change of air and managing velocity of air facilitates physiological responses such as sweating that aid rejection of heat from the body on hot days. The health implications of individual factors affecting thermal comfort have been widely discussed in literature (CIBSE, 2015).

Achieving thermally comfortable affordable housing requires an understanding of the thermal needs of the occupants. Various metrics such as degree discomfort hours and cooling demand, quantify the thermal needs of occupants and are available in literature. This cooling requirement must be viewed at the urban and national scale to understand their implications on energy generation and associated economic impacts. Moreover, the energy and climate consequences of providing thermal comfort accumulate to significance at such scaled up levels. Hence, it is essential to consider balancing the implementation of different measures undertaken towards thermal comfort provision in affordable housing.

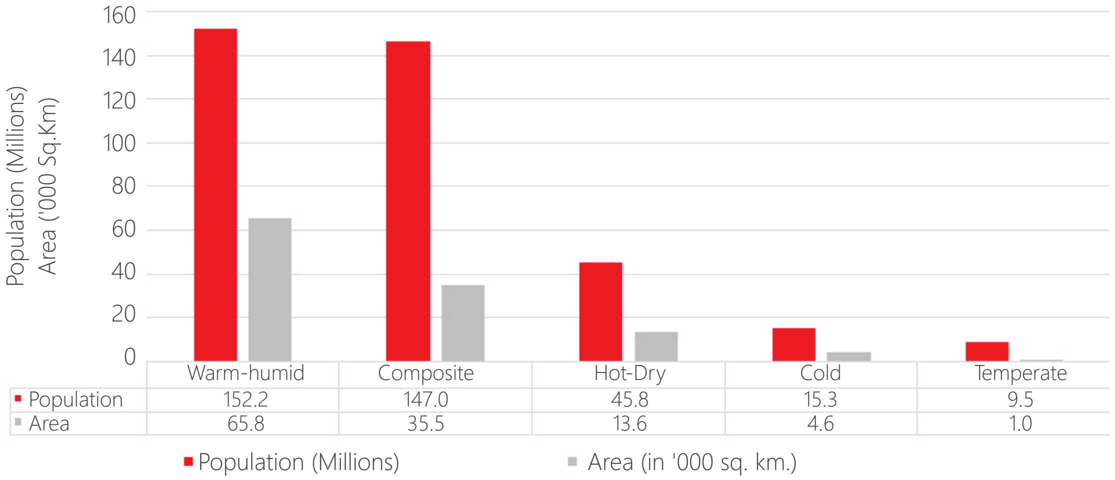
1.2 Thermal comfort and cooling demand

1.2.1 Cooling demand

As per 2011 census, majority of population in India lives in warm- humid and composite climates (GOI, n.d.). The graph in Figure 4 indicates that major metropolitan cities of India that house the urban population (which form 35% of the total Indian population) lie in warm - humid and composite climates. Residents of cities falling in these climate zones along with hot-dry climate experience high cooling degree days every year. The Figure 5 presents projections of growth in residential built-up area in both urban and rural India. The total increase in urban residential built-up area is estimated to be greater than threefold between 2020 and 2050. It is projected to rise from 5.9 billion sq. m. to 22.2 billion sq. m. over three decades (2020-2050). Moreover, the per capita residential built-up area in urban Indian cities will increase from 12.6 sq. m. to 24.2 sq. m. in the same time frame (MOEFCC, 2019).

As observed in Figure 5, nearly two-thirds of our urban building stock that will exist in 2050 is yet to be built. Hence, our new construction must account for not just present cooling requirements but also our future cooling requirements. For this to happen, it is critical to develop an understanding of how our cooling demand is evolving. The India Cooling Action Plan estimates an eight-fold increase in cooling demand from

2017-2018 to 2037- 2038. For buildings sector alone, this demand will swell up to 11 times from the baseline over a span of mere two decades (Figure 6). The increase reflects the soaring demand to cool the spaces in our residences, offices, and other buildings. Up to a 30% reduction is possible in the Total Primary Energy Supply (TPES) for India through the implementation of efficient design and technology that reduces the cooling demand. The India Cooling Action Plan sets the following goals to promote sustainable cooling and thermal comfort for all.



	Warm-humid	Composite	Hot-Dry	Cold	Temperate
▪ Population	152.2	147.0	45.8	15.3	9.5
▪ Area	65.8	35.5	13.6	4.6	1.0

Figure 4: Population and area distribution in the five climate zones of India.
Source: "Census 2011", Government of India, (2011), available at: http://www.censusindia.gov.in/2011census/dchb/DCHB.html

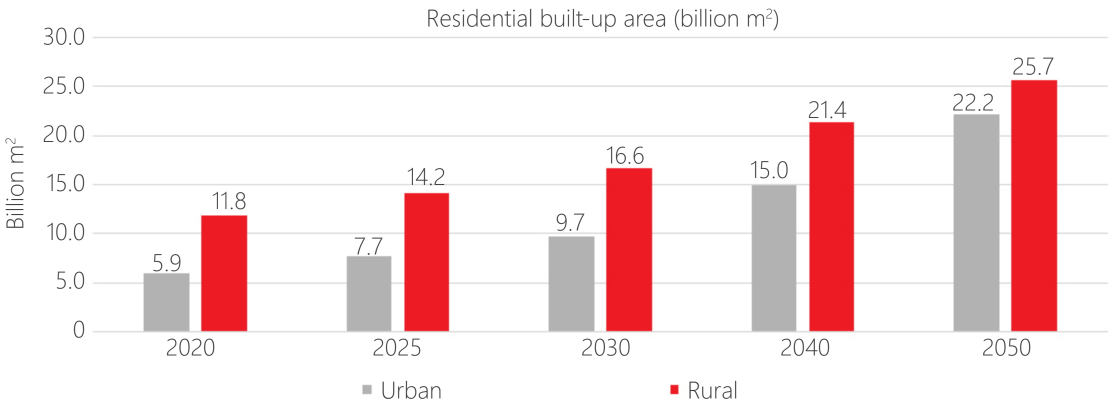


Figure 5: Projected increase in residential built-up area in urban and rural India.
Source: ICAP

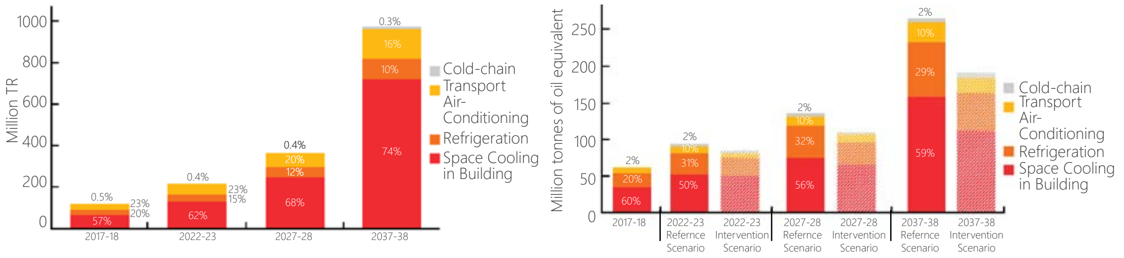


Figure 6: Above: Sector-wise growth in cooling demand; Below: India's Total Primary Energy Supply (TPES) for cooling.
Source: India Cooling Action Plan (redrawn)

1. 20-25% reduction of cooling demand across various sectors by 2037-2038
2. 25-40% reduction in cooling energy requirements by 2037-2038
3. 25-30% reduction in refrigerant demand by 2037-2038
4. Training and certification of 1,00,000 service technicians by 2022-2023
5. Recognizing “cooling and related areas” as a thrust area of research

Figure 7 presents a comparison between the cooling demand in cities of India and those in China and USA. As evident from the graph, major Indian cities have high population and cooling degree days. Therefore, their cooling demand to combat uncomfortable conditions is also high. When residential buildings are designed in a non-sustainable manner, the reliance on active cooling that uses devices such as air-conditioners increases to achieve thermal comfort. With rapid urbanization, rising temperatures due to urban heat island effect and surging disposable incomes, the household room air-conditioner penetration, observed to be 5% in 2011 in India is bound to increase (Sustainable and Smart Space Cooling Coalition, 2017). Increased room air-conditioner penetration further translates to higher peak demands and increased energy consumption for space cooling. The average daily load curves in major Indian cities such as Mumbai and Delhi (shown in Figure 8) suggest peak consumption at late night during summer. This is indicative of night-time cooling required in residences.

1.2.2 Energy demand of thermal comfort

The housing demand of the increasing city population will reverberate at the city level in the form of densification of built fabric. To accommodate the growing population, cities will have to increase the amount of liveable space resulting in greater number

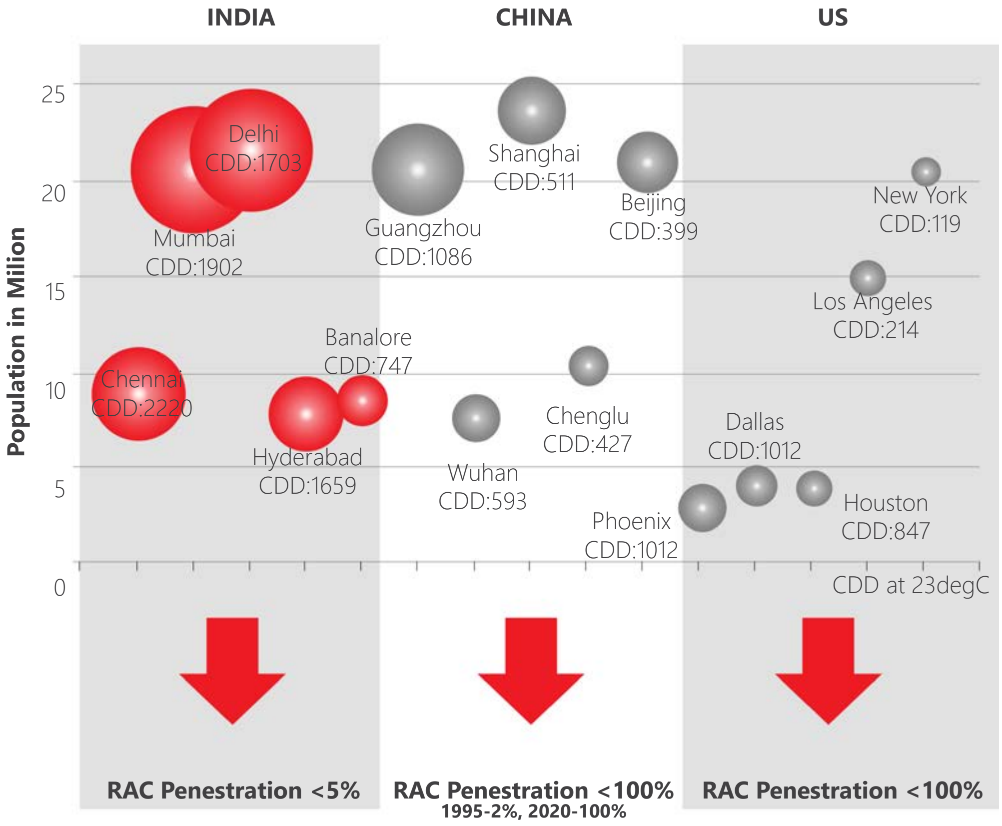


Figure 7: Cooling demand in India, China, and USA

Source: Sustainable and Smart Space Cooling Coalition (2017). Thermal Comfort for All - Sustainable and Smart Space Cooling. New Delhi: Alliance for an Energy Efficient Economy (Redrawn) of dense, high-rise apartments than ever before. The number of households in India are estimated to rise from 272 million in 2017 to 328 million by 2027 with additional 58 million households build up in the following decade leading to approximately 386 million by 2037(MOEFCC, 2019).

With surging disposable income and improved lifestyle expectations of the residents, the cities will experience higher thermal comfort demand. When viewed in the context of global temperature rise, it indicates increase in energy consumption for space cooling. The penetration of RACs in Indian households was found to be nearly 8% in 2017. The same is expected to climb to 21% by 2027-28 and 40% by 2037-38 (MOEFCC, 2019). As a result, cities will have to increase energy generation capacity and develop mechanisms to address peak load demands that will be higher than ever before.
Annual energy consumption and carbon emissions stemming from various ways of actively cooling spaces is shown in Figure 9. The chart indicates that in 2017, the greatest share comes from Room Air Conditioners (RAC)- 48.8 TWh out of 126 Twh (38%) of total annual energy consumption and 57.0 MTCO2e out of 124 MTCO2e (46%)

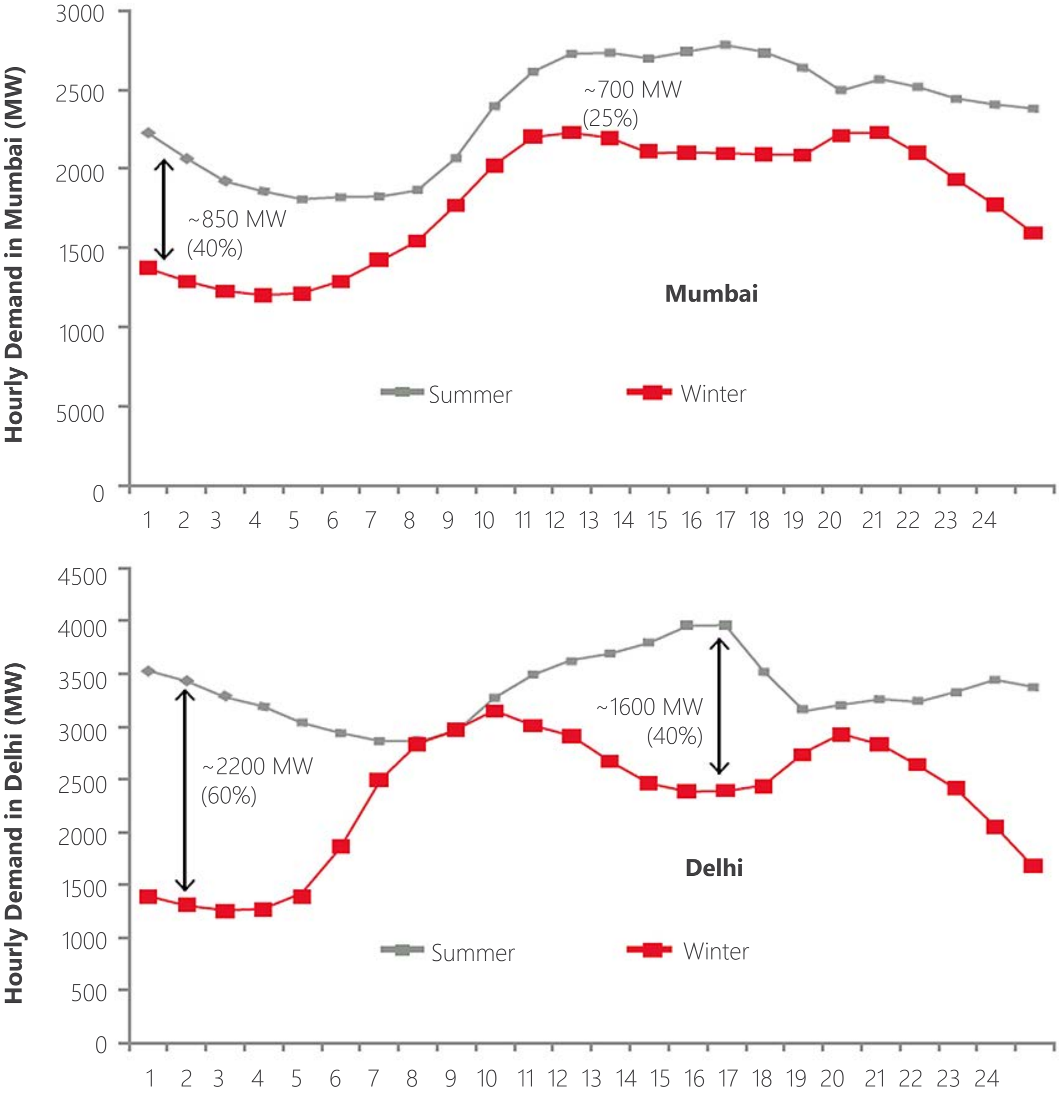


Figure 8: Average daily load curves in Mumbai and Delhi for summer v/s winter.
Source: LBNL (2014). Avoiding 100 New Power Plants by Increasing Efficiency of Room Air Conditioners in India: Opportunities and Challenges. [online] Available at: https://ies.lbl.gov/sites/default/files/lbnl-6674e.pdf

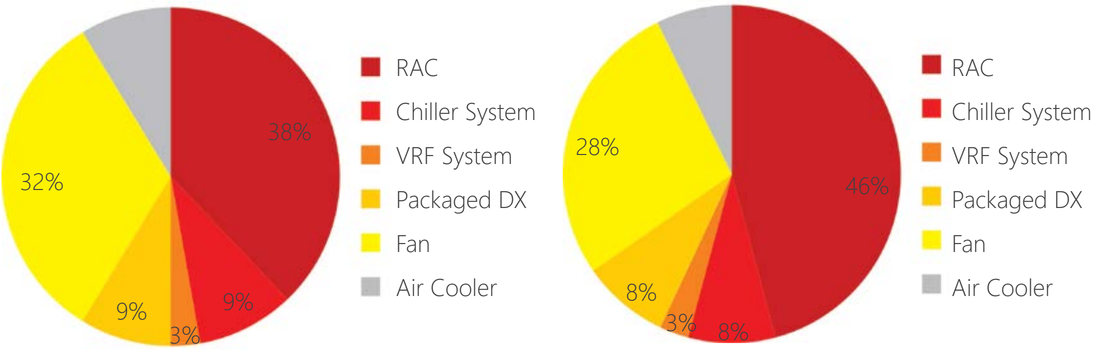
of total annual carbon emissions. Other common methods of active space cooling in residences include fans and air coolers (MOEFCC, 2019).

The heavy energy and climate implications of these electro-mechanical systems, found commonly in existing buildings must be mitigated while ensuring thermal comfort for all. This can be achieved by using innovative technological and design solutions.

1.2.3 Global scenario and environmental interactions

Another major contributor to globally increasing cooling demands and need for thermal comfort is climate change. One of the significant phenomena in global climate change is escalating global temperatures. The number of cooling degree days in a year are increasing tremendously due to two reasons- increasing global temperatures and increasing number of days with such high temperatures. Consequently, the heat stress generated in occupants is affecting productivity and therefore, overall economies of the countries. Figure 10 shows the percentage of world population that is at risk due to heat exposure. For example- in 2025, it is estimated that nearly 40% of the world population will be exposed to heat-related risks for more than 35days per year. It also shows estimations on how this value is expected to alter over the coming decades.

Climate change events are also responsible for economic losses to the countries. The United States of America has suffered losses of USD 3.45 trillion (measured in terms



2017 Annual Energy Consumption=126TWh **2017 Annual carbon Emission=124 mtCO2e**

Figure 9: Impact of need of Thermal Comfort: Consumption and Emission
Source: Ministry of Environment, Forest & Climate Change, Government of India. (2019, March). India Cooling Action Plan. Retrieved from http://ozonecell.nic.in/wp-content/uploads/2019/03/INDIA-COOLING-ACTION-PLAN-e-circulation-version080319.pdf

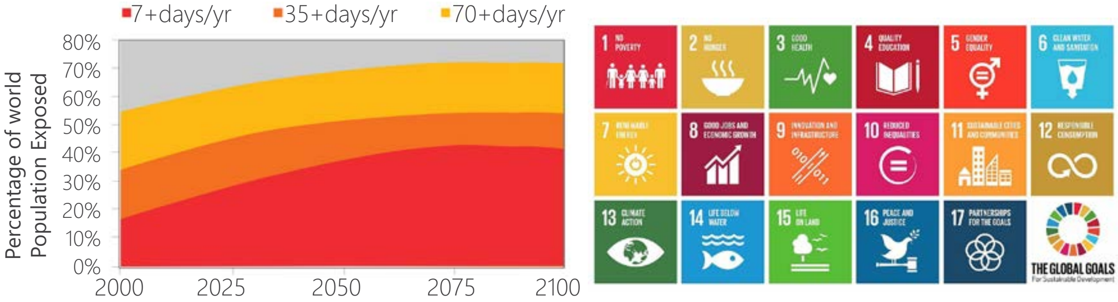


Figure 10: (Left) Percentage of world population exposed to heat risks in coming decades; (Right) UNSDGs
Source: Tord Kjellstrom, PhD, Mmeng. Impact of Climate Conditions on Occupational Health and Related Economic Losses. Asia-Pacific Journal of Public Health. January 2015. Climate Change and Labour: Impacts of Heat in the Workplace. International Labor Organization (ILO). April 2016

of Purchasing Power Parity). It is estimated that extreme heat events may cause up to two trillion dollars loss in labour productivity. India's economy itself, could suffer up to 450-billion-dollar loss (Kjellstrom, Maitre, Saget, Otto, & Karimova, 2019). Thermal comfort is increasingly becoming an important enabler of health, productivity, and prosperity. This is recognized by international agencies like the United Nations who have set Sustainable Development Goals (SDGs). Some of these related to thermal comfort and housing are enlisted below:

1. SDG 3: Health and Well Being
2. SDG 7: Ensure access to affordable, reliable, sustainable, and modern energy for all
3. SDG 9: Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation (industry focused)
4. SDG 11: Make cities and human settlements inclusive, safe, resilient, and sustainable (building focused)

Recently, the occurrence of heat waves across the globe has increased in frequency. In the year of 1999-2000 alone, heat waves have caused nearly 4,95,000 deaths globally. The temperatures during the heat wave of May 24-30, 2015, in India reached nearly 50 °C as shown in Figure 11.

It is essential to realize that the relevance of providing thermal comfort to building occupants is not limited to its energy and carbon implications but also extends to include the health of occupants in today's climate change scenario. The lifespan of

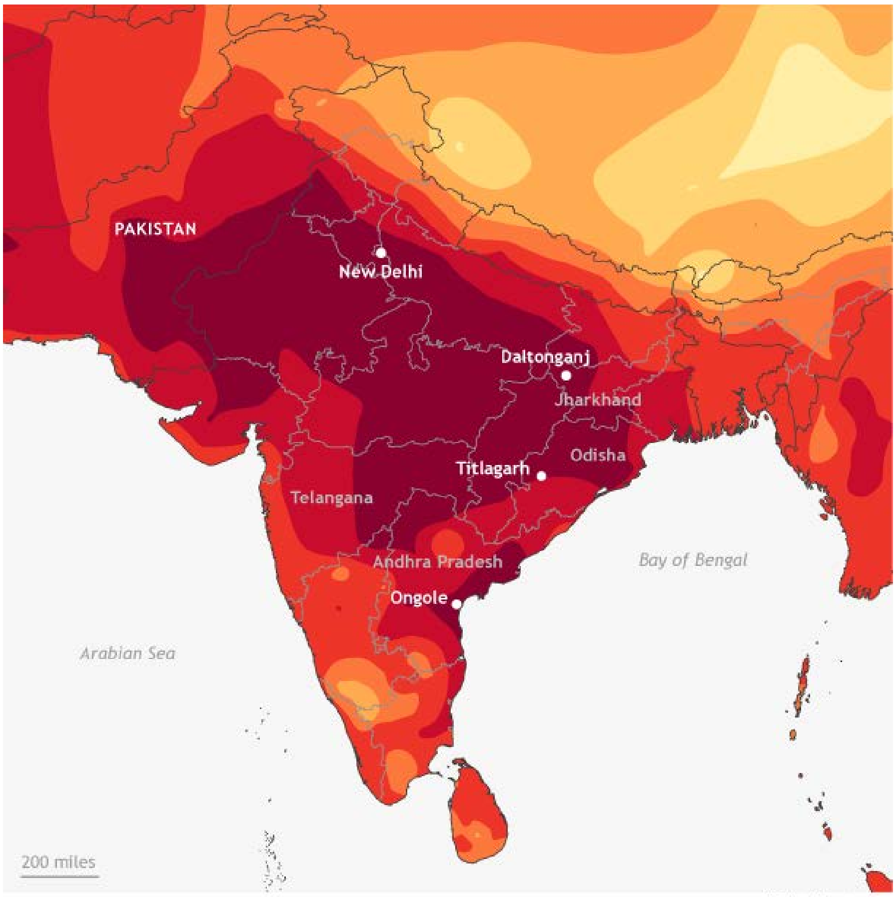


Figure 11: Heat stress due to changing global climate

Source: https://www.climate.gov/news-features/event-tracker/india-heat-wave-kills-thousands residences constructed in contemporary scenario is estimated to be nearly 60-80 years. This means that while the lighting systems can be upgraded every 2-5 years and electro-mechanical systems like HVAC can be modified after 7-12 years, the same does not apply to retrofitting the whole building or its envelope necessarily. Designing buildings with optimized envelopes provide the opportunity of coupling environmental protection and economic savings with thermal comfort for occupants.

1.3 Contemporary approaches

1.3.1 Cooling requirement in BAU vs deep-cut scenarios

Assuming thermal comfort provision for all at the national level, the space cooling requirement in urban residential buildings was estimated to be 896 TWh_{th}/year in 2020 in India. Here TWh_{th}/ year is a unit to measure the amount of thermal energy that must be removed from the building to maintain thermal comfort for occupants. The properties of building envelope influence the rate and extent of heat that can be removed from the buildings. The same demand races upwards of 2914 TWh_{th}/year by 2050 in Business-As-Usual (BAU) scenario. However, it is possible to redefine the curve of rising space cooling demand in urban residential India in a deep-cut scenarios to a 30% reduced value of 2006 TWh_{th}/year (Maithel, et al., June, 2020). Figure 12 illustrates the projected state-wise rise in urban residential space cooling energy requirement in 2050 under BAU and deep-cut scenarios. It is noteworthy that states experiencing a warm and humid climate depict higher cooling requirement than other climates.

The deep-cut scenario refers to a proposition of implementing aggressive measures such as improvements in building envelope technologies and cooling technologies to reduce the cooling demand. Target values for metrics like Residential Envelope Transmittance Value (RETV) of envelope and U-value of roof for both existing and new buildings are set for different time periods in the deep cut scenario. Similarly,

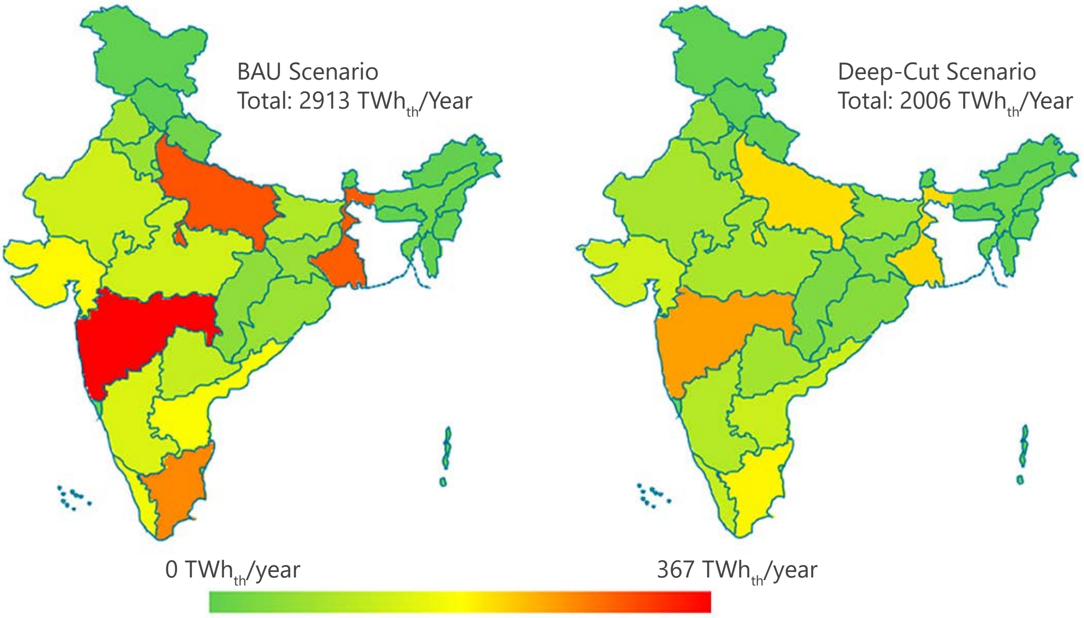


Figure 12: Urban residential space cooling energy requirement map of India, 2050
Source: Developing Cost-Effective And Low-Carbon Options To Meet India's Space Cooling Demand In Urban Residential Buildings Through 2050

improvements in $\text{CoP}_{\text{equivalent}}$ (indicates the cooling provided with respect to energy consumption) are considered for cooling technologies.

Additionally, the coupled effect of envelope and cooling technology related measures listed in the deep-cut scenario, can translate into a reduction of peak load demand for cooling. The amount energy generation required to meet the estimated peak load cooling demands in the year 2020 was 404 GW. The same is expected to inflate to 722 GW by 2050. However, in the deep-cut scenario, this inflation can be reduced by nearly 55% i.e., from 722 GW in BAU scenario to 330 GW.

Ramping up the energy generation capacity to meet the cooling demands and ensure thermal comfort for all has economic implications. Capital investment in the infrastructure of power or electricity generation becomes an urgent expense. Hence, the 391 GW of power generation which is avoided in deep-cut scenario is a crucial achievement. For the country's economy, it means that an investment of nearly INR 16,00,000 crore for energy production can be circumvented.

1.3.2 Impact of Building envelope

In India, buildings typically have a lifespan of 60-80 years. Within this lifespan, various systems may undergo improvements at varied rates. Hence, scope of reducing energy impact of the systems is limited until it is time to retrofit with more efficient alternatives. This is often referred to as the lock-in period for the system. Buildings may have lighting systems with a lock-in period of 2-5 years while the same for HVAC systems varies from 7- 12 years, considering both split and package systems. However, the envelope of a building undergoes retrofitting at much greater intervals. This translates into higher energy and environmental costs for decades if the envelope assembly is not developed to reduce cooling loads during the design phase of the project. Therefore, it becomes crucial to ensure optimized building envelope design before construction as it presents two-fold benefit-

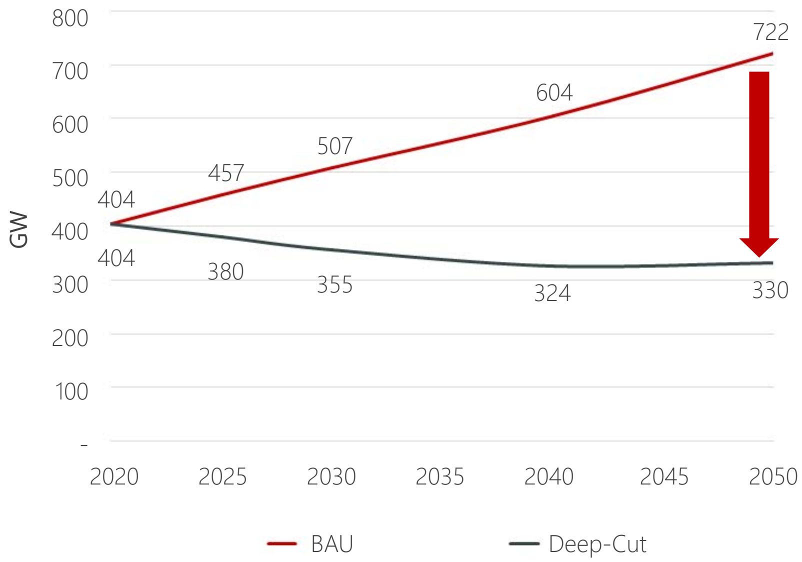


Figure 13: Peak Load for Cooling systems (GW)
Source: Developing Cost-Effective and Low-Carbon Options to Meet India's Space Cooling Demand In Urban Residential Buildings Through 2050

1. Reduces cooling loads on other building systems
2. Reduces associated economic impacts such as HVAC sizing, etc

Considering building envelope optimization as one of the most effective strategies for minimizing energy and cost footprints, the effect of the strategy on thermal comfort can be understood through various metrices. Optimizing building envelope as a standalone strategy with respect to its RETV value demonstrates opportunity to significantly reduce cooling demand by decreasing the discomfort degree hours (DDH).

DDH is a measure of the degree of heating or cooling needed to obtain thermally comfortable indoor environment. It accounts for the difference between outside dry bulb temperature and indoor base temperature (which is thermally comfortable) and the duration (measured in hours) for which the difference persists. Hence, it has a unit of °C.h.

Figure 15 shows that a reduction of around 40-50% in DDH is possible solely by designing envelopes with lower RETV value of 8 W/m2 as compared to the 18.5 W/m2 in BAU scenario in New Delhi and Mumbai. Figure 16 indicates that the investment required in construction industry to enable the use of optimized building envelope technologies in new and retrofit buildings until 2050 is nearly15-20 lakh crores. This investment can be re-rerouted from the potential savings from avoided power generation capacity.

1.3.3 Provisions in code

To achieve the needful reduction in cooling demand, national guidelines, codes, and tools have been developed for implementation. The Government of India launched Energy Conservation Building Code (ECBC) in 2007 to set the minimum energy performance for commercial buildings in India. The code was revised in 2017 to include incremental performance levels to encourage developers to not only meet the minimum mandatory requirements but exceed them as well. Similarly, the Eco-Niwas Samhita (Part-1) was launched in 2018 to include minimum performance requirements for residential building envelope. The Part-2 of residential building energy code- Eco

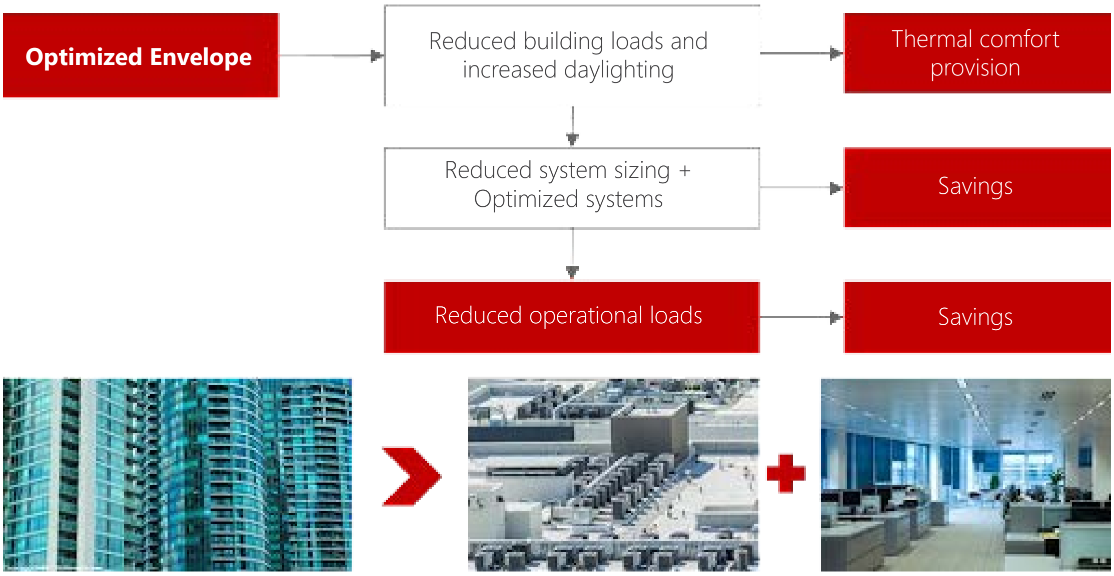


Figure 14: Reduced operational energy loads and economic benefits with thermal comfort provision from optimized building envelope

Niwas Samhita (ENS) has also been launched in 2021 along with a compliance tool to extend the inclusion of building systems in addition to envelopes. The codes contain provisions for achieving thermal comfort by optimizing the building envelope i.e. walls, fenestrations, and roof, as shown in Figure 17.

The ENS specifies a maximum value of thermal transmittance of the roof (U-value) as 1.2 W/ m^2.K for all climatic zones. Thermal transmittance or u-value (U-factor) is defined by the ECBC as the amount of heat transmitted in unit time through unit area of a material or construction and the boundary air films, induced by unit temperature difference between the environments on each side. Another metrics defined by the ENS to address heat transfer through building envelope (except roof) is the Residence Envelope Transmittance Value (RETV). RETV is the net heat gain rate (over the cooling period) through the building envelope (excluding roof) of the dwelling units divided by the area of the building envelope (excluding roof) of the dwelling units. The code specifies that envelopes of buildings constructed in four of the five climate zones in India must not exceed a RETV value of 15 W/m^2.

1.3.4 Heat Action Plans

The government agencies at various levels have established frameworks for actions to reduce the impact of extreme climate events and reinforce the safety of the residents. These measures are spread over multiple domains from healthcare to urban

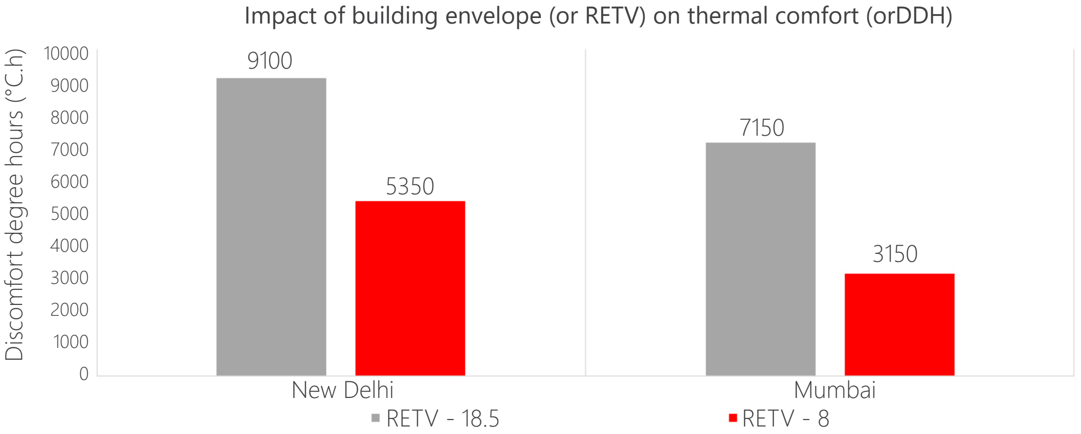


Figure 15: Impact of building envelope on discomfort degree hours.
Source: IETP: Developing Cost-Effective and Low Carbon Options to Meet India's cooling Demand in Urban Residential Building Through 2050

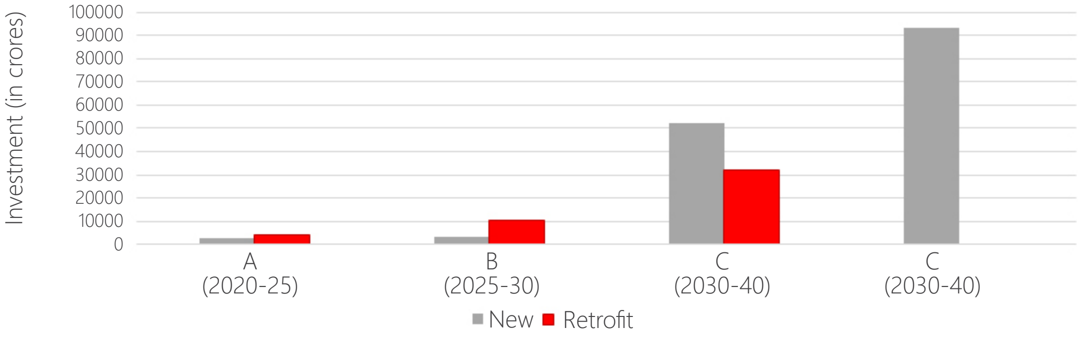


Figure 16: Additional Investment in Construction under Deep Cut Scenario – Envelope Technologies (New)
Source: IETP: Developing Cost-Effective and Low Carbon Options to Meet India's cooling Demand in Urban Residential Building Through 2050

Figure 17: ECO NIWAS Samhita: ECBC Residential
Sources: Bureau of Energy Efficiency, Government of India, & Ministry of Power. (2018). Eco-Niwas Samhita-Part I: Building Envelope. Retrieved from https://www.beeindia.gov.in/sites/default/files/ECBC_BOOK_Web.pdf

interventions and more. Some of the measure undertaken by Ahmedabad Municipal Corporation (AMC) and its partners to tackle heat waves - the most prominent extreme climate event for the city of Ahmedabad is:

- Issuing guide of measures towards 'extreme heat planning' for the city residents.
- These guides are used to educate the general masses about the frameworks in place for mitigating heat stress through public awareness and community outreach programs. Moreover, activities like engagement of social media, press, and interpersonal communication create further widespread awareness.
- The guide divides the year into three segments of 4 months each based on the amount of heat experienced annually in the city. Various measures have been listed for each phase of the year.
    a. *Phase I: Pre-heat season (January through March)*
    b. *Phase II: During the heat season (March through July)*
    c. *Phase III: Post heat season (July through September)*

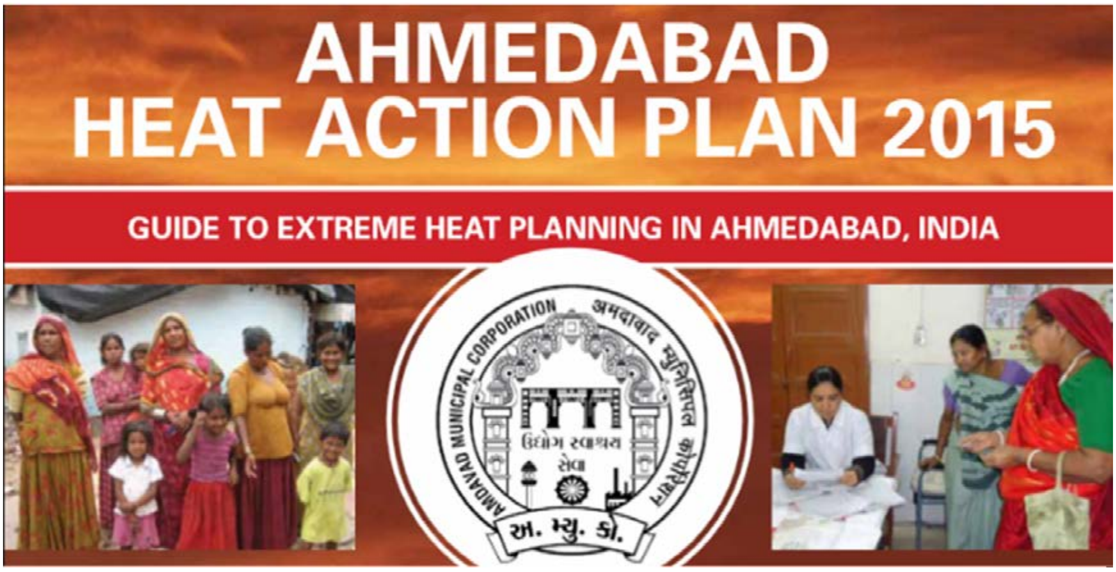

AHMEDABAD
HEAT ACTION PLAN 2015
GUIDE TO EXTREME HEAT PLANNING IN AHMEDABAD, INDIA

Figure 18: Heat Action Plan launched by the Ahmedabad Municipal Corporation (AMC) and its partners.
Source: https://www.climate.gov/news-features/event-tracker/india-heat-wave-kills-thousands

- Based on the forecasting by IMD, coordination between various stakeholders is established for creating readiness to tackle the heat stress. Health department, hospitals, disaster management agencies, and NGOs working for the same are alerted for the potential situation of heat wave. Figure 19 explains the designed procedure to activate various networks for managing operations during heatwave.
- Creating region specific city-wide alerts to prepare the population in advance of the likely event of heat wave. The urban authorities issue alerts and advisories of different severity for varied regions based on the temperature that the region is predicted to experience during the heat wave.
- In addition to issuing alert, the urban authorities also facilitate capacity building programs. These are held for the healthcare professionals to equip them with skills and tools required to prevent and manage the impacts of the event on the city population. Together, the urban authorities and healthcare workers aim to achieve

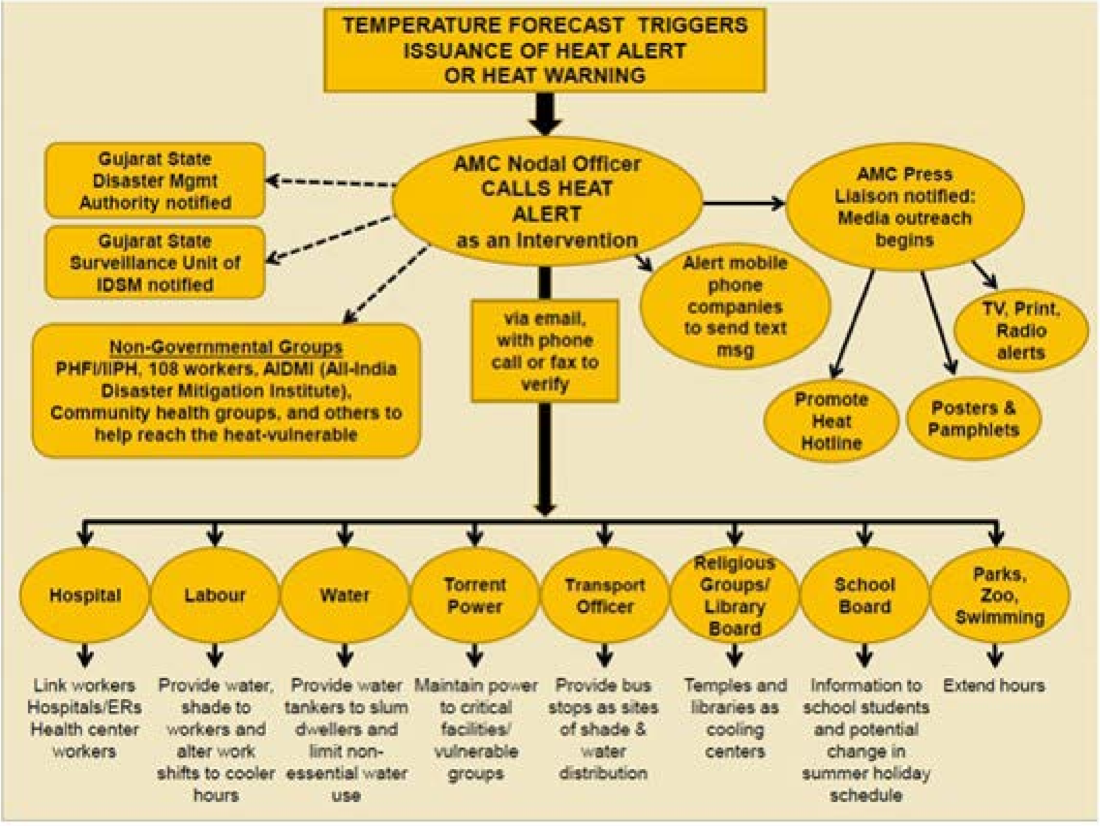
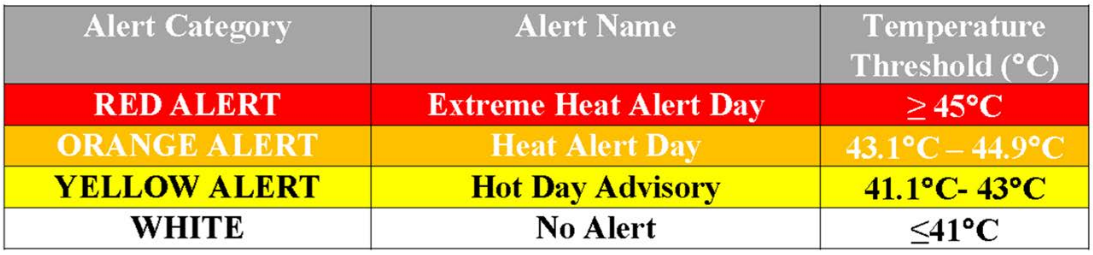


Figure 19: Workflow to alert residents and prepare for heatwave events triggered by climate change
Source: Ahmedabad Municipal Corporation. (2019). Ahmedabad Heat Action Plan. Retrieved from https://www.nrdc.org/sites/default/files/ahmedabad-heat-action-plan-2018.pdf



Alert Category	Alert Name	Temperature Threshold (°C)
RED ALERT	Extreme Heat Alert Day	≥ 45°C
ORANGE ALERT	Heat Alert Day	43.1°C – 44.9°C
YELLOW ALERT	Hot Day Advisory	41.1°C- 43°C
WHITE	No Alert	≤41°C

Figure 20: Alert warnings sent to educate residents on the nature and intensity of the expected heatwave
Source: Ahmedabad Municipal Corporation. (2019). Ahmedabad Heat Action Plan. Retrieved from https://www.nrdc.org/sites/default/files/ahmedabad-heat-action-plan-2018.pdf

low mortality rate due to heat stress and reduced morbidity levels that may make individuals prone to heat stress and its impacts.

1.4 Factors affecting thermal comfort

1.4.1 Categorization of factors

The thermal comfort of occupants is influenced by various parameters at play. Since thermal sensations arise from the interaction of human body with its immediate surrounding, the influences on thermal comfort are present either in the indoor environment or around/ within the body of the occupant present in the indoor space. Hence, the factors affecting thermal comfort can be mainly categorized into environmental and personal factors. These are explained in detail in sections 1.4.2 and 1.4.3. Apart from the personal and environmental factors, additional factors that affect thermal comfort are explained in section 1.4.4.

As mentioned previously in section 1.1.2, the skin surface temperature of human body is a function of its distance from the core. It is therefore not surprising that the skin surface temperature varies in outdoor conditions with different air temperatures. Figure 21 shows the different locations of the body for which skin surface temperatures in cold, neutral, and hot indoor environments have been indicated in Table 1.

Table 1: Skin surface temperature at various locations of the body in cold, neutral, and hot indoor environment.

Body Part	Skin Location	Cold (15 °C)	Neutral (27 °C)	Hot (47 °C)
A	Forehead	31.7	35.2	37
B	Back of Neck	31.2	35.1	36.1
C	Chest	30.1	34.4	35.8
D	Upper Back	30.7	34.4	36.3
E	Lower Back	29.2	33.7	36.6
F	Upper Abdomen	29	33.8	35.7
G	Lower Abdomen	29.2	34.8	36.2
H	Tricep	28	33.2	36.6
J	Forearm	26.9	34	37
L	Hand	23.7	33.8	36.7
M	Hip	26.5	32.2	36.8
N	Side thigh	27.3	33	36.5
O	Front thigh	29.4	33.7	36.7
P	Back thigh	25.5	32.2	36
Q	Calf	25.1	31.6	35.9
R	Foot	23.2	30.4	36.2

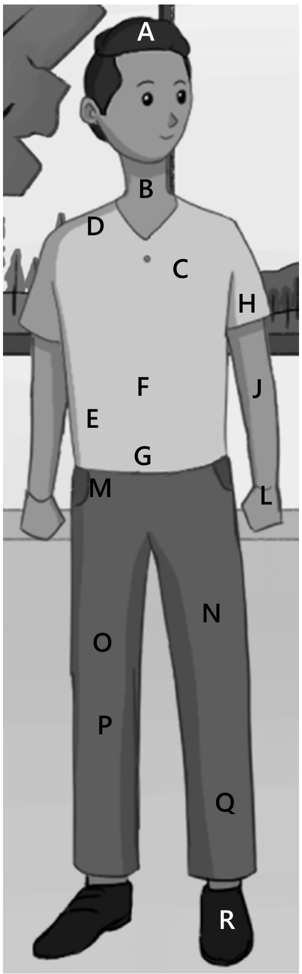


Figure 21: Skin surface temperatures location points

1.4.2 Environmental factors

The environmental parameters affecting thermal comfort of occupants are detailed in this section:

- **Air Temperature**: Air temperature, scientifically termed as dry-bulb temperature (DBT) is measured using a thermometer freely exposed to air but shielded from radiation and moisture. The value of DBT is usually expressed in Celsius. It is the average temperature of air surrounding the environment. It contributes to the understanding of the amount of heat present in the air around the occupant and hence influences the direction and rate of heat transfer between the individual and the environment. Comfortable air temperature is subjective to the amount of clothing (Clo value) and activity level (Met rate) of the occupant. The temperature of air can affect the rate of evaporation on skin surface and convective currents in the indoor environment.
- **Relative Humidity**: Relative Humidity is a term used to describe a percentage of the amount of water vapor present in the air to the maximum amount of water vapor that the air can hold at the specific temperature and pressure. Hence, the relative humidity is affected by the DBT and the pressure of the air. At higher relative humidity values, the amount of vapor in air is closer to the maximum value it can hold. This reduces the rate of heat transfer through evaporation from skin. Hence environments with higher relative humidity values feel hotter than those with lower values. Lower humidity levels facilitate sweating but can also cause dryness of skin, eyes, and throat.
- **Mean Radiant Temperature (MRT)**: The mean radiant temperature accounts for the radiant heat transferred from the surfaces of an enclosure to a point in space. It is dependent on the ability of a surface to emit the incident heat, also known as emissivity of the material. The MRT is defined as the uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body is equal to the radiant heat transfer in the actual non-uniform enclosure. It is calculated using globe temperature (T_g) measured using a globe thermometer and air temperature (T_a). The average of mean radiant and ambient air temperatures, weighted by their respective heat transfer coefficients is termed indoor operative temperature (ASHRAE, 2021).
- **Air Speed**: It is the average speed of the air surrounding an occupant, with respect to location, and time. More simply, the rate at which air moves through a point is known as the air speed. It is a scalar quantity measured in m/s. Since the speed of air changes constantly, it is averaged over time intervals between one to three

Figure 22: Factors affecting thermal comfort- Air Temperature (Tair) and Relative Humidity (RH)

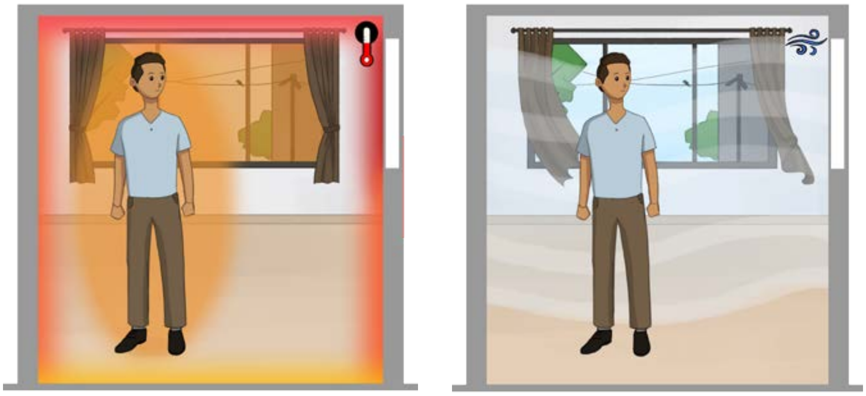


Figure 23: Factors affecting thermal comfort- Mean Radiant Temperature (MRT) and Air Speed

minutes. Moreover, it also varies for different heights of the occupant such as ankles, head, etc. Hence, for calculation air speed is also averaged over height at ankles, waist and head of the occupant which may be in standing or seating position.

The influence of air speed in thermal comfort is regardless of the direction of air flow. Moving air facilitates the evaporation of sweat from the skin surface, thereby contributing to thermal comfort.Elevated air speeds can be used to improve thermal comfort beyond the maximum limit of temperature established by codes and standards (ASHRAE, 2021)(Loveday, et al., 2016).

1.4.3 Personal factors

Certain personal factors also affect the sensation of thermal comfort. These are detailed

Figure 24: Factors affecting thermal comfort: Clothing Value (CLO)

as follows:

- **Clothing value**: The amount and type of clothing worn by an individual affects the transfer of heat from the skin to the surrounding environment. Clothing acts as a barrier or resistance to sensible heat transfer. The degree of resistance depends on material of the clothing and number of layers in the ensemble. The insulation provided by an individual garment includes effective resistance of the garment material and the thermal resistance of the air layer trapped between the garment and the skin (CIBSE, 2015). This factor is quantified by ASHRAE as ‘CLO’ level. Regional factors such as climatic condition of a location, social factors such as cultural attires induce variability in CLO levels of occupant throughout the world.
- **Metabolic rate**: The metabolic rate is the level of transformation of chemical energy into heat and mechanical work by metabolic activities within an organism. It is expressed in met units where 1 met = 58.2 W/m^2. The MET rates of various human activities shown in Figure 25 can be referred in (CIBSE, 2015) and (ASHRAE, 2021).

1.4.4 Other factors

Certain other activities and phenomenon also influence the thermal comfort of human bodies. These are listed below:

- **Short term physiological adjustment**: As the name suggests, these physiological adjustment measures are induced in the body when it experiences a larger change in environmental factors over an extremely short duration of time. An example would be when an individual reached home from their workplace on a hot summer evening in a city like Ahmedabad. Irrespective of the mode of transportation for the commute, the person’s body experiences some form of thermal comfort. They may attempt to counter the counter the discomfort by changing their clo value or reducing their metabolic rate by sitting down for some time. Hence, thermal comfort of an individual is affecting when they are required to undergo acclimatization over short durations of time.
- **Long term physiological adjustment**: These are induced when the body experiences a completely new climatic condition over prolonged periods. Usually, the body is adjusted to the seasonal variations of the regions they inhabit. When the place of habitation changes, the body takes time to adjust to the new weather conditions. An example of the same would be if a person relocates to a cold country like Canada in the winter months from a tropical country like India. In this case the body experiences much lower temperatures in Canada, than what it is used to in the

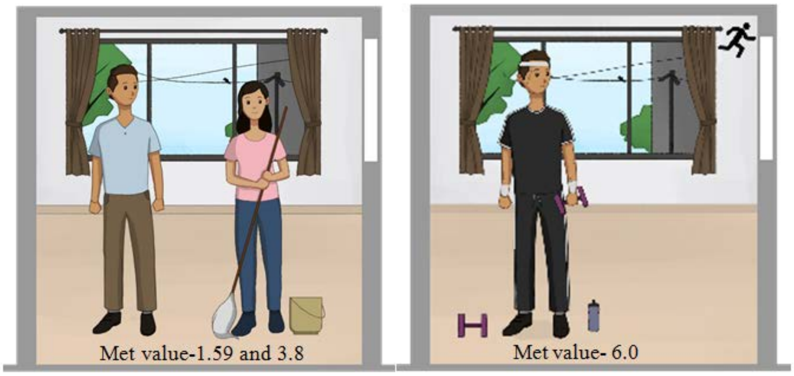


Figure 25: Factors affecting Thermal Comfort: Metabolic Rates (MET)

winter months of India. This will trigger physiological responses such as shivering. Hence, additional measures such as higher set points for indoor air temperature, higher clo. values are needed to boost the body's physiological responses in initial stage of acclimatization process. However, the body adjusts to the new climatic conditions and its seasonal variations over a longer time.

- **Body shape and fat**: It has been observed that the percentage of body fat and body muscle affect the thermal comfort of the individual. The amount of fat stored in a body can affect the rate at which body generates heat and the capability of the body to store or lose this heat through heat transfer at skin. It is likely that individuals with high mean body muscle to body fat ratio experience less thermal discomfort at lower temperatures than their counterparts (Tuomaala, Holopainen, Piira, & Airaksinen, 2013).
- **Age and gender**: The normal adaptive control of an elderly person may become less effective due to age. This may result from reduced thermal sensitivity of the ageing human body (CIBSE, 2015). Additionally, ageing also brings lower metabolism. Similarly, the thermoregulation mechanism of a new-born may not be fully developed. Hence age of the individual influences personal thermal comfort range. Climate chamber studies have established that women are more sensitive to temperature variations than men (Fanger, 1982). This may lead to females feeling colder and hotter earlier than men in the same thermal environment.
- **State of health**: The medical condition of a human body dictates the performance of the thermoregulation mechanism. Conditions such as obesity, dementia and others may affect the individual's thermal sensations and tolerance towards temperatures. The body's ability to generate physiological responses to achieve thermal comfort may be improved by maintain good health through exercise. Moreover, physically challenged individuals are more varied in their thermal responses than general population (Parsons K. C., 2002)

Figure 26: Other factors affecting Thermal Comfort Left: short term physiological adjustments; Right: Long term physiological adjustments

2

BUILDING PHYSICS AFFECTING THERMAL COMFORT

2.1 Introduction

Starting from factors influencing heat transfer, the chapter establishes the definitions of terminologies used in building physics. It proceeds to explain the phenomenon of heat transfer between buildings and their immediate surrounding and highlights the laws governing the science of heat transfer. Further, it describes the various ways in which heat is transferred through different elements of the skin of the building i.e., the building envelope. Lastly, the chapter describes how the amount of heat transferred inside a building is a function of the following:

- *building envelope characteristics*
- *operation patters of the openable elements of the building envelope*
- *climate of the place where building is situated.*

2.2 Factors Influencing Heat Transfer

Thermography images of buildings and human in different built environment show the amount of thermal energy on the surface of different building elements. Figure 28 shows that thermal energy is non-uniform in any indoor or outdoor spaces and amongst its occupants. This suggests that heat is constantly being exchanged between surfaces of various objects, occupants, and the indoor air. Just as heat transfer between human body and its surrounding air takes place at the surface of the skin, heat transfer in buildings happens at the building envelope. Factors such as window size, orientation of the façade, geometry of the building, internal volume and many others are responsible for the amount and nature of heat incident on the building envelope. Further, the choice of material used in envelope assembly and their thickness determine the amount of

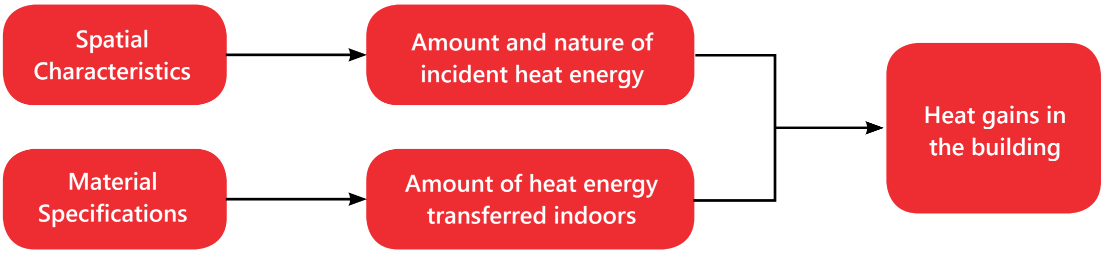


Figure 27: Role of spatial characteristics and building material in heat ingress

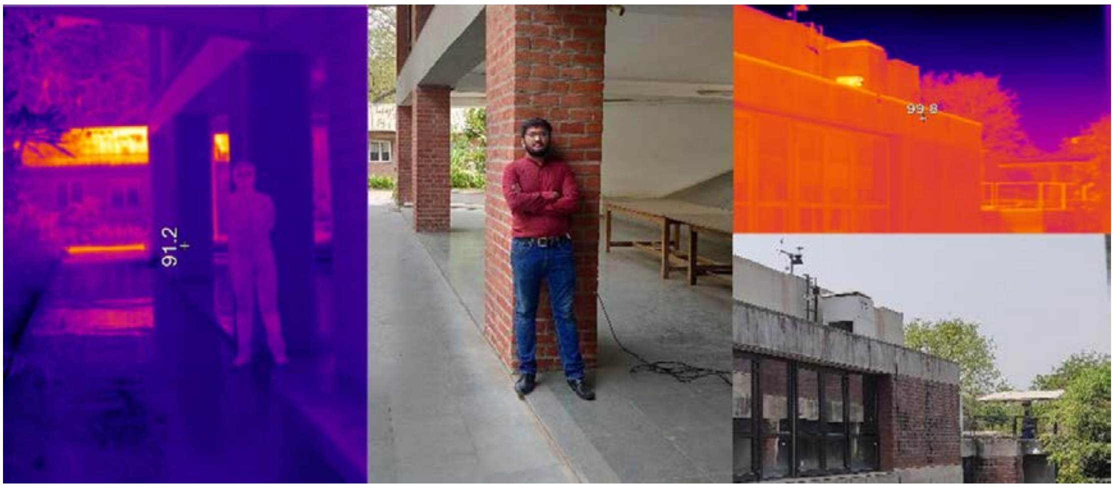


Figure 28: Thermal images of buildings and surroundings show presence of varying amount of heat energy at different surfaces suggesting constant heat transfer.

heat transferred indoors. For this reason, the energy demand of the occupants and thermal comfort in the spaces inside the building are highly influence by the spatial characteristics and material choices of a building.

2.3 Energy and Heat

To understand and design buildings that account for the thermal interactions, it is crucial to develop an understanding of thermal energy itself and its functioning mechanisms. Interaction of bodies with varying thermal energy in built environment system includes the forms of thermal energy, heat transfer mechanisms and governing laws and principles as well as the factors influencing the transfer.

Thermodynamically, a system is a region under study such as a room, a floor, or a building. The extent of the region is defined by a system boundary, and components outside of the same constitute the external environment. So, a thermodynamic system as a region in space or a quantity of matter bounded by a closed surface (ASHRAE, 2021). Exchange of mass and/or energy happens across this system boundary. A system is termed as open system when energy and mass both are exchanged between the system and its surroundings whereas a closed system is one that allows exchange of only energy and not mass. However, it is noteworthy that in both systems a real or imaginary, fixed or movable boundary must be established to distinguish between the system itself and its surrounding (ASHRAE, 2021) This boundary may be fixed or movable. In case of building taken as a system, the envelope is considered as the boundary to understand its thermal interactions with the external environment.

Energy of a system is its potential to do work. When a force ‘F’ moves a mass ‘m’ over a distance ‘x’, mechanical work ‘W’ is said to have been done as shown in Figure 30. A system expends its internal energy to do work on its surroundings. Similarly, when a system at a higher temperature loses heat (a form of energy) to its cooler surroundings, its internal energy also decreases. Thermal energy is caused by the motion of molecules and/ or intermolecular forces (ASHRAE, 2021).

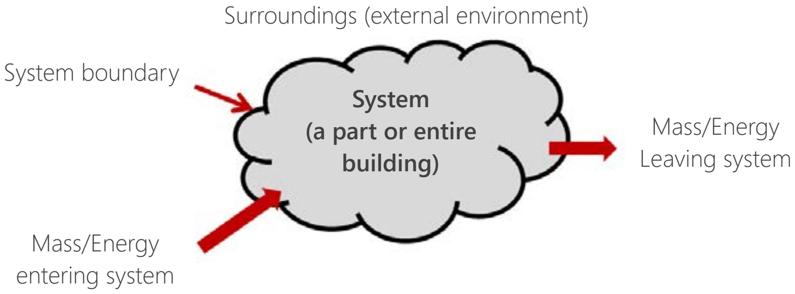


Figure 29: Energy and mass exchange between system and external environment across system boundary

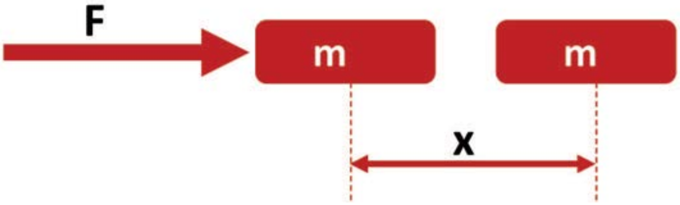


Figure 30: Work 'W' is done when Force 'F' moves a body of mass 'm' over distance 'x'.

At the macroscopic level, a system's energy can be categorized into kinetic and potential energy. On the other hand, microscopic energy of a system, also called its internal energy is the sum of all energy resulting from the arrangements, forces and movement of its molecules and/ or atoms. This includes:

a. Sensible energy: resulting from the translational, rotational, and vibrational movement of molecules/ atoms
b. Latent energy: energy gained or released to change phase
c. Chemical energy: resulting from atomic bonds
d. Atomic energy: resulting from bonds within the nucleus.

In the context of buildings, the term internal energy is restricted to sensible and latent energy as chemical and atomic energy are not applicable.

Heat is a form of energy that cannot be fully converted into useful work. This is because some part of it is always lost to the surroundings. For example, consider a system that uses heat energy to boil water. The system does work to raise the temperature of the water using this heat energy. However, some of this heat is always dissipated. Hence, 100% of the heat energy cannot be converted to useful work. This form of energy is classified as low-grade energy. In technical terms, the efficiency of converting heat energy into another form of energy or work is always less than 100%.

On the other hand, work can be fully converted into any form of energy. This is because work transfers energy through organized motion of particles.

2.4 Laws of Thermodynamics

Energy can be converted from one form to other and exchanged between two systems. However, such exchanges and conversions occur in accordance with the proven laws of thermodynamics.

The **first law of thermodynamics** quantifies the relationship between the internal energy of the system, work performed on or by the system and the heat added or

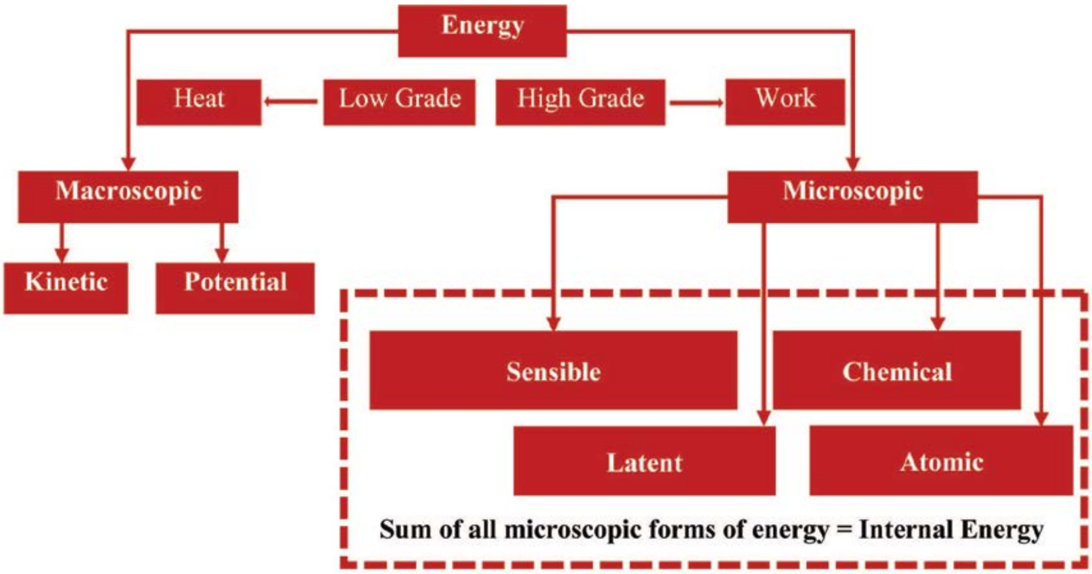


Figure 31: Forms of energy

removed from the system through the equation:

$$\Delta U = Q - W$$

Equation 1: First law of thermodynamics; equation for change in internal energy

Here ΔU is the change in internal energy of a system, Q stands for heat added to the system and W refers to the work done by the system. Famously known as the law of conservation of energy, it states that for an isolated system, the total energy of the system remains conserved. The change in internal energy of a system can be calculated by subtracting the work done by the system from the heat supplied to the system. If overall, the system gains heat or is subjected to work, its internal energy is said to have increased (its thermal energy increases). According to equation, ΔU will be positive. In case, the system loses heat, its internal energy will decrease, and the equation will yield a negative value of ΔU. The energy balance of any open or closed system can be given by:

$$\begin{aligned}&[\text{Net amount of energy added to the system}]\\ &\qquad = [\text{Net increase of stored energy in the system}]\end{aligned}$$

Source: ASHRAE Fundamentals

The **second law of thermodynamics** establishes the direction of heat flow in natural processes. Heat flows from objects that have higher heat energy, indicated by higher temperature to a body at lower temperature, naturally. Consider a glass of water at 40°C placed in a room with ambient air temperature at 20°C. According to first law of thermodynamics, heat exchange between glass of water and room will be such that their total thermal energy is conserved. However, the second law of thermodynamics establishes that the glass of water will lose heat to room till a point where their temperatures are close enough to reduce the rate of heat transfer to a negligible value. In order to reverse the direction of heat flow i.e. transfer heat from a colder body to a hotter body, sufficient amount of external work must be done on the system.

2.5 Modes of Heat Transfer

Heat flows from higher to lower temperature in three ways- conduction, convection, & radiation as illustrated in Figure 33.

Conduction - When the surface of bodies at different temperature, are in direct contact with each other, heat is transferred through conduction. An example of this can be a person standing on a cool floor. Here the heat is being transferred from the person's body to the floor through the feet (Sala, Gallo, & Sayigh , Elsevier, 1999). Since conductive heat transfer takes place between two surfaces with different temperatures, it is possible that the surfaces belong to the same solid object or different bodies. An example is when a metal rod is heated up at one end, the other end also begins to feel hot. This happens because the atoms at the first end transfer some of the heat energy obtained, to the atoms next to them . Further the hand holding the rod also receives

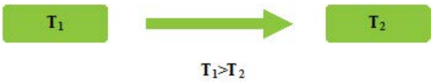


Figure 32: Second Law of Thermodynamics gives the direction of heat flow

heat through conduction. In buildings, heat transfer through conduction happens at windows, walls, and roof i.e., across the whole building envelope. This will be discussed in detail in Section 2.5.1.

Convection - Heat is transferred through convection in a system when a layer of fluid (liquid or gas) is present between two objects or surfaces at different temperatures in a system. In this method heat energy reaches from one point to the other through the motion of the fluid. For more details refer section 2.5.2.

Radiation - Radiative heat transfer happens through the electro-magnetic waves generated by the atoms or molecules of an object having heat energy. Unlike conduction and convection, heat transfer through radiation does not require a medium. Radiative heat transfer is explained in detail in section 2.5.3.

2.5.1 Conduction Principles

Heat Transfer through conduction happens across two surfaces that are in contact with each other. Conductive heat transfer happens at the molecular level through the motion of the molecules. Hence, for heat flow through conduction, the system must be stationary to maintain continuous contact.

In the context of buildings, the internal and external surfaces of the building envelope elements such as the external walls are at different temperatures. This is because the indoor environment is calibrated to maintain thermal comfort irrespective of the variable outdoor conditions. On a hot sunny day, the temperature of inside surface of the wall is much lower compared to the outside surface temperature. According to the second law of thermodynamics, heat will flow from the outer surface to inner surface

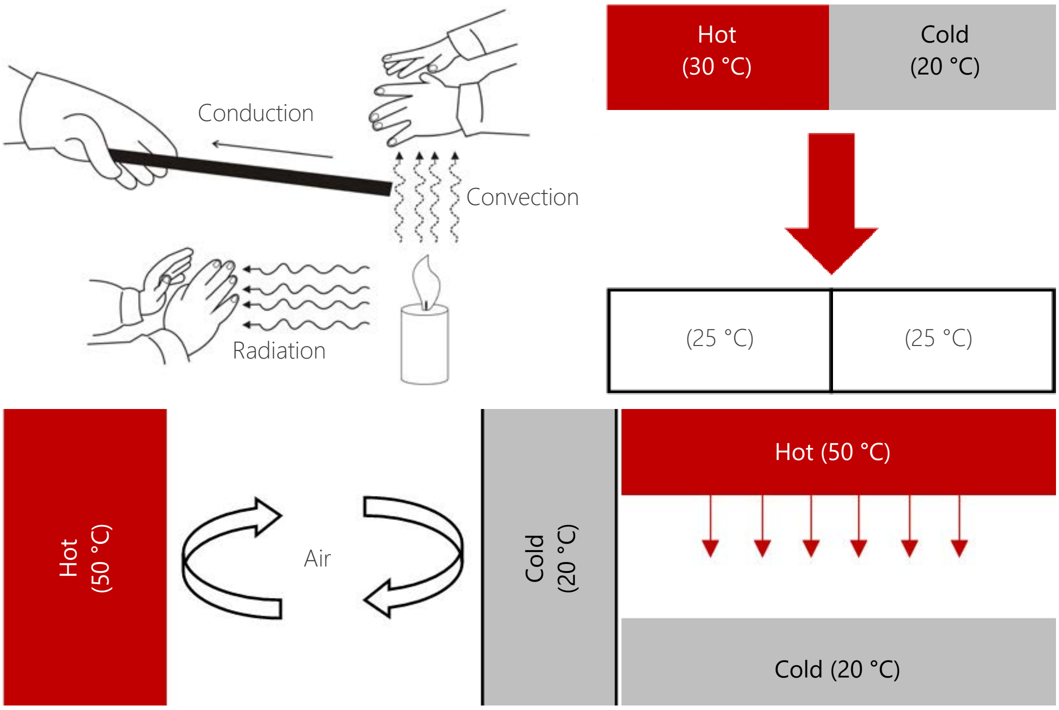


Figure 33: Clockwise- Forms of heat transfer; Conduction; Radiation; Convection
Source- https://thefactfactor.com/facts/pure_science/physics/conduction/9868/; Rawal, R., 2021. Heat Transfer and Your Building Envelope, Solar Decathlon India

through the thickness of the wall as shown in Figure 34.

To design thermally comfortable residential buildings, amount of heat transferred to the indoors must be estimated to decide appropriate heat gain reduction strategies. The quantification of conductive heat transfer begins with the assumption that the system is steady state. Consider a wall of thickness d, with surface temperatures of outside and inside wall as T1 and T2 respectively, such that T1> T2 as shown in Figure 33. Naturally, heat will flow from T1 to T2 according to second law of thermodynamics and attempt to bring the system to a state where T1 = T2. However, if T1 and T2 remain constant despite incident solar radiation, heat transfer and other phenomenon, the system is said to be in steady state. It means that the system is not accumulating heat over time. For a steady state system with heat transfer in only one dimensional, heat flow (Q) and heat flux (q) can be calculated by the following equations where k is the thermal conductivity of the material and A is the surface area of the objects in contact.

$$Q = k\,A\,\frac{T_1 - T_2}{d} \qquad \text{(S.I. Unit- watts)}$$

Equation 2: Heat Flow Rate (Q) formula

$$q = k\,\frac{T_1 - T_2}{d} \qquad \text{(S.I. Unit- watts per sq. m.)}$$

Equation 3: Heat Flux (q) formula

The thermal conductivity of a material is a measure of its ability to conduct heat. According to Equation 3, the heat flux (q) of a material is equal to thermal conductivity (k) for a unit temperature difference (T_1-T_2 = 1 Kelvin) over a unit distance (d = 1m). The thermal conductivity of a material is a function of temperature and moisture. With change in temperature and/ or humidity, materials allow heat to flow through their mass at different rates. However, for the normal range of temperatures experienced in a building, variations due to relative humidity can be considered negligible in the case of certain building materials such as steel, bricks, etc .

In addition to thermal conductivity, building materials also have a capacity to absorb some of the heat energy. The specific heat capacity of a material is defined as the quantity of heat (in Joules) that must be added to a unit mass (kg) of the material to raise its temperature by 1 K (or 1°C). The S.I. Unit of specific heat capacity is J/kg.K. It can also be expressed in MJ/m^3.K. The thermophysical properties like thermal conductivity, specific heat capacity and density of some common walling materials and surface finishes are listed in Table 2.

Thermal conductivity of walling material and thickness of the wall are important

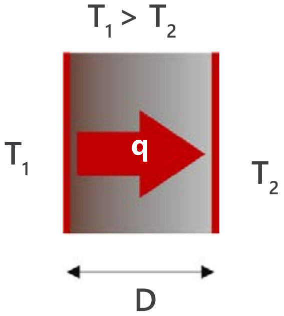


Figure 34: Conductive heat transfer through building wall

parameters to consider during the design of climate- responsive residential architecture. The conductive heat gains through the wall surfaces are highly influenced by the building material and construction methods.

The thermal performance of a stone wall is more appropriate in hot and dry climate to control the heat gain as compared to warm and humid climate. As can be seen from Table 2, the specific heat capacity of natural limestone is on the higher end of the range. This means that a stone wall can store more heat energy. The greater the amount of heat storage in the thermal mass of the wall, the lesser is the heat transferred to the indoors. Similarly, a stone wall of greater thickness will be able to transfer less heat than a stone wall of lesser thickness.

Another crucial aspect in managing conductive heat transfer through walls is the time taken by the wall to transfer the heat indoors. The outer surface of the wall begins to heat in the morning and reaches peak temperature by noon. However, a thick wall made of low thermal conductivity material will delay the transfer of heat indoors until a time when the outside temperature is already past its peak of the day. Now, the outside temperature is reducing while the indoor temperature is slowly gaining the delayed heat till the point in time when outdoor and indoor environment to reach the same temperature. This is followed by a reverse in the direction of heat transfer as soon as the indoor temperature tries to rise higher. This phenomenon of delay in heat transfer due to thermal properties of building materials is termed as thermal lag. Graph representing indoor air temperature for walls with high and low thermal mass

Table 2: Thermal conductivity, density and specific heat capacity of common building materials and surface finishes
Source: Thermo-Physical-Optical Property Database of Construction Materials, U.S.- India Joint Center for Building Energy Research and Development (CBERD) and Ministry of New and Renewable Energy (MNRE)

Materials	Density (kg/m³)	Thermal Conductivity (W/m.k)	Specific Heat Capacity (J/kg.K)
Walls			
Autoclaved Aerated Concrete Block (AAC)	642	0.184	0.794
Resource Efficient Bricks (REB)	1520	0.631	0.9951
Concrete block (25/50)	2427	1.396	0.4751
Concrete block (30/60)	2349	1.411	0.7013
Calcium Silicate Board	1016	0.281	0.8637
Cement Board	1340	0.438	0.8113
Sandstone	2530	3.009	1.5957
Stone (Jaisalmer Yellow)	3006	2.745	2.0954
Stone (Kota)	3102	3.023	2.0732
Bamboo	913	0.196	0.6351
Surface Finishes			
Plaster of Paris (POP) powder	1000	0.135	0.9536
Cement Plaster	278	1.208	0.9719
Plywood	697	0.221	0.7258

with respect to outdoor DBT is shown in Figure 35 .

In conclusion, considering the thermophysical properties of the walling materials in combination with possible thickness options during the design phase presents an opportunity to lower the dependence on electro-mechanical systems, thereby contributing to the goal of thermally comfortable affordable housing.

2.5.2 Convection Principles

Transfer of heat through convection depends upon the bulk movement of the medium- a fluid. Convective heat transfer is the transfer of heat energy by the convective currents formed in the bulk of the fluid when the heated fluid moves away from the source of the heat.

"For heat transfer to be considered convection fluid in contact with the surface must be in motion; if not, the mode of heat transfer is conduction. If fluid motion is caused by an external force (e.g., fan, pump, wind), it is forced convection. If fluid motion results from buoyant forces caused by the surface being warmer or cooler than the fluid, it is free (or natural) convection."(ASHRAE, 2021).

In buildings, convective heat transfer occurs in two ways. Firstly, the temperature of indoor wall surfaces is higher than that of the indoor air temperature. Hence, air moving in space near the walls, roofs and other surfaces will absorb the heat from these surfaces as shown in Figure 35. The equation governing the quantification of heat exchange is presented below.

$$Q = hA\Delta T \quad \text{S.I. Unit- Watts}$$

Equation 4: Convective heat transfer formula

Here Q (amount of heat transferred by convection) can be obtained as a product of A represents the surface area in consideration, ΔT that stands for temperature difference between surface and air near it at the specified location and h represents heat transfer coefficient. Heat transfer coefficient is a combination of convective heat transfer

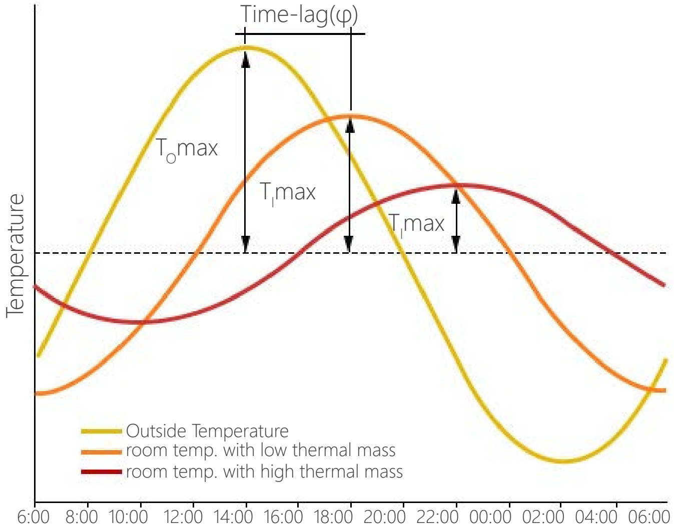


Figure 35: Thermal mass of a building affects increases the time taken by heat to flow from outside to inside
Source: European High Quality Low Energy Buildings (https://www.new-learn.info/packages/euleb/en/glossary/index6.html)

coefficient (h_c) and radiative heat transfer coefficient (h_r).

$$h=h_c+h_r$$

Equation 5: equation for heat transfer coefficient

Heat transfer by convection depends on the temperature difference between the surface and the air, the orientation of the surface, surface roughness or emittance, the air velocity, and the direction of heat flow. These parameters are characterised by a heat transfer coefficient (h_c). (CIBSE, 2015). The equations to derive heat transfer coefficient in common air conditions and occupant positions are presented in Table 4. Additionally, the values of hc in still air (velocity<0.1 m/s) with varying direction of flow are presented in Table 3.

The heat transfer coefficient (h) is calculated as inverse of resistance of thin film of air present adjacent to the wall or roof surfaces. (h = 1/Rs). Typical values of film resistance for inside and outside surfaces are presented in table 5. Surface film resistances indicate heat transfer from or to a surface by the effects of convection and radiation. Due to the presence of greater air movement outdoors, the mean surface film resistance values for exterior surfaces are lower than that of interior surfaces. Calculations for heat ingress estimations in indoor space through wall that address surface film resistance for convective and radiative heat transfer at outside and inside wall surfaces in addition to conductive heat gains through the wall are available in various literature resources (BEE, 2021).

Heat transfer coefficient is useful in understanding the impact of natural convective flow on the thermal environment of the space. Further, it is helpful in calibrating the desirable air velocity to maintain thermal comfort through forced ventilation. Forced ventilation is used in low energy cooling technologies such as night-time cooling through ventilation (refer chapter 9 for more details). Forced ventilation is the intentional movement of air into and out of a space using mechanical fans and other systems (ASHRAE, 2021).

2.5.3 Radiation Principles

Radiative heat transfer is the exchange of heat energy between two surfaces obeying the laws of electromagnetics. All matter emits thermal radiation at its surface when its temperature is above zero (i.e., it has some heat energy) in the form of photons of varying frequencies (ASHRAE, 2021). Since photons do not need a medium to travel, heat transfer through radiation can happen even in vacuum. The frequency of the

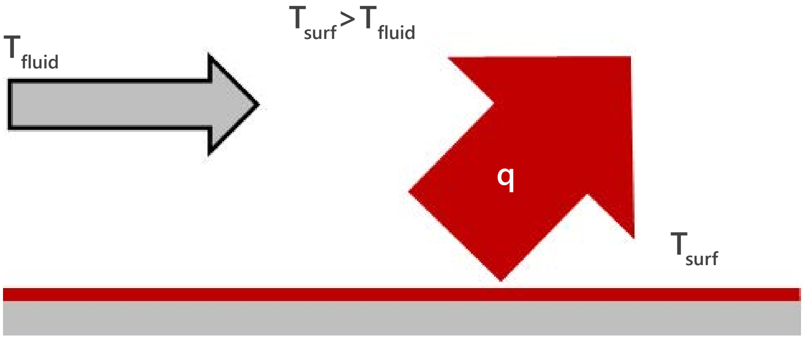


Figure 36: Convective heat transfer from inside surface of wall to the indoor air

Table 3: Convective heat transfer coefficient values for varying directions.
Source: (CIBSE, 2015).

Direction of heat flow	Convective heat transfer coefficient (h_c)
Horizontal	2.5
Upwards	5.0
Plaster (light weight)	0.7

Table 4: Equations from convective heat transfer coefficients
Source: (ASHRAE, 2021)

Equation	Limits	Condition	Remarks/Sources
$h_c = 8.3V^{0.6}$ $h_c = 3.1$	$0.2 < V < 4.0$ $0 < V < 0.2$	Seated with moving air	Mitchell (1974)
$h_c = 2.7 + 8.7V^{0.67}$ $h_c = 5.1$	$0.15 < V < 1.5$ $0 < V < 0.15$	Reclining with moving air	Colin and Houdas(1967)
$h_c = 8.6V^{0.53}$	$0.5 < V < 2.0$	Walking in still air	Nishi and Gagge (1970) (V is walking speed)
$h_c = 5.7(M - 0.8)^{0.39}$	$1.1 < M < 3.0$	Active in still air	Gagge et al (1976)
$h_c = 6.5V^{0.39}$	$0.5 < V < 2.0$	Walking on treadmill in still air	Nishi and Gagge (1970) (V is treadmill speed)
$h_c = 14.8V^{0.69}$ $h_c = 4.0$	$0.5 < V < 1.5$ $0 < V < 0.5$	Standing person in moving air	Developed from data presented by Seppãnen et al. (1972)

Table 5: Surface resistance values for inside and outside surfaces.
Source ISO 6946

Heat flow direction	Rsi	Rso
Horizontal (± 30°)	0.13	0.04
Up	0.10	0.04
Down	0.17	0.04

emitted photons, in the case of building surfaces usually lies in the infrared or far infrared region of the electromagnetic spectrum as shown in Figure 37.

Heat transfer through radiation is a surface phenomenon. The frequency of the emitted photons is subject to the emissivity of the surface. This means that the frequency of photons emitted by a surface painted white may be different from that of a surface painted black. The surface of any building material or object subjects the incident radiation to either reflection, transmission, or absorption. In actual cases, different ratios of the incident light are subjected to the mentioned interactions as shown in Figure 38. This establishes that each surface may have the following properties

- Reflectance (ρ): It is the ratio of amount of radiation reflected by the surface to the total incident radiation.
- Transmittance (τ): It is the fraction of incident radiation transmitted across the cross section of the object. In case of opaque surfaces, transmissivity is zero as the object is opaque to the radiation meaning it does not allow radiation to pass through its

cross section.

- Absorptance (α): The amount of radiation absorbed in proportion to total incident radiation is termed as absorptance of a surface. In case of a perfect black body, all the incident radiation is absorbed.

According to law of conservation of energy, sum of these terms is always one i.e.,

$$\alpha + \rho + \tau = 1$$

Equation 6: Sum of absorptance, reflectance, and transmittance is one.

For an opaque surface, $\tau = 0$ and $\alpha + \rho = 1$. For a black surface, $\alpha = 1$, $\rho = 0$, and $\tau = 0$.

Emittance is the total amount of thermal energy emitted by a body per unit area and per unit time for all possible wavelengths. Emissivity of a material at a given temperature is the ratio of the total emissive power of a body to the total emissive power of a perfectly black body at the same temperature.

The radiative heat transfer between two surfaces at different temperatures is dependent upon the relative size, orientation, shape, and temperature of the surfaces along with their emissivity and absorptivity (ASHRAE, 2021).

The radiative heat gains through fenestration are given by the following equation-

$$Q_s = A \times G \times SHGC$$

Where Qs is the radiative heat gain, A is the area of the fenestration, G represents global irradiance and SHGC stands for Solar Heat Gain Coefficient. SHGC is a measure of the amount of solar radiation (heat) passing through the entire window, including the frame. SHGC is expressed as a number between 0 and 1.0. Lower SHGC means lower transmission and subsequently, lower radiative heat gains.

(BEE, 2021) provides further understanding of conductive, convective, and radiative heat transfer in buildings through numerical examples for individual cases and combinations of modes of heat transfer.

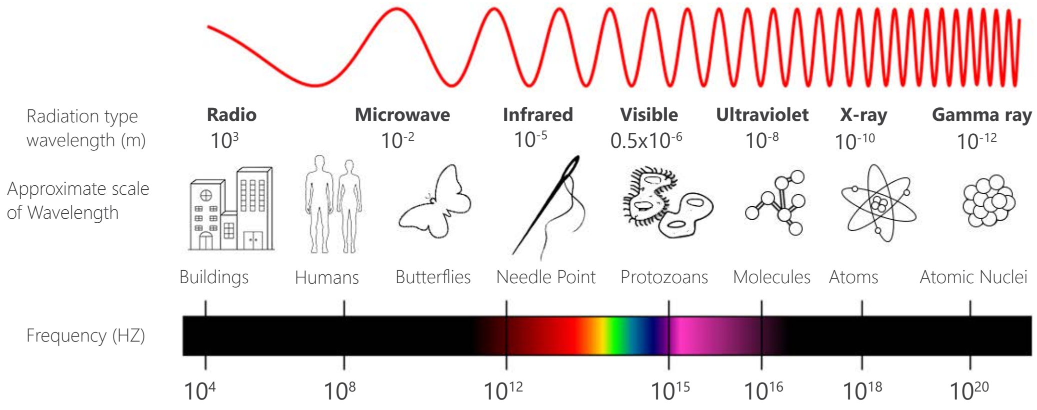


Figure 37: Electromagnetic wave spectrum

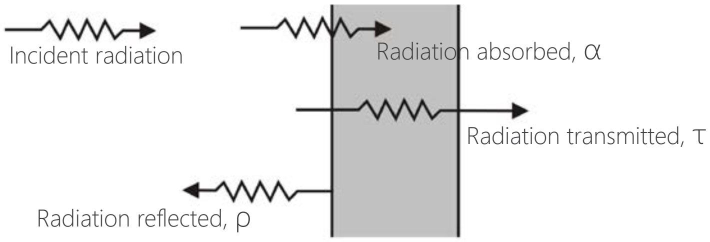


Figure 38: Total incident radiation on an object is either reflected, transmitted, or absorbed by the object.

2.6 Outdoor Climate and Heat Transfer

2.6.1 Definition of Climate

NASA defines climate as the description of the long-term weather pattern in a particular area. A more detailed definition of climate provided by World Meteorological Organization (WMO) and adopted by the Intergovernmental Panel on Climate Change (IPCC):

"Climate in a narrow sense is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization. The relevant quantities are most often surface variables such as temperature, precipitation, and wind. Climate in a wider sense is the state, including a statistical description, of the climate system."(IPCC, 2018)

The definition establishes the frame of time required to define the climate of a location as 30 years taking the phenomenon of climate change into consideration. Climate is expressed in terms of surface variables through temporal metrics such as daily, monthly, and seasonally averaged temperatures, precipitation levels, wind speeds and direction. Metrics such as daylight or sunshine hours are also relevant and seasonally averaged temperatures, precipitation levels, wind speeds and direction. Metrics such as daylight or sunshine hours are also relevant.

2.6.2 Determinants of Climate - Tilting of Earth

The climate of a location is the result of multiple factors. Primarily, the tilting of earth's axis by 23.5° causes the northern and southern hemispheres to experience different seasons as the Earth revolves around the sun. These seasonal variations in temperature, precipitation and other surface variables when experienced annually over a span of nearly three decades help in defining the climate of the location.

2.6.3 Determinants of Climate- Solar Radiation

The tilting of earth allows some parts of the it to receive more direct solar radiation than other parts. As a result, these areas are more heated up than the other regions resulting in temperature differences in air over these regions. The thermal and pressure differences in the air cause winds to blow generating recurring wind patterns across the globe.

The total solar radiation emitted by Sun and reaching the Earth has a wavelength ranging from 0.1-1000 µm. However, due to Sun's high energy, most of this radiation

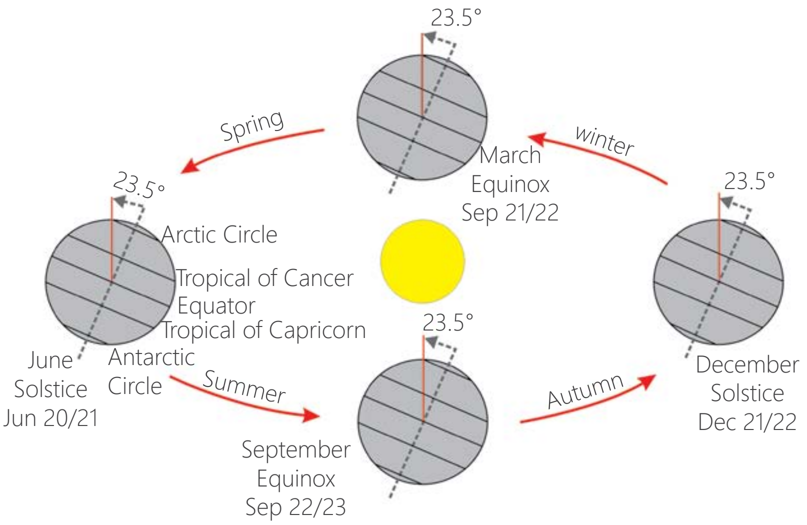


Figure 39: Tilting of Earth's imaginary axis by causes seasons
Source: Derived from (Szokolay, 2014)

is short-wave i.e., ultra-violet and visible light. The Earth's atmosphere is mostly transparent to this incoming short-wave radiation. Hence only 25% of it is reflected by the ground and clouds into the space at the same wavelength as incident radiation. Out of the remaining 75%, nearly 25% is absorbed by the gases such as ozone present in our atmosphere(World Meteorological Organization, 2022). The remaining 50% of the radiation reaches Earth's surface in either diffused or direct manner. This heat accumulated in the earth's atmosphere and ground causes Earth to emit the radiation back in space. However, since the temperature of Earth is much lower than the sun, the emission is in the form of electromagnetic waves of longer wavelength i.e., in the infrared region. The greenhouse gases present in Earth's atmosphere such as carbon dioxide and even water vapour absorb the Earth's emitted long wave radiation and heat the layer of atmosphere closest to Earth's surface. This is also the reason for preventing excess accumulation of greenhouses gases in the atmosphere as it will result in overheating of the lower atmosphere and Earth's surface.

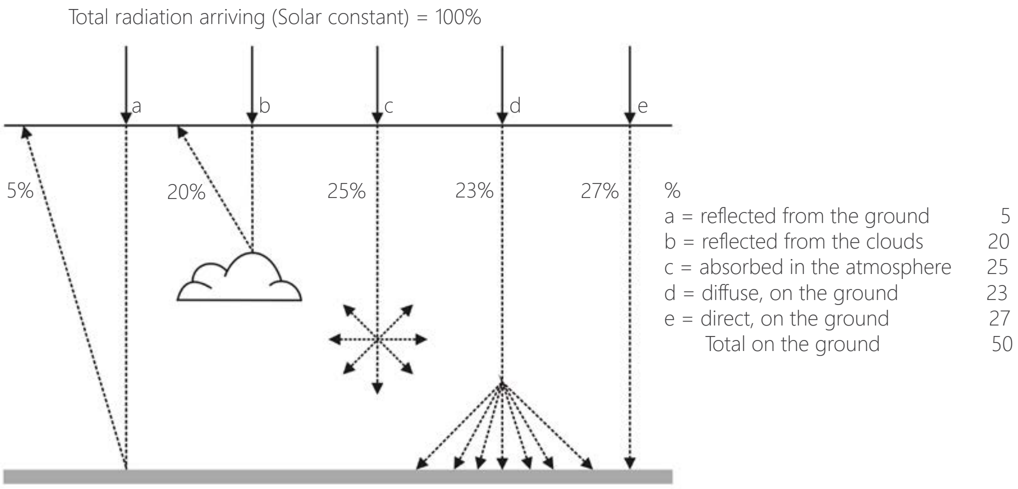


Figure 40: Solar radiation incident on Earth's surface is either reflected from clouds or ground into space, absorbed by clouds or reaches the ground in a diffused or direct manner.

2.6.4 Determinants of Climate- Latitude

The latitude of a location is its distance from the equator. At higher latitudes, the incident solar radiation enters the earth's atmosphere at an angle such that it covers a larger area on the ground when compared to solar radiation at equator due to the curvature of the earth. It also must travel longer distance in the atmosphere due to this angle of incidence before reaching the earth's surface. As a result, most of the radiation reaching the ground is diffused and less intense, leading to lower temperatures and a cooler climate. Alternatively, near the equator, the radiation enters almost perpendicular to the atmosphere and travel a short distance before reaching the ground. Therefore, the high amount of direct sunlight reaching the earth's surface characterize regions near equator with higher temperatures especially in the afternoons.

2.6.5 Determinants of Climate- Terrain

Terrain refers to the vertical and horizontal dimensions of the land surface. It is characterized by metrics such as elevation, slope, and orientation of terrain features. Mountains, plains, hills etc. are examples of terrains. Elevation of a place influences precipitation levels of an area. For example, higher elevations increase the rate of precipitation on the windward side of the mountain causing its microclimate to differ from that of the leeward side. The proximity to a water mass also affects the climate as constant heat is exchanged between air over water and air over land mass due to different specific heat capacity of water and land. This regulates the seasonal variations in temperature making summers less hot and winter less cold. Additionally, humidity levels are higher at places near water bodies.

2.6.6 Determinants of Climate- Sky cover

Sky cover refers to the number of opaque clouds covering the sky. As established earlier, the clouds reflect and diffuse the long-wave radiation emitted by earth's surface to enable cooling. Hence, greater the presence of clouds, higher will be the surface temperature.

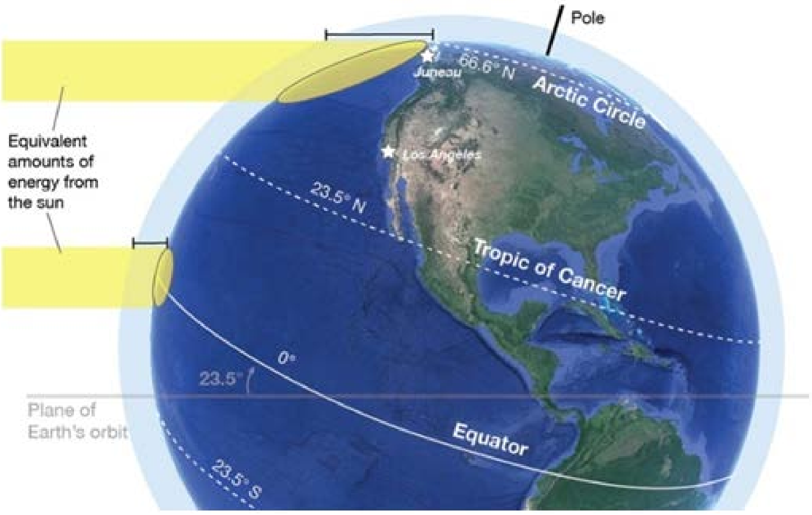


Figure 40: Solar radiation falls travels through less atmosphere near equator than at poles.
Source: image © Map data: SIO, NOAA, U.S. Navy, NGA, GEBCO, US Dept. of State Geographer; Image: Landsat, Google.

2.7 Climate Zones of India

The Köppen-Geiger climate classification system (Figure 41) consists of five main climate groups- A (Tropical), B (Dry), C (Temperate), D (Continental), and E (Polar). Based on precipitation and temperature patterns, further sub-groups are assigned in the system. However, this classification was developed from the perspective of vegetation growth in different climates. A simpler climate classification was proposed by Atkinson in 1953 from the perspective of architectural design. Based on the same, India’s climatic zones are depicted in Figure 43.

The five climate zones identified in India are descried below:

Cold climate- Cities located in cold climate typically experience a mean monthly temperature of less than 25°C. An example of an Indian city with cold climate is Shimla.

Temperate- The characteristics of moderate climate include seasonal variation of heating and cooling load such that neither can be considered severe. A city with temperate climate is Bengaluru

Hot and dry- In this climate, the diurnal temperature variations i.e. difference in peak high temperature during the day and peak low temperature during the night are high. This is a result of low relative humidity levels of air. As a result of dry air, evaporative cooling mechanisms work well in this climate. Ahmedabad in western India experiences hot and dry climate along with more than half of Rajasthan.

Warm and humid- Warm and humid climate is identified by presence of high relative humidity in the air that compounds the effects of warm temperature. While actual

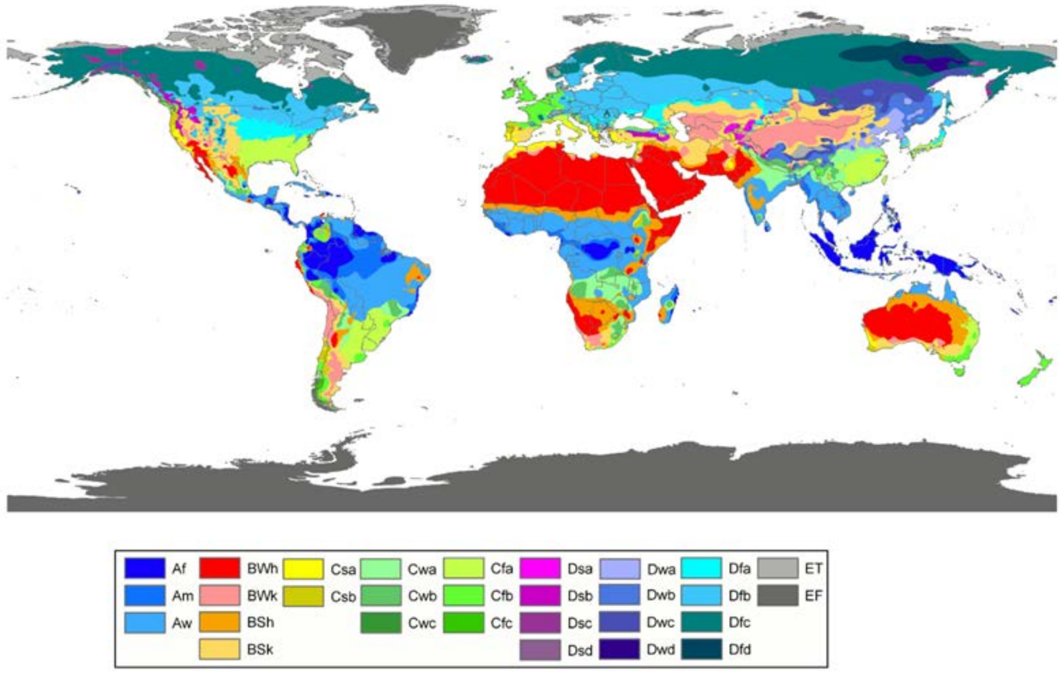


Figure 41: Koppen-Geiger climate classification of the world

Source: "Present and future Köppen-Geiger climate classification maps at 1-km resolution". Nature Scientific Data. DOI:10.1038/sdata.2018.214.

heating is usually not as severe as it is in hot and dry climate, the high humidity levels restrict cooling mechanisms through evaporation for humans and radiation for the earth's surface. This also results in smaller diurnal temperature variation. The climate of Chennai can be categorized as warm and humid.

Composite- If a location cannot be categorized into any of the above climates over a span of 6 months or more, it is said to belong to composite climate. Typically, composite climate is characterized by severe summers and winters with a definite spell of considerable precipitation in the monsoon months. The areas around New Delhi experience composite climate.

The city or location must experience the characteristics of the climate for at least six months to belong to the given climate.

2.8 Influences on various modes of heat transfer

2.8.1 Spatial design decisions vs construction materials and methods

The contribution of spatial design decisions and construction material & method

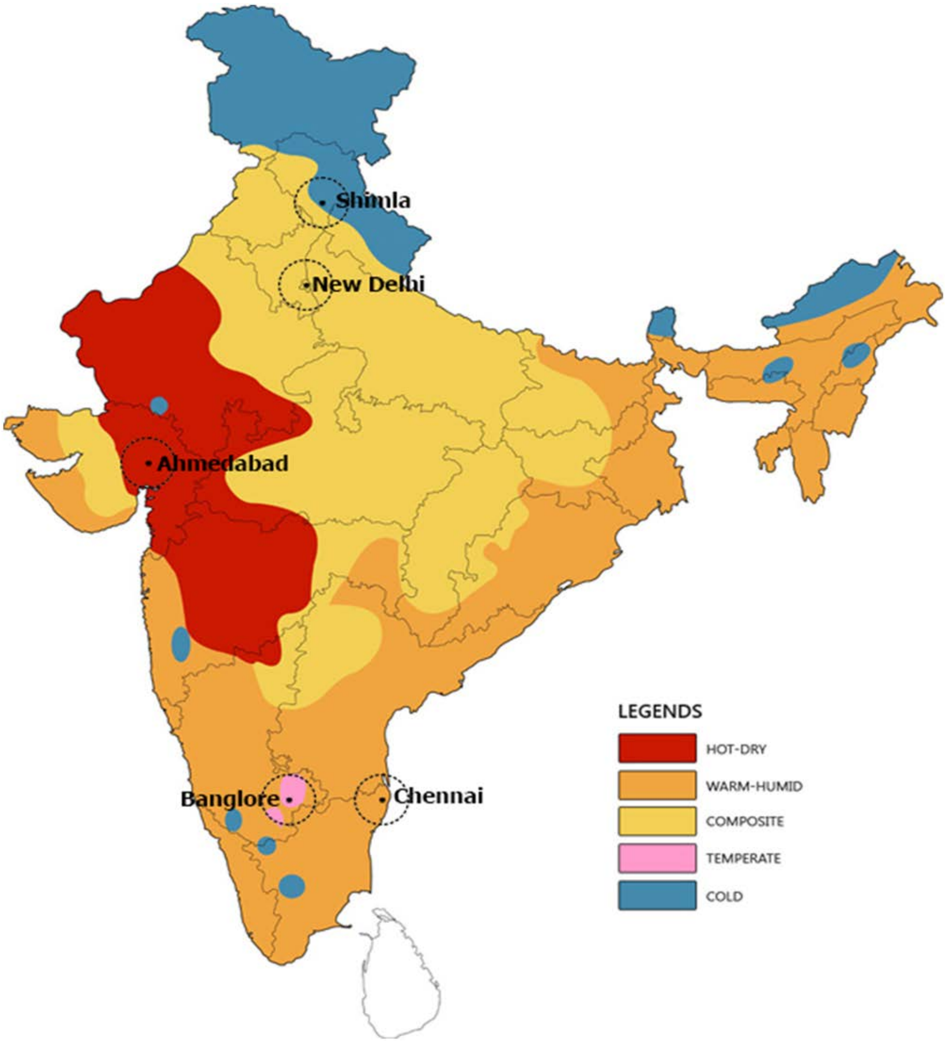


Figure 42: Climate zone map of India;
Source: Bansal, N. K., & Minke, G. (Eds.). (1995). Climatic Zones and Rural Housing in India. ForschungszentrumJülich GmbH, Zentralbibliothek.

choices towards heat transfer from all three modes through various elements of building envelope is highlighted in Table 6.

Conduction: As previously explained, walls transfer heat through conduction in accordance with the thermal conductivity of the walling material. Since walls have the largest surface area amongst all building envelope elements, they receive maximum solar radiation. Hence, the total conductive heat transferred through walls accumulates to high values. The choice of walling material in terms of thermal conductivity and specific heat capacity can lower the conductive heat gains through wall, and subsequently the cooling loads of operating the buildings.

In the case of windows, orientation, position, and shading factor are some design decisions that contribute to lower conductive heat gains. However, window assembly construction details such as double paned windows allow for a greater reduction in heat transfer through conduction than spatial design decisions. In terms of building material and construction methods, roofs offer similar opportunities as wall.

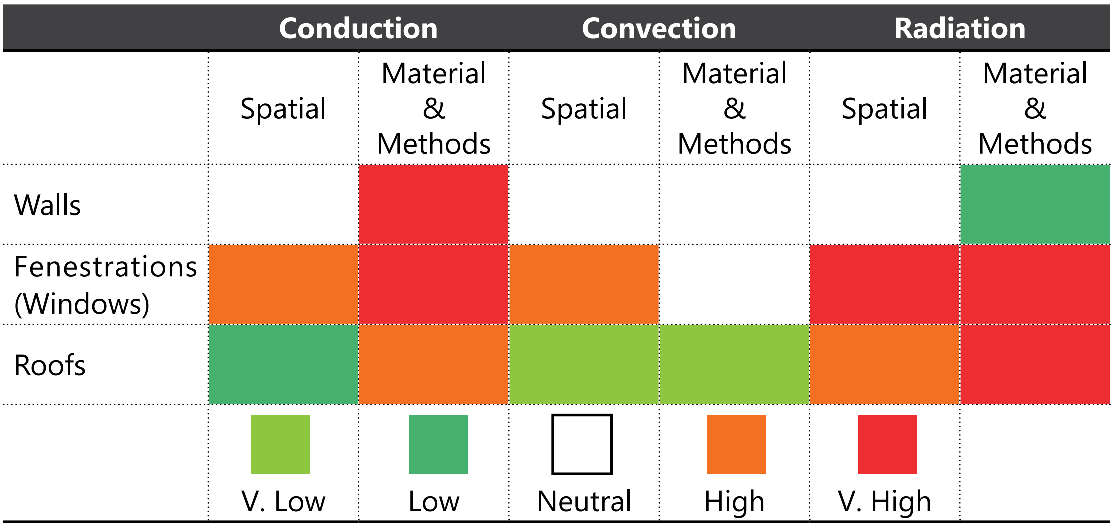
Convection: Since convective heat transfer happens only in the presence of fluids, the walls play minimum to no role in transferring heat through convection. Hot air present near the roof has very low impact on convective heat transfer.

Radiation: The radiative heat transfer is maximum through the glazed part of the windows. Hence, both spatial and material-based choices impact the radiative heat transfer through windows.

2.8.2 Operation strategies

The operation patterns of windows in various climates also affects the amount of heat transferred between outdoors and indoors. In hot and dry climate, conductive heat gains can be avoided through windows, and indoor temperatures can be maintained at a steady value even with high diurnal variations if the windows are always kept closed as shown in figure 44. On the other hand, opening windows at night in warm

Table 6: Impact of spatial design decisions and material choices on conductive, convective, and radiative heat transfer through walls, fenestration, and roof.
Source: Rawal, R., 2021. Heat Transfer and Your Building Envelope, Solar Decathlon India.



	Conduction		Convection		Radiation	
	Spatial	Material & Methods	Spatial	Material & Methods	Spatial	Material & Methods
Walls		🟥				🟢
Fenestrations (Windows)	🟧	🟥	🟧		🟥	🟥
Roofs	🟢	🟧	🟩	🟩	🟧	🟥
	🟩 V. Low	🟢 Low	⬜ Neutral	🟧 High	🟥 V. High	

and humid climate offers ventilation to the indoors while always maintain lower indoor temperature when compared to windows always shut and always open cases.

2.8.3 Spatial characteristics in various climates

Due to large surface areas of walls, conductive heat transfer is one of the biggest sources of heat gain in buildings. Hence, it is important to keep conductive heat gains through walls and roof in check, especially in the hot and dry climate. For this reason, external building surface area to building volume ratio is a crucial spatial design measure in hot and dry climate. Additionally, conductive heat gain through windows can be controlled through the placement and orientation of windows referred to as fenestration details, their shading design, and appropriate thermal characteristics of windows (U-value).

Since convective cooling is the main strategy in maintaining thermally comfortable indoors in warm and humid climates, spatial design measures such as orientation, surface to volume ratio and thermal characteristics of fenestrations play only a measured role. Here, more important factors are massing of the built form and location of fenestrations such that they allow for pressure driven ventilation to happen. Evaporative cooling

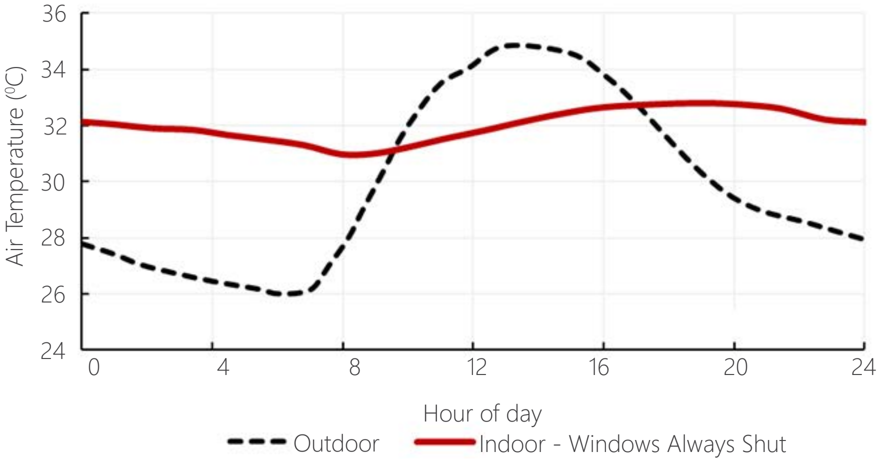


Figure 43: Impact on heat gains due to reduced convection

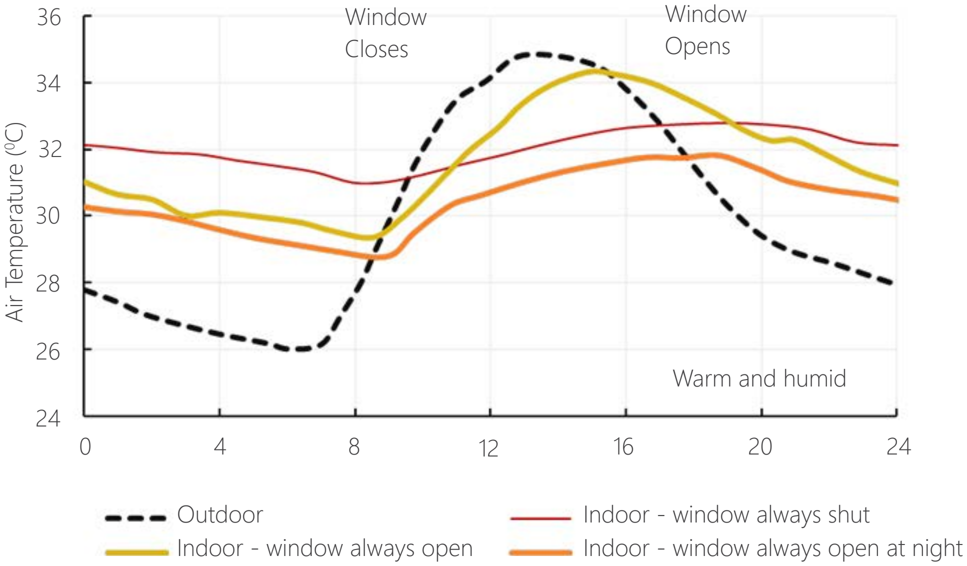


Figure 44: Impact on heat gain due to measured convection

Table 7: Impact of design strategies on heat transfer through building envelope in various climates.

	Conduction	Convection	Radiation
Geometry - Massing	HD	🟧 WH	🟥 All Climates
Orientation	🟩	WH	🟥 All Climates
External Surface to Building Volume Ratio	🟧 HD	WH	🟩 HD
Extent of Fenestration and Thermal Characteristics	🟧 HD	WH	🟥 All Climates
Internal Volume – Stack Ventilation	X	🟥 HD	X
Location of Fenestration – Pressure Driven Ventilation	X	🟥 WH	X

🟩 V. Low 🟩 Low ⬜ Neutral 🟧 High 🟥 V. High

WH: Warm Humid HD: Hot-Dry TE: Temperate CM: Composite CO: Cold

effective in hot and dry climate also relies on movement of air for cooling which makes provision of stack ventilation by managing internal volume of built structures in this climate a relevant strategy for cooling.

Radiative heat transfer is dictated by the amount of solar radiation falling on the building envelope surfaces and the properties of the material surface to absorb, reflect or transmit the incident radiation. For this reason, geometry and orientation of built structure, surface area exposed to east and west directions, window-to-wall ratio (fenestration extent) and thermal characteristics of the window are relevant considerations in design. In hot and dry climate, specifically, the surface to volume ratio also has a low impact on radiative heat gains.

2.9 Metrics that Matter

Table 7 lists parameters of building components that determine the heat transfer through the building envelope. The R-value or U-values of all walling technologies and systems determine the heat transfer through conduction in the buildings. In case of external walls, the thermal mass expressed as specific heat capacity of the walling material is another relevant metric, especially in the hot and dry climate. In case of fenestration systems, conductive heat gains are determined by the U-values or R-values of the window assemblies including skylights. Same applies for doors. Moreover, solar heat gains characterized by SHGC of the glazing will determine heat transfer through the transparent glass surfaces. Visible Light Transmittance levels determine the amount of daylight entering the space in terms of illumination. Hence high VLT is desirable for naturally lighting the space. However, to reduce solar heat gains, low e-coating can be applied to appropriate glazing surface.

Lastly, the heat transfer through roofs can be considered similar to walling material in terms of thermal conductivity and relevance of R-value. However, to reduce radiative heat gains, surface of roof exposed to the outdoors can be treated with coatings that increase solar reflectance.

Table 8: Relevant metrics for building envelope elements in terms of heat transfer
Source: Rawal, R., 2021. Heat Transfer And Your Building Envelope, Solar Decathlon India

Parameter	Metric	Building envelope element
Thermal Conductivity	R value – U value	Walls • Internal • **External**
Thermal Mass	Specific heat capacity	
Thermal Conductivity (Frames and Glass)	R value – U value	**Fenestration** • **Windows** • Skylights • Doors
Solar Gains	Solar Heat Gain Coefficient	
Visible Light Transmittance	VLT	
Thermal Conductivity	R value – U value	**Roofs** Floors Foundations
Thermal Emissivity	Solar Reflectance	

3

FUNDAMENTALS OF THERMAL COMFORT

3.1 Introduction

This chapter presents the globally accepted definition of thermal comfort that dwells into both quantitative and qualitative aspects of the concept. It also underlines the role of building operation mechanisms in thermal comfort. Elaborating on the qualitative aspect of thermal comfort, the chapter presents explanation of thermal comfort metrices having a subjective scale of assessment. Further the chapter presents the two most widely used theories for thermal comfort assessment- heat balance method and adaptive comfort theory. Lastly the chapter concludes with a discussion on the various types of local thermal discomfort that occupants may encounter in a thermally neutral environment.

ASHRAE defines thermal comfort as the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation. (ASHRAE, 2020). This qualitative definition of thermal comfort states that thermal comfort is a state of mind. While it can be estimated through numerically determined values such as temperature, relative humidity, and others, it also has a component of subjectivity in terms of personal perception, preference, and sensitivity to changes in thermal environment to name a few. Hence, assessment of thermal comfort of occupants incorporates a subjective scale in addition to the numerically determined metrics.

As established in Section 1.1.2 of this document, the core body temperature of humans must be maintained around 37°C for healthy survival. Lack of thermal comfort triggers physiological responses in body. Elevated heart rates and loss of concentration often accompany thermal discomfort. When unchecked, it may cause the core body temperature to rise or drop, increasing the risk of encountering pyrexia or hypothermia. Ultimately, it can even lead to vomiting, unconsciousness, irreparable damage to cells and even death. Hence, buildings must be designed to provide thermal comfort to maximum number of occupants for most parts of inhabitation. Achieving and maintaining thermal comfort in buildings requires knowledge of influencing factors elaborated in section 1.4. The same are summarized below:

- Environmental Factors
    - Air Temperature (S.I Unit- °C)
    - Relative Humidity (measured in %)
    - Mean Radiant Temperature (S.I Unit- °C)
    - Air Velocity (S.I Unit- ms^{-1})
- Personal Factors
    - Activity/ Metabolic Rate (S.I Unit- MET)
    - Clothing (S.I Unit- CLO)
- Other Factors
    - Short-term and long-term acclimatization
    - Body shape and fat
    - Gender and age
    - Status of health

3.1.1 Building Operation Modes

It has been observed that perception of thermal comfort in occupant does not depend merely on human physiology and heat transfer mechanisms between the environment and body. It is also influenced by social factors and the occupants' psychological responses to the environment (Race, 2006). Occupants have been observed to shift their thermal preferences based on the available the mechanisms to condition the space for achieving thermal comfort.

Along with the shift in thermal preference, another domain of possible alteration is sensitivity towards thermal environment. Changing the building operation mode from air- conditioned to naturally ventilated in a pleasant outdoor climate condition, may render occupants less or more sensitive to metrics such as higher air speed. Hence, it is essential to consider various modes of building operation and their influences on thermal comfort perception of occupants.

3.1.2 Naturally Ventilated Buildings

Ventilation is intentional introduction of outdoor air into a building through open windows, doors, grilles, and other planned building envelope penetrations whereby airflow is driven by naturally occurring forces such as wind and buoyancy to provide fresh air and/ or ventilation cooling (ASHRAE, 2021). For a building to be naturally ventilated, it must have operable windows with the operation regulated by the occupants to maintain their thermal comfort. The windows may have dynamic components such as louvres to regulate the amount of air exchanged.

Naturally ventilated buildings do not condition air with mechanical cooling i.e., electro-magnetic devices such as room air-conditioners and others are not operated within these buildings. However, presence of air-motion devices such as ceiling or pedestal fans is inclusive. These devices contribute to air movement within the space without affecting the air temperature. They may aid in pushing hot indoor out of the windows or redistribute a cool breeze entering from window across the whole space to facilitate thermal comfort of occupants.

Figure 45: Naturally ventilated space using operable windows and air motion devices.
Source: Mehta, D. (n.d.). M. Planning Studio, Cept University. Aakrutiarchitects.Retrieved from https://www.aakrutiarchitects.com/cept-university

3.1.3 Mixed Mode Buildings

Buildings that use both natural ventilation and mechanical cooling are said to operate in mixed mode. Hence, buildings offering mixed mode operation must house mechanical cooling of some form (room air-conditioners, HVAC systems, etc) along with operable windows. Air motion devices such as ceiling fans may also provide supportive air movement. Mixed mode operation within buildings can be of following types:

- **Spatial mixed mode**: In this mode of operation, some of the spaces in a building are naturally ventilated while others are mechanically cooled simultaneously. The characteristics of this operation mode is that spaces can be differentiated based on presence of mechanical cooling systems. Operation hours of mechanical cooling may vary daily, monthly, or seasonally. An example of such a building would be academic institutions where classrooms or studios operate in natural ventilation mode while administrative offices may use mechanical cooling in summer months and natural ventilation during remaining year.

- **Temporal mixed mode**: In this format, the entire building is ventilated either naturally or mechanically based on the time of the year or day. A simple example would be a corporate office where mechanical cooling works during the occupancy hours in summer months to ventilate and cool all the functional spaces within the building. The same building may use natural ventilation to cool the spaces when outdoor temperatures are more favourable during the winter season.

- **Concurrent mixed mode**: In this system mechanical cooling is used simultaneously with natural ventilation in the same space. In this system energy consumption may be higher as the cooling obtained by mechanical devices may be lost through the windows. Due to this possibility, buildings usually do not prefer to operate in this mode. However, an example of concurrent mixed mode in action can be large trade exhibitions where cooling is provided by mechanical systems while doors and windows may remain open.

3.1.4 Air-Conditioned Buildings

Air-conditioned buildings use mechanical cooling systems at all times of the year during occupancy hours to maintain desirable indoor thermal environments. Outside of occupancy hours, natural ventilation using operable windows may be deployed to maintain the coolth.

3.2 Thermal Comfort Metrics

3.2.1 Preference, Comfort, and Acceptability

Thermal comfort among occupants of a building can be predicted using metrics such as thermal sensation, acceptance, preference, and satisfaction.

Thermal sensation- The human body has hot and cold receptors at various locations of the skin that allow an individual to sense the amount of thermal energy in an object that they touch. The brain converts this combination of senses at different body parts into an overall thermal sensation. It is usually measured as sensation vote on a seven-point scale (cold to hot) defined by ASHRAE Standard 55.

Table 9: Thermal Comfort Metrics: Preference, Comfort and Acceptability

PMV	Sensation Vote	Acceptance Vote	Preference Vote
-3	Cold	-	-
-2	Cool	Very Unacceptable	Want Cooler
-1	Slightly Cool	Unacceptable	Want Slightly Cooler
0	Neutral	-	No Change
+1	Slightly Warm	Acceptable	Want Slightly Warmer
+2	Warm	Very Acceptable	Want Warmer
+3	Hot	-	-

Thermal acceptance- This metric conveys whether the thermal environment of the occupant is either acceptable to them or otherwise. The acceptance vote is measured on a four-point scale ranging from very unacceptable to acceptable.

Thermal preference- This metric considers the affinity that individuals may have towards certain thermal sensations. The preference vote is measured on a five-point scale (want cooler to want hotter).

Thermal satisfaction- This is a binary metric that refers to the contentment of the occupant with their thermal environment.

Example- An occupant may have a thermal sensation of the neutral order in a space. They may also display acceptance of their neutral thermal environment. However, they may prefer to inhabit a slightly warm environment. In this case, their thermal preference would be a slightly warmer environment. However, they may or may not be satisfied with their neutral thermal environment.

3.2.2 PMV

Developed by Povl Ole Fanger, Predicted Mean Vote (PMV) is an index that aims to predict the mean vote expected to arise from averaging the thermal sensation vote of a large group of people in a given environment. It is used to obtain predicted percentage of dissatisfied occupants. The PMV/PPD system is an example of a steady state heat balance model. The 'predicted mean vote' (PMV) combines the influence of air temperature, mean radiant temperature, air movement and humidity with that of clothing and activity level into one value on a seven-point thermal sensation scale shown in Figure 45.A value between -0.5 to +0.5 on the PMV scale is the normal acceptable range according to ASHRAE 55. ISO 7730:2005 defines three categories of acceptable thermal comfort. These are listed below in terms of PMV values.

Table 10: Acceptable thermal comfort bands listed in ISO 7730:2005

Band	PMV Range
A	$-0.2 < PMV < +0.2$
B	$-0.5 < PMV < +0.5$
C	$-0.7 < PMV < +07$

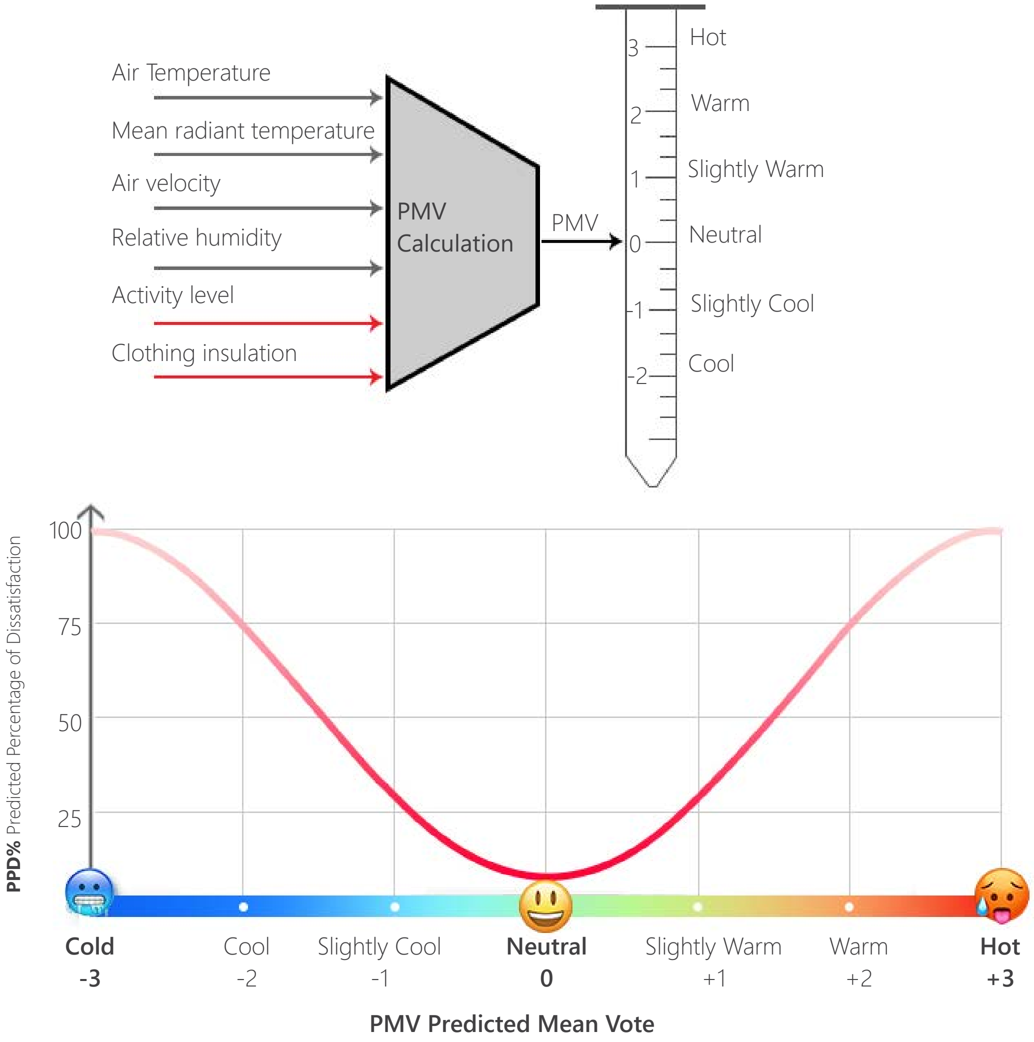


Figure 46: Thermal Comfort Metrics: PMV and PPD
Source: Guenther, S. (2021). What Is Pmv? What Is Ppd? The Basics of Thermal Comfort. Simscale. Simscale. Retrieved from https://www.simscale.com/blog/2019/09/what-is-pmv-ppd/

3.2.3 PPD

Predicted Percentage of Dissatisfied occupants (PPD) refers to the percentage of occupants likely to experience thermal dissatisfaction out of the total number of occupants. ISO 7730:2005 defines the hard limit as ranging between -2 and +2, for existing buildings between -0.7 and +0.7, and new buildings ranging between -0.5 and +0.5.These are listed below in terms ofPPD values. The PPD can range from 5% to 100%, depending on the calculated PMV. For comfort ranges to comply with standards, no occupied point in space should be above 20% PPD. While it is scientifically impossible to fully please everyone, the purpose of these indices is to try to provide ensure acceptance of thermal environment for 80% of occupants in each space, while mitigating factors that cause overwhelming discomfort.

Table 11: PPD ranges corresponding to acceptable PMV ranges as defined in ISO 7730:2005

Band	PMV Range	PPD (%)	Temperature (°C)
A	-0.2 < PMV < +0.2	< 6	24.5 ± 1
B	-0.5 < PMV < +0.5	< 10	24.5 ± 1.5
C	-0.7 < PMV < +07	<15	24.5 ± 2.5

3.2.4 Discomfort Degree Hours (DDH)

Discomfort Degree Hours, a metric for thermal comfort prediction, is inclusive of the duration and extent of discomfort experienced or predicted over a year. Calculated based on India Model for Adaptive (thermal) Comfort (IMAC). It is the summation of difference of hourly operative temperature and IMAC band acceptable temperature only for hours when temperature goes outside IMAC temperature band with 80% or 90% acceptability range.

$$DDH\ (annual) = \sum_{i=1}^{8760} |\ (T_i - T_{acceptable})|$$

$$T_{acceptable} = T_{lower}\ \ when\ T_i\ < T_{lower}$$

$$T_{acceptable} = T_{upper}\ \ when\ T_i\ > T_{upper}$$

Where T_i indicates the measured or achieved operative temperature at i^{th} hour, $T_{acceptable}$ indicates either the lower (T_{lower}) or the upper limit (T_{upper}) of the targeted operative temperature based on IMAC comfort model.

The India Model for Adaptive Comfort (IMAC) proposes a range of acceptable indoor operative temperatures as opposed to a single value. Hence, for discomfort towards cooler end, the lower limit of the comfort range should be considered while calculations for DDH on the hotter side should use the upper limit. Understanding of DDH over a one-year period is a standard duration to include building performance in all seasons. However, when addressing peak cooling/ heating loads in the building design, the duration may change to a specific day or week. Lower DDH indicates higher amount of thermal comfort provision within the building throughout the year. The duration usually considered for DDH calculation is one year.

3.3 Heat Balance Method

The heat balance method presents a physics based mathematical model that establishes thermal comfort when heat loss from the body is exactly equal to heat produced within the body. The heat balance method gives following equation:

$$M\text{-}W = q_{sk} + q_{res} + S = (C + R + E_{sk}) + (C_{res} + E_{res}) + (S_{sk} + S_{cr})$$

Where M = rate of metabolic heat production, W/m^2
Where M is the rate of metabolic heat production, W is the rate of mechanical work accomplished; q_{sk} is the total rate of heat loss from skin; q_{res} is the total rate of heat loss through respiration; C + R is the sensible heat loss from skin; E_{sk} is the total rate of evaporative heat loss from skin; C_{res} is the rate of convective heat loss from respiration; E_{res} is the rate of evaporative heat loss from respiration; S_{sk} is the rate of heat storage in skin compartment; S_{cr} is the rate of heat storage in core compartment.

The heat balance method approaches thermal comfort from a biological perspective.

- If heat generation rate > heat loss rate, individual will feel warm/ hot
- If heat generation rate < heat loss rate, individual will feel cool/ cold
- For thermal comfort, heat generation rate = heat loss rate

The heat balance method provides quantification of the heat exchange between human body and immediate surrounding environment. However, it does not address

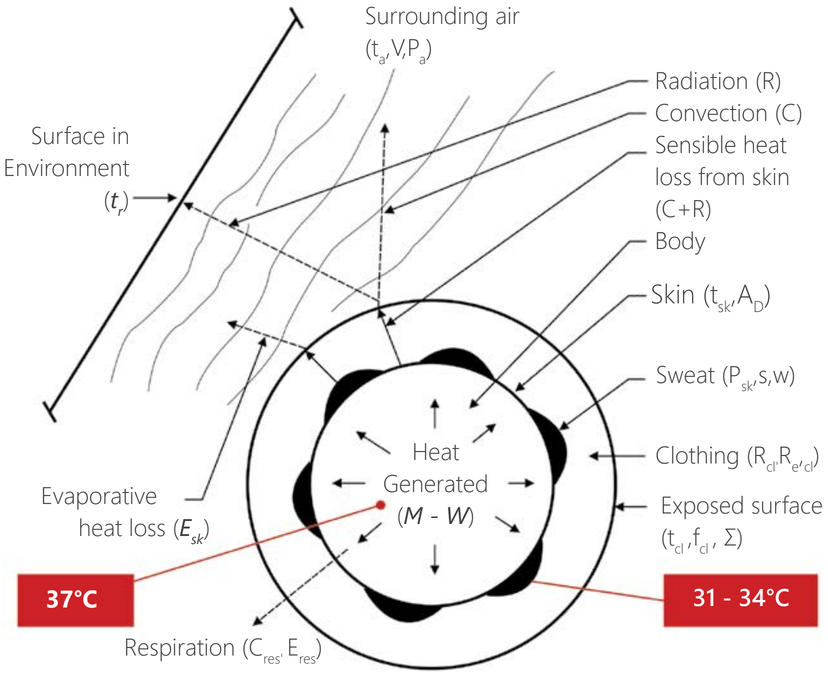


Figure 47: Comfort Theory - Heat Balance Method
Source: Fantozzi, F., & Lamberti, G. (2019). Determination of thermal comfort in indoor sport facilities located in Moderate Environments: An overview. Atmosphere, 10(12), 769. https://doi.org/10.3390/atmos10120769

the psychological adaptation measures and their influence on thermal comfort. To acknowledge the influence of behavioural and psychological adaptations of the human body, the Adaptive Thermal Comfort Model was developed.

3.4 Adaptive Thermal Comfort Method

Since the beginning of 19th century, studies have presented various perspectives and theories on the concept of thermal comfort and the human perception of the indoor thermal environment (Houghton & Yaglou, 1923a) and (Houghton & Yaglou, 1923b). Other pioneering works presented thermal comfort as a self-regulating mechanism as opposed to the then prevalent static view, by establishing a relationship between indoor environmental conditions, outdoor environmental conditions, and the perception of thermal comfort (Auliciems, 1969a), (Nicol & Humphreys, 1973),(Humphreys, 1976), (Humphreys, 1978). These studies mentioned behavioural thermoregulation stemming from altering posture, activities, and clothing levels. They also highlighted the thermoregulatory adjustments in the body to enable acclimatization processes.

Further research into these concepts utilized field studies leading to the formulation of the three adaptive principles- behavioural, physiological, and psychological (de Dear, Brager, & Cooper, 1997). While the studies established clear influence of the adaptive principles on thermal comfort, further research was needed to develop holistic knowledge of each principle and their interactions (Schweiker, et al., 2014).

Behavioural adaptation- It includes modification to clothing or adjustments to the indoor thermal environment (by opening windows or using fan) to facilitate favourable levels of heat transfer between the body and the environment. These behaviours influence the rate of internal heat generation and body heat loss through conduction, convection long-wave radiation, and/or evaporation. The outdoor conditions affect the probability of these behaviours in occupants (Nicol F. , 2001), (Baker & Standeven, 1997), (de Carli, Olesen, Zarrella, & Zecchin, 2007), (Haldi & Robinson, 2009), (Cândido, de Dear, & Lamberts, 2011), (Schiavon & Lee, 2013) and (Wang, Ji, & Su, 2018).

Physiological adaptation- Physiological adaptation measures are triggered in the human body when it receives repeated stimuli of being outside the comfort range on either hot or cold side to reduce the thermal stress on the body. Termed as acclimatization process, the continuous stimuli from non-neutral conditions cause alterations in the physiological parameters such as metabolic rate, onset temperature of sweating and more (van Marken Lichtenbelt, Kingma, van der Lans, & Schellen, 2014), (Hori, 1995) and (Taylor, 2014). Studies have also deliberated on the additional positive health effects of exposure to such non-neutral conditions (Hanssen, et al., 2015) and (Pallubinsky, et al., 2017).

Psychological adaptation- When the perception of control over thermal environment is altered, certain psychologically adaptive measures may take place (Fountain, Brager, & de Dear, 1996), (Hellwig, 2015), and (Boerstra A. C., 2016). For example, when presented with the choice to open windows in an office occupants perceive it as having higher level of control over their thermal environment. This widens their range of acceptable indoor temperatures. Changes in expectations also work in the same manner. (Brager & de Dear, 2003), (Strengers, 2008), (Luo, et al., 2016) and (Wang, Ji, & Ren, 2017)

Adaptive thermal comfort model takes into consideration all three- physiological, psychological, and behavioural aspects of occupants and their influence on perception of thermal comfort. It prescribes indoor setpoint temperature to address 90% acceptability of thermal environment among occupants at granular timescales as opposed to a static set point-based conditioning.

Due to its prominence, early standards for the indoor environment mainly relied on the heat-balance approachfor providing thermal comfort criteria. However, in 2004, ASHRAE introduced its Standard 55 (ASHRAE, 2004) which shifted to the adaptive approach as a method for indoor thermal comfort in naturally ventilated buildings. Further the European SCATs study (McCartney & Nicol, 2002)contributed to the formation of EN 15251:2007 (CEN , 2007), its successor EN 16798 (CEN, 2019) and ISO 17772-1 that provide a similar method for free running buildings.

Based on the degree of personal control offered over the indoor environment, the use of adaptive approach or heat balance approach was defined in the second version of Dutch ISSO 74. It combined the heat balance method for heated spaces with adaptive model for non-heating periods (Boerstra, van Hoof, & van Weele, 2015).

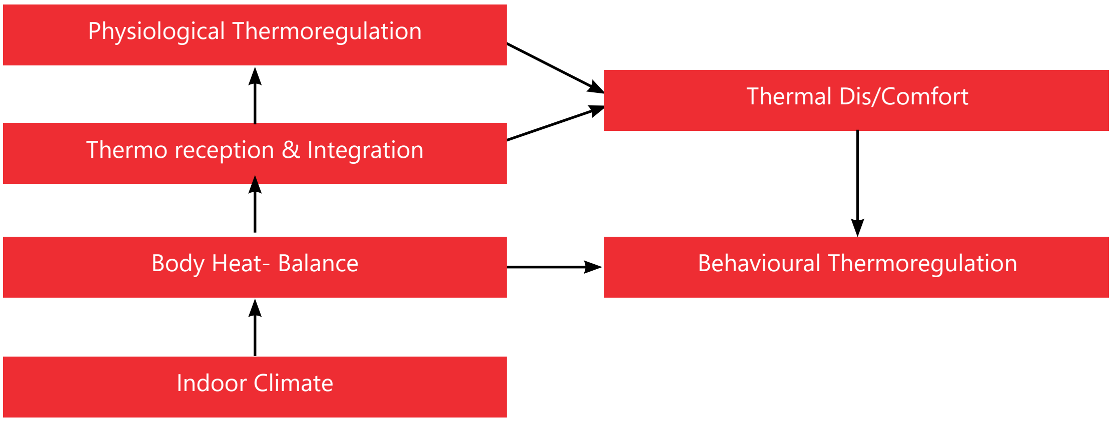


Figure 48: Comfort Theory: Adaptive Thermal Comfort Method

The India Model for Adaptive Comfort (IMAC) approach addressed the prevalent five Indian climatic zones and increasing adoption of mixed mode buildings (Manu, Shukla, Rawal, Thomas, & Dear, 2016). Surveys comprising of ventilated, mixed mode and air-conditioned buildings informed the formulation of two separate adaptive models- one for naturally ventilated and one for mixed mode buildings. The IMAC equations were subsequently included in the National Building Code 2016. Additionally, ECBC 2017 refers to NBC as the standard for thermal comfort requirements. Recent advancements include development of IMAC specifically for the residential sector (IMAC-R) (Rawal, et al., 2022).

3.5 Local Thermal Discomfort

Studies have identified that it is possible for occupants to feel uncomfortable even if they feel thermally neutral overall. This usually happens when one or more parts of their body are either too warm or too cold. Such non-uniformities in body heat flow, however small they may be, cause the thermoregulatory system of the body to compensate. As a result, the physiological efforts of the body in maintaining temperatures are increased. Local thermal discomfort is also a reason why it is highly unlikely for indoor spaces to achieve 100% thermal acceptability. To accommodate this, most standards like ASHRAE specify conditions to ensure 80% acceptability of the thermal environment amongst occupants.

Often cold windows, uninsulated walls, improperly sized heating panels on the wall or ceiling and other such factors lead to asymmetry in thermal radiation. Several studies

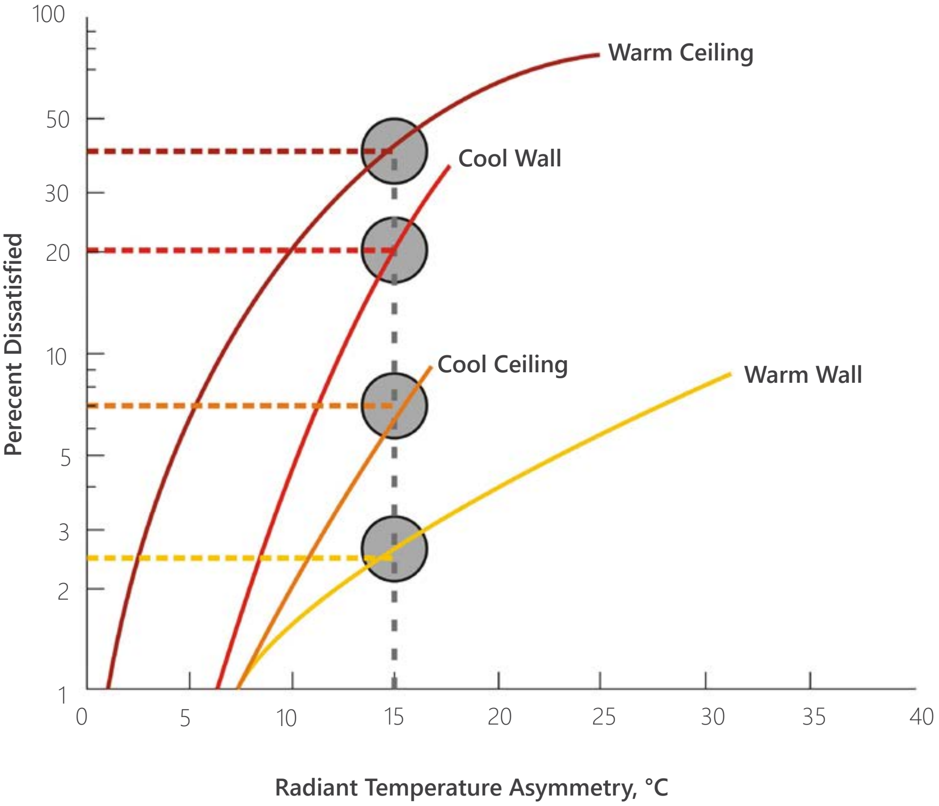


Figure 49: Occupant dissatisfaction levels due to radiant temperature asymmetry in walls and roof. Source: Abushakra Bass, Akers Larry, Baxter Van, Hayte Sheila & Paranjpey Ramesh (2017). ASHRAE Fundamentals SI edition.

have highlighted the influence of asymmetric thermal radiation. (ASHRAE, 2021) The subjects in these studies were always in seated position in a thermally neutral environment with exposure to thermal discomfort resulting from excessive asymmetry. Their reactions on thermal comfort sensations were used to establish the relationship between radiant temperature asymmetry and percentage of dissatisfied occupants. Fanger et al. (1980) exceptionally influenced the recommendations in ISO Standard 7730 and ASHRAE Standard 55 where guidelines pertaining to warm overhead surfaces and cold vertical surface are provided (ASHRAE, 2021).

Radiant asymmetry is the difference in radiant temperature of the environment on opposite sides of the person. More precisely, radiant asymmetry is the difference in radiant temperatures seen by a small flat element looking in opposite directions (ASHRAE, 2021).

3.5.1 Radiant Temperature Asymmetry – Walls and Roof

Figure shows that when the difference in air temperatures and surface temperature of the ceiling is 15°C, such that the ceiling is warmer than the air, nearly 40% of the occupants express thermal dissatisfaction. For the same amount of radiant thermal asymmetry (i.e., 15°C), a smaller number of occupants express dissatisfaction with cooler walls. Table 11summarizes the recorded PPD levels in various cases pertaining to walls and ceilings.

Table 12: Percentage of dissatisfied occupants with radiant thermal asymmetry of 15°C

Radiant thermal asymmetry (15°C) cause	Warm Ceiling	Cool Walls	Cool Ceiling	Warm Walls
PPD	40%	20%	08%	02.5%

The descending order of PPD expressed in radiant thermal asymmetry for walls and ceilings can be given as
Warm Ceiling > Cool Wall > Cool Ceiling > Warm Wall.

Establishing PPD in various cases of warm/ cool ceiling or warm/ cool wall is helpful in designing the quantity and positioning of radiant panel to provide thermal comfort in the occupied spaces.

3.5.2 Radiant Temperature Asymmetry – Floors

Figure 51 and Figure 52 represent the percentage of occupants dissatisfied in three cases of different floor temperatures 15°C, 24°C, and 36°C. Table 13 summarizes the recorded PPD in each case.

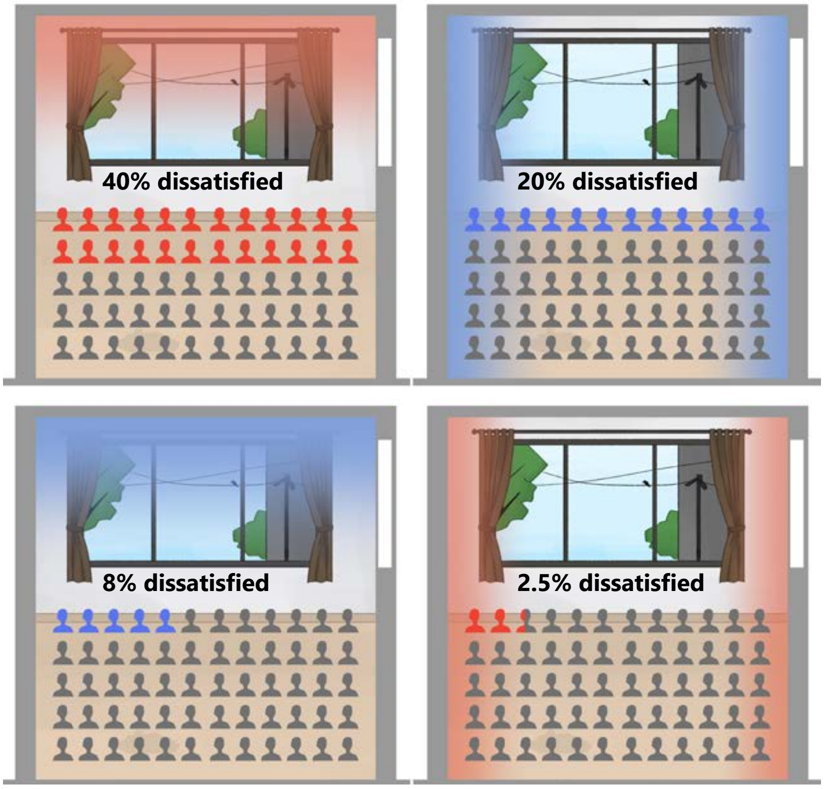


Figure 50: Representation of radiant thermal asymmetry in walls and roof with resultant percentages of dissatisfied occupants.

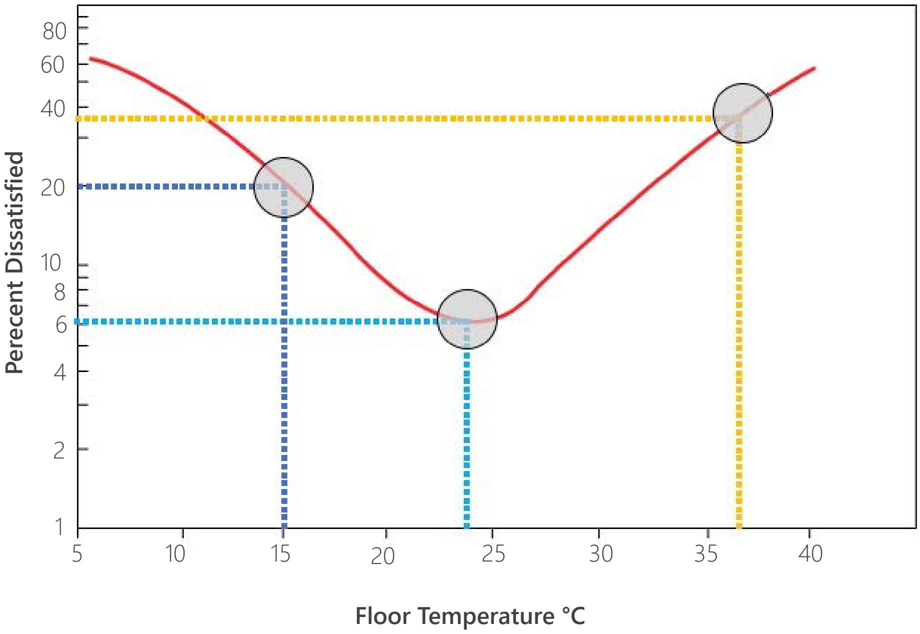


Figure 51: Occupant dissatisfaction levels due to radiant temperature asymmetry in floor. Source: Abushakra Bass, Akers Larry, Baxter Van, Hayte Sheila & Paranjpey Ramesh (2017). ASHRAE Fundamentals SI edition.

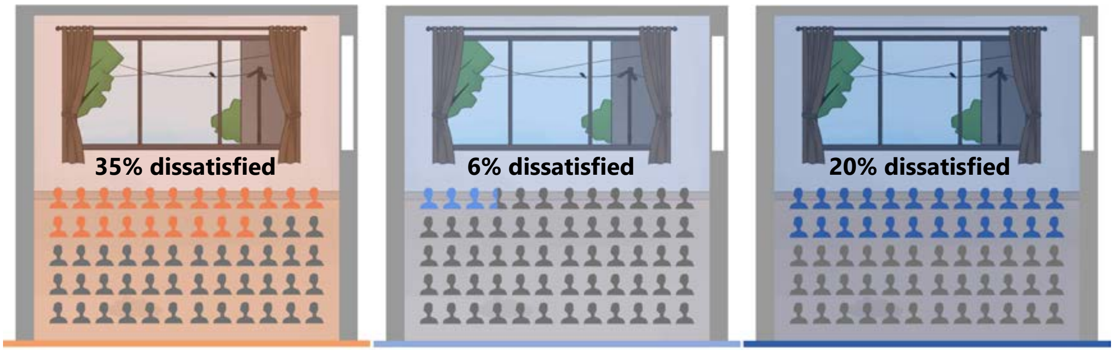


Figure 52: Representation of radiant thermal asymmetry in floor with resultant percentages of dissatisfied occupants.

Table 13: PPD corresponding to radiant thermal asymmetry arising from floor temperatures of 15°C, 24°C and 36°C.

Categorization of floor temperature	Cold	Cool/ Neutral	Warm
Floor temperature	15°C	24°C	36°C
PPD	20%	06%	35%

The descending order of PPD expressed due to floor temperature is **Warm Floor > Cold Floor> Cool Floor.** An explanation of why cooler or neutral floor temperatures are preferred over warm floors lies in the understanding of

- the amount of hot and cold receptors present at the base of our feet
- The sensitivity level of these receptors towards heat or coolth.

3.5.3 Radiant Temperature Asymmetry Between head and ankles

Table 14 represents the percentage of occupants dissatisfied in two cases of radiant thermal asymmetry between air temperatures near the head and ankles of seated occupants.

Due to the tendency of warm air to rise, the air temperature inside a space, increases with increase in height above the floor. Hence the air temperature around the head of an occupant is not same as that near their ankles. If the difference of air temperatures near these locations is large, local thermal discomfort can occur. Even when the occupants are in thermal neutrality, warm discomfort experienced near the head and/ or cold discomfort at the feet or near ankles can affect the overall thermal comfort of occupants. The influence of vertical air temperature difference on thermal comfort has been presented in various studies (ASHRAE, 2020). Figure 53 shows the percentage of people in seated position dissatisfied when temperature differences between head and ankles range from 0 to 12 °C.

Table 14: PPD corresponding to radiant thermal asymmetry of 4°C and 8°C between head and ankles in seated position

Air temperature difference between head and ankles	4°C	8°C
PPD	11%	60%

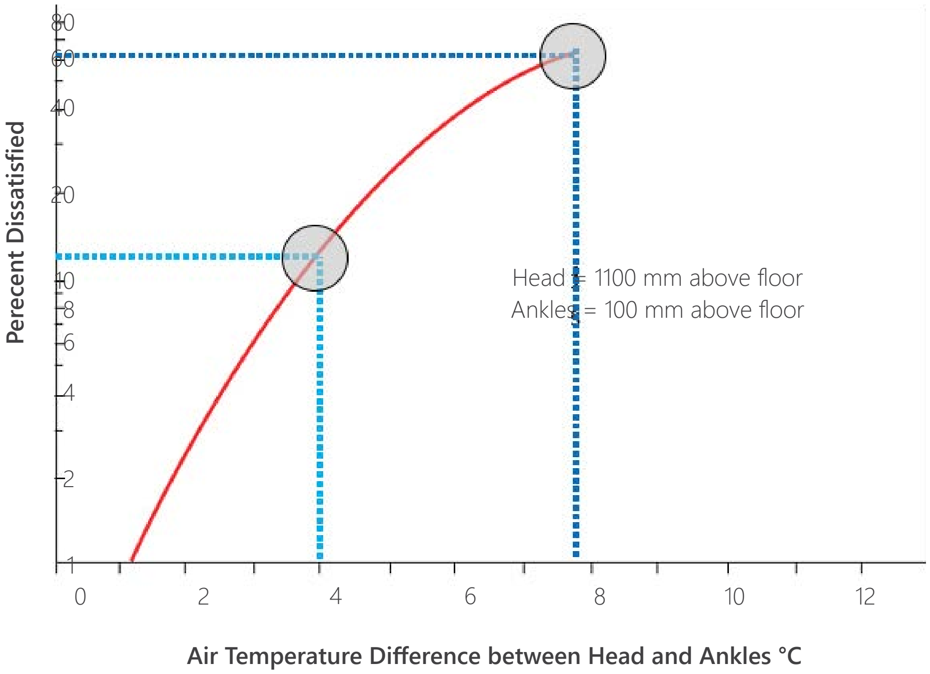
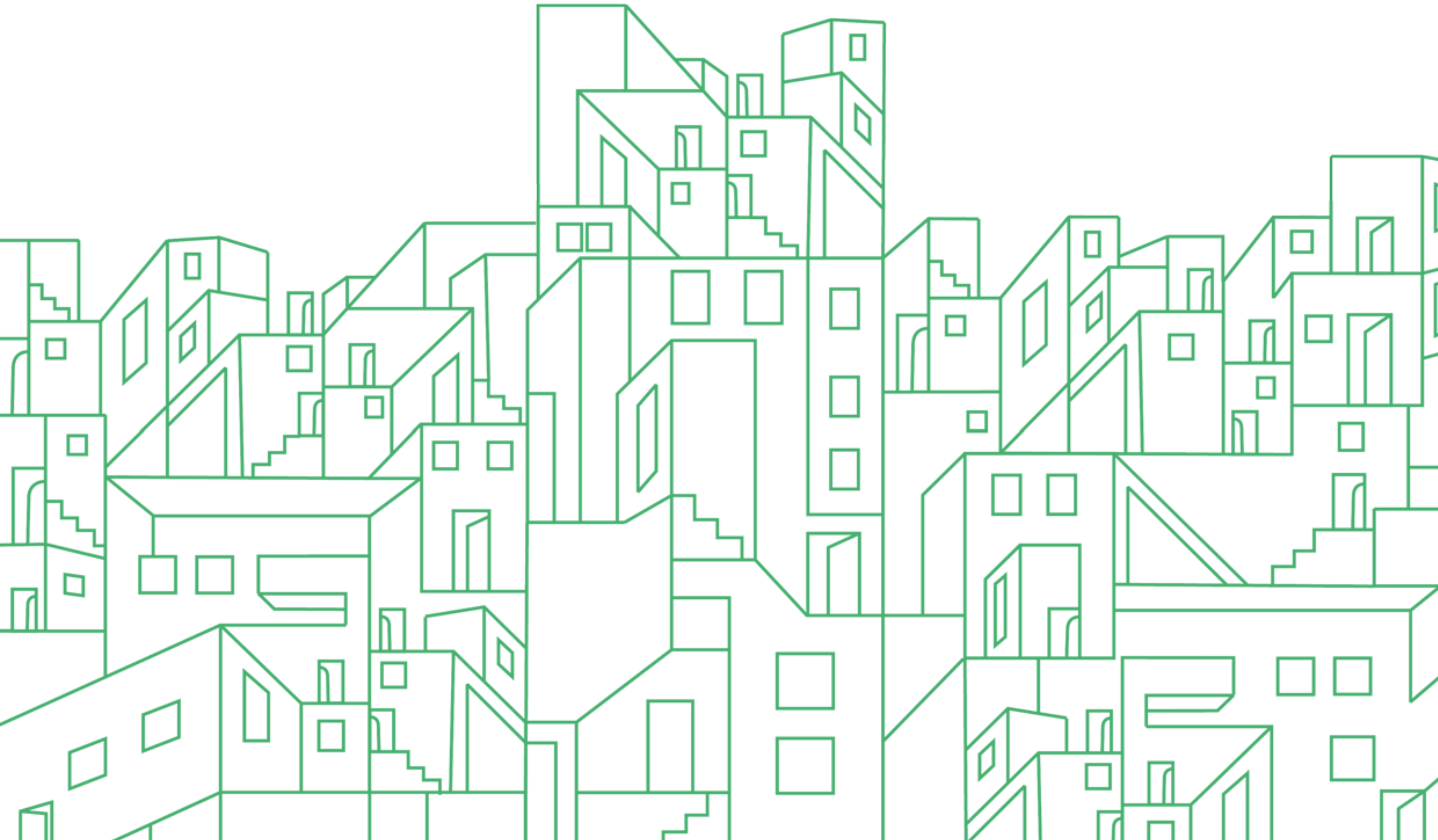


Figure 53: Percentage of Seated People Dissatisfied as Function of Air Temperature Difference Between Head and Ankles

Source: Abushakra Bass, Akers Larry, Baxter Van, Hayte Sheila & Paranjpey Ramesh (2017). ASHRAE Fundamentals SI edition.

4

AFFORDABLE HOUSING PASSIVE DESIGN STRATEGIES



4.1 Introduction

This chapter begins with a discussion on the definition of passive design measures. It proceeds to corelate passive design measures and their performance with the previously explained modes of heat transfer. Further, the chapter introduces the relevance of individual spatial design decision based and construction material based passive design measures. The interactions of these measures within themselves and overall impact on RETV is also explained. Further, the relevance of building operation strategies for thermal performance is established. The role of ventilation is in maintain thermal comfort is explained. Approach to designing efficient ventilation in all seasons is explained through theory and proven through experimental observations shared in case study.

4.1.1 Definition

While a universally accepted scientific definition of passive design does not exist, it can be explained as no or low-cost strategies that use building envelope components to maintain thermally comfortable indoor environment. It is noteworthy that passive design since passive design strategies do not involve use of electro-mechanical systems, they cannot lower the indoor air temperature. However, they can help to maintain thermal comfort. This is because passive design measures either reject the heat or delay the transfer of heat from outdoors to indoors to ensure excess heat does not enter the indoor spaces. Similarly building operation strategies such as natural ventilation, use air speed to induce thermal comfort at elevated air temperatures in certain cases. Passive design strategies can be broadly categorized into spatial design decisions-based strategies and construction material-based strategies.

Spatial design: This is the first layer of decision chain that holds potential to reduce heat gains in a building. Choices such as building form, orientation, shading elements, and more determine the amount of solar radiation reaching the envelope surface. By rejecting maximum possible solar radiation from interacting with the building envelope, spatial design strategies allow lower heat gains in the buildings.

Construction Material: After optimizing spatial design, the second approach for minimizing heat gains is selection of building envelope material. Preferences pertaining to construction materials of the envelope categorize as construction material-based design decisions.

Since most of the spatial design strategies have no to minimum cost implications, exhausting possible passive design strategies applicable in a project, followed by addressing material choices is instrumental in designing thermally comfortable affordable housing. Moreover, examining the possible contribution of building operation modes, especially naturally ventilation can guide design of façade elements i.e., fenestrations to effectively reduce discomfort hours at no additional cost.

4.1.2 Strategies for various modes of heat transfer

As established in chapter 2, there are three modes of heat transfer in buildings-conduction, convection, and radiation. Further, heat transfer through conduction happens through building envelope materials while convective heat transfer occurs due to motion of air in buildings. Radiation allows heat to enter the indoor space primarily through windows and roof.

Passive design strategies may tackle either one or a combination of these modes of heat transfer.

Orientation, and massing of the building act as passive design strategies by influencing the quantity and quality of radiation reaching the envelope surface. Similarly, shading devices obstruct the amount of radiation entering the buildings through windows. Fixed or movable shading devices can be chosen depending on the trajectory of sun and direction of the façade. Shutters, jalis, and vertical screens can also act as effective shading strategies to reduce radiative heat transfer (BEE, 2021).

Spatial design measures such as high volume to surface area of the indoor space and form of the roof can contribute to thermally comfortable indoors, especially in hot and dry climates. Since hot air rises towards the ceiling, designing spaces with high volume to surface area ratio (essentially taller structures) is an effective strategy. Additionally, strategic placement of windows defines the air flow patterns in the space and hence, facilitates ventilation that has potential to provide thermal comfort at elevated air velocities.

Since conductive heat transfer relies solely on the materials used in the building envelope and their capacity to restrict or allow heat flow, conductive heat transfer can only be addressed through material choices. Chapter 6 provides further detail on construction material and envelope assembly designing.

Table 15: Passive design strategies categorized based on modes of heat transfer

Mode of heat transfer	Passive Design strategies applicable
Conduction	Materials and Construction
Convection	Space Volume, Building form- (Roof form, plan)
Radiation	Orientation Shading/ Brise Soleil, jail etc

4.2 Initial Strategies

4.2.1 Form and orientation

Decisions concerning form and orientation modulate the interactions of solar radiation with the building throughout the year (DeKay & Brown , Wiley, 2014). Simulation results of a building with fixed floor area in the hot and dry city of Ahmedabad show that a square form leads to a peak cooling load of about 8.45 kW on a specific summer day. If a building with same floor area is designed in a rectangular form with the ratio of its sides as 1:2 or 1:3, the peak cooling load changes depending on the orientation of the longer side. In both cases, an East-West orientation i.e., the longer walls face north and south, shows a lower peak cooling load than North-South orientation. Results from the conducted simulation studies are shown in Figure 54 and key takeaways are summarised as follows:

- Rectangular building form with 1:2 proportions is most suitable in hot and dry climate
- Preferred orientation to reduce solar gains in northern hemisphere is east-west
- Smarter orientation, wherever possible, can reduce peak cooling loads for the same floor

4.2.2 Window-to-wall ratio

Another passive design strategy to control the heat ingress in buildings through glazing is optimizing the ratio of glazed are to total wall area referred to as window-to-wall area ratio (WWR).

WWR is defined by the total fenestration area to the total gross area of the building envelope which is limited to 70 percent(BIS, 2016).

Determining the WWR helps to bring accuracy to predictions of contribution of radiative heat transfer through windows towards total cooling load of the building. Further, various combinations of form, orientation, and WWR can be developed and assessed to minimize cooling load during the design phase. Figure 55 represents the comparison between annual cooling loads for various window-to-wall area ratios

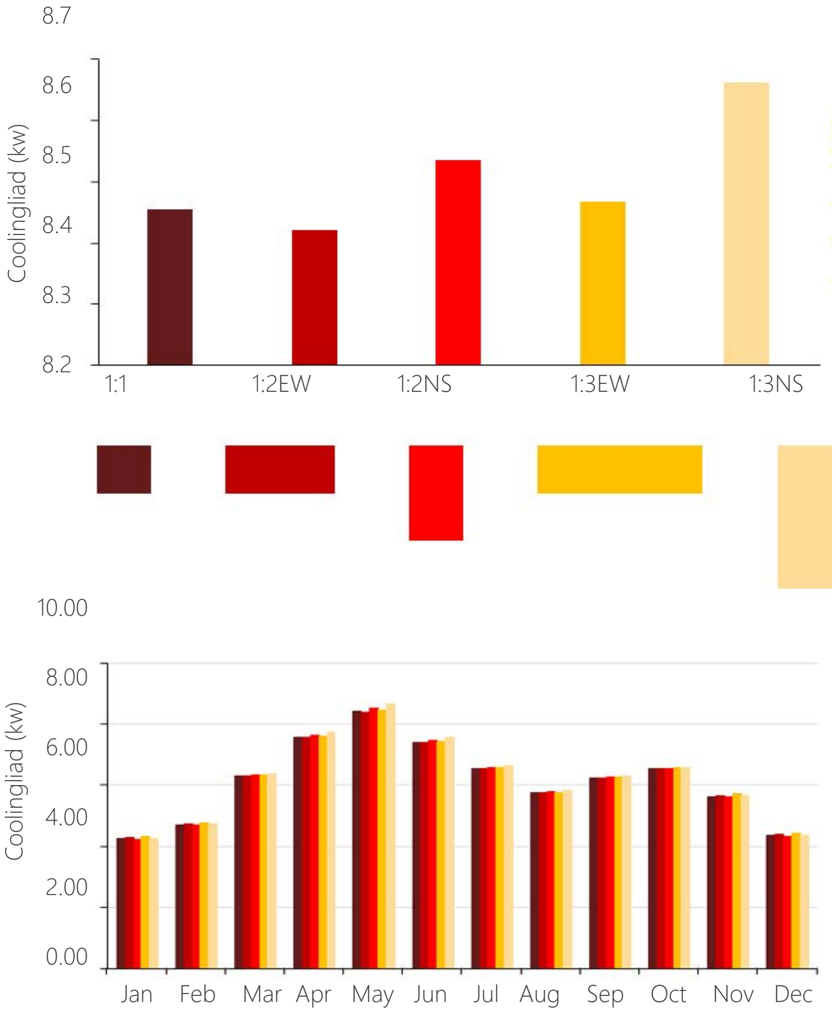


Figure 54: Top: peak cooling load for various forms and orientations; Bottom: variations in peak cooling load for each month for all sample cases.

(WWR) of business-as-usual buildings and buildings following prescriptive baselines detailed in ECBC with the same construction area. It can be observed that in both BAU cases, heat gains are higher for all WWR cases. Key takeaways from the simulation studies include:

- Greater WWR escalates the cooling load significantly in BAU cases. However, compliance with ECBC code results in reduced cooling load across the four WWR cases.
- Moreover, the cooling loads of nearly all WWR options in ECBC compliant building remain lower than the minimum WWR of 20% in BAU i.e. compliance with ECBC offers more flexibility in choosing WWR to increase daylighting
- Even with less favourable orientations, cooling loads can still be reduced by designing for code compliance

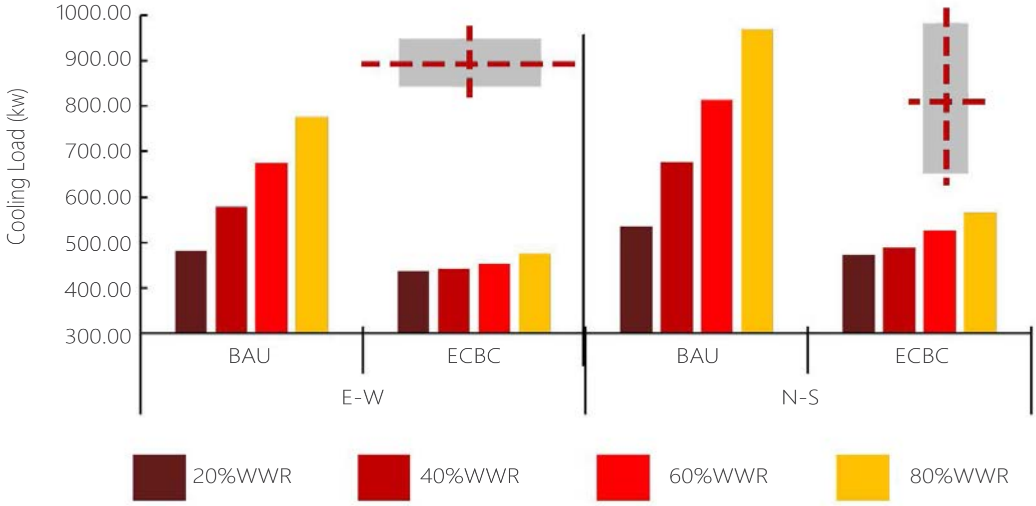


Figure 55: Comparative analysis of various WWR levels in East-West and North-South orientations for business-as-usual and ECBC compliant buildings

4.2.3 Shading strategies

In addition to orientation and WWR, shading strategies for the glazed components of building façade also offer reduced cooling loads for the buildings.Figure 56 presents comparison for cooling load in BAU buildings and buildings following shading measures and building envelope metrics prescribed in ECBC, ECBC and ECBC super buildings for window shading. BAU case presents cooling load in kW when no shading is present on the windows while ECBC, ECBC+, and ECBC super cases depict cooling loads for efficient construction when 600 mm of window shading is provided as per right-side image in Figure 56 for all windows of the simulated building.

In the context of India, fixed shading elements such as chajjas and box windows are more suitable to provide shading on the northern and southern facades of the building which receive radiation from sun with high altitude angle. However, dynamic/movable shading is required to protect the eastern and western facades of the building from the angular sun. Further, India receives a significantly large fraction of diffused radiation (due to presence of dust and clouds in the atmosphere) which the fixed shading systems cannot address. Hence, external movable shading devices/systems that are adjustable in different positions depending on the sun's trajectory throughout the day are more efficient in blocking the solar radiation from entering the building (BEE, 2021). Key takeaways include:

- Code compliance by addressing SHGC through shading provisions can lower cooling loads.
- Fixed horizontal shading is useful in blocking radiations from the overhead sun in the North and South oriented facades
- Dynamic movable external shading systems, vertical shading elements like fins are more useful in cutting radiations when the sun is at a lower altitude i.e., in East and West facades

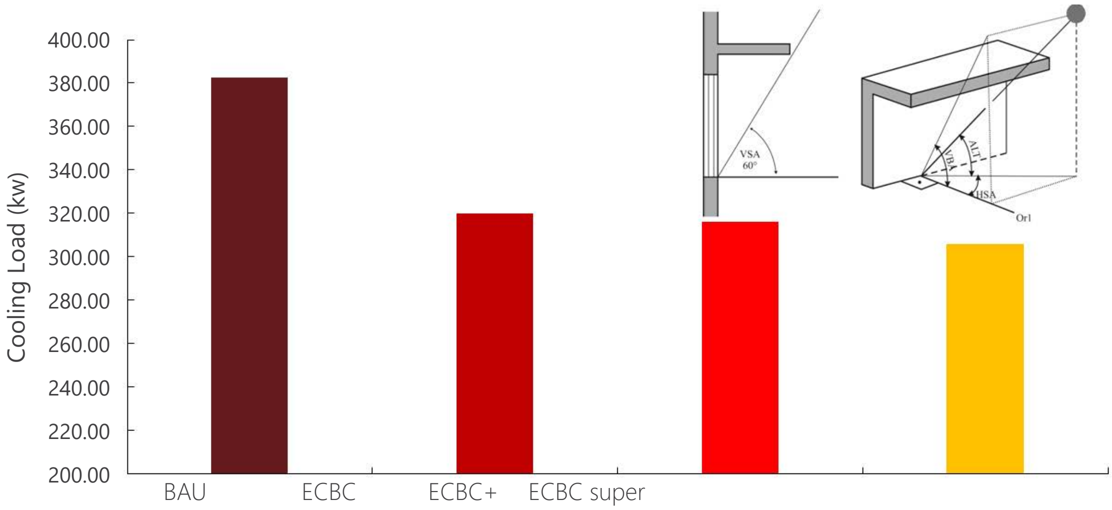


Figure 56: Left- Cooling loads for BAU, ECBC, ECBC+, and ECBC super buildings having 600mm shading over windows in all cases except BAU; Right- specifications of shading simulated for ECBC, ECBC+, and ECBC super buildings.

4.2.4 SHGC

Pertaining to glazing and fenestration systems, the Solar Heat Gain Coefficient (SHGC) factor of window glass is the ratio of heat transferred to the indoors (through both direct admission of short-wave radiation and internal emission post absorption of long wave radiation), to the total amount of radiation incident on the glass (BIS, 2016). Figure 57 presents the correlation between shading of windows and SHGC factor. The first and second graphs represent SHGC of an unshaded and shaded window (600 mm overhang) respectively. As can be observed in the third graph the difference in SHGC for the two cases is significant. Lower the SHGC, lower will be the cooling load of the space (ASHRAE, 2021).

Low SHGC values of the glazing system can also be achieved using low e-glass (refer section 5.4 for more details), window tints, reflective coatings, and other options. However, consideration of Visible Light Transmittance (VLT) levels to ensure adequate use of daylighting is relevant to maintain low energy consumption. The same is discussed in further detail in section 5.4.

4.2.5 RETV

A significant construction material-based passive measure to reduce solar heat gains is achieving RETV value of 15 W/m2. The same is prescribed in ENS (Bureau of Energy Efficiency, 2018). As shown in Figure 58, for a typical affordable multi-family housing building, measures such as installing insulation in walls, meeting prescribed roof U-value by using high solar reflective paint or material in the roof can lead to low RETV values. Further lowering of RETV to ensure compliance with ENS can be achieved by reducing

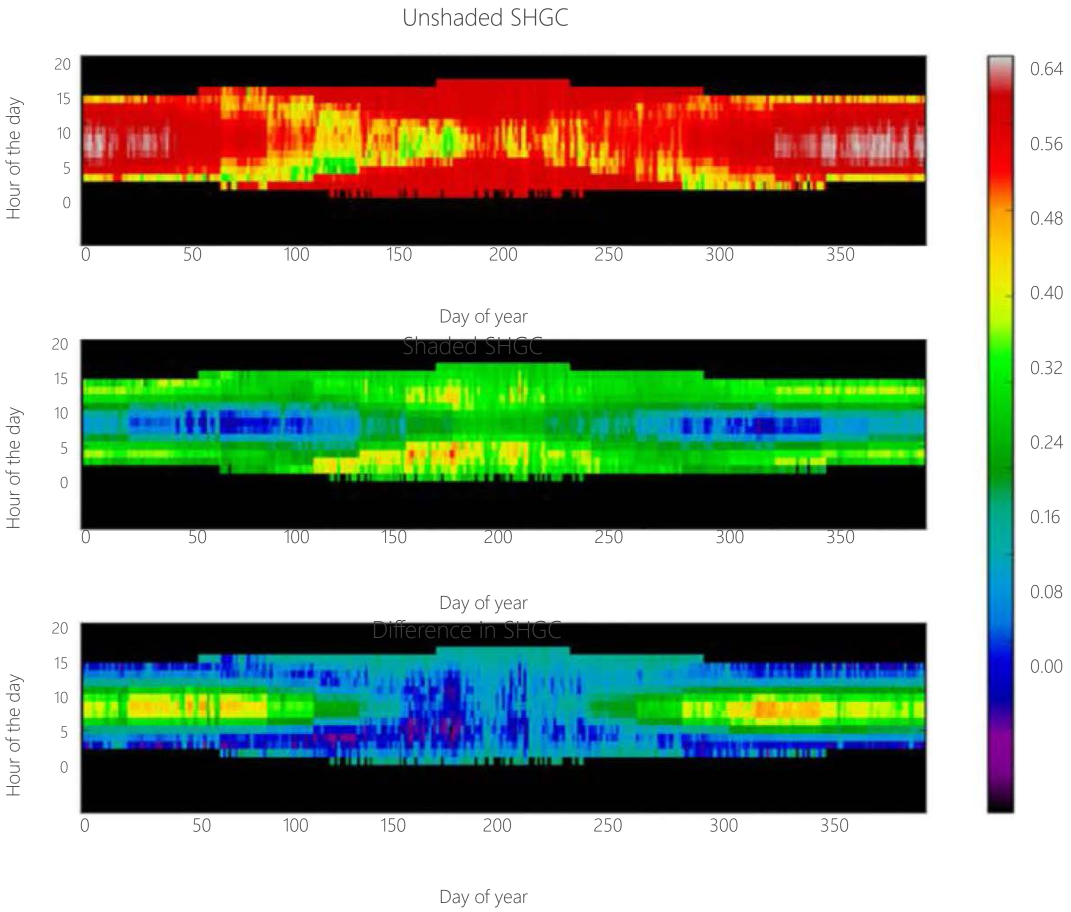


Figure 57: Top- SHGC values of an unshaded window throughout the year; Middle- SHGC values of the same windows in case of shading present throughout the year; Bottom- Difference in SHGC values of the first two graphs.

SHGC value of glass while maintaining desirable VLT and U-value. Hence, combination of multiple passive design measures can contribute to RETV value of 15 W/m2 or less making thermally comfortable affordable and resilient housing a possibility.

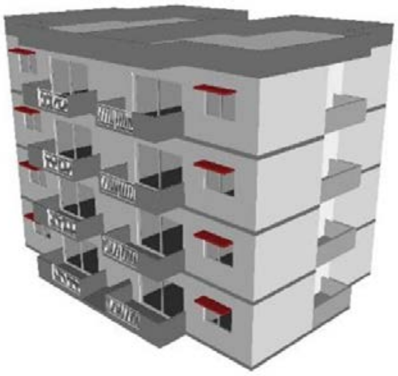
4.2.6 Construction configuration

The thermal performance of a building envelope component depends on the selection of materials for each layer of the assembly- walls, windows, or roof. Decisions such as presence of insulation in the assembly, thickness of various layers, sequence of layers affects the overall performance of the wall in given climate.

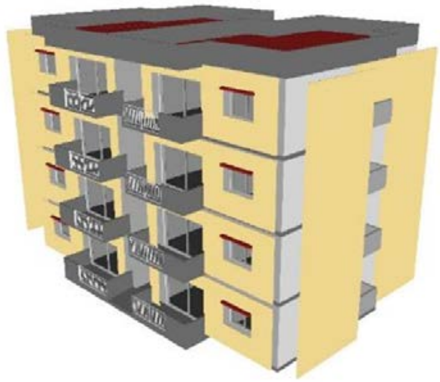
4.2.7 Interaction between parameters

Since architectural design for each project vary in specifications, it is not feasible to adopt the same pathway in achieving prescribed RETV values. However, with varying start points and design decision priorities, it is possible to reach the same end goal as shown in Figure 60.

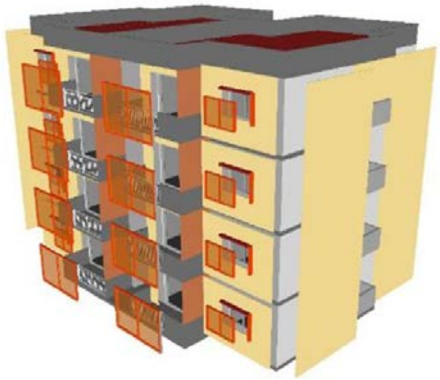
Several studies on vernacular architecture of Indian cities have emphasized the contribution of traditional passive design strategies. Appropriate use of materials, spatial organization and construction techniques together ensure comfortable environment inside these houses (Radhakrishnan, Shanthi, Nagan, & Sundarraja, 2016). Hence, calibrated implementation of traditional and advanced passive design measures can



RETV- 21.0 W/m²
Business-As-Usual
Building Envelope



RETV- 18.0 W/m2
Building Envelope Details:
Better insulation in walls and roof
(U-value)
High solar reflectance on
roof (SRI)



RETV- 15.0 W/m2
Better Windows (U Value, SHGC, VLT,
Building Envelope Optimization)

Figure 58: Top- RETV value of typical affordable multifamily residential building; Middle- RETV value after initial envelope optimization strategies; Bottom- RETV value meeting ENS compliance after glazing related optimization strategies

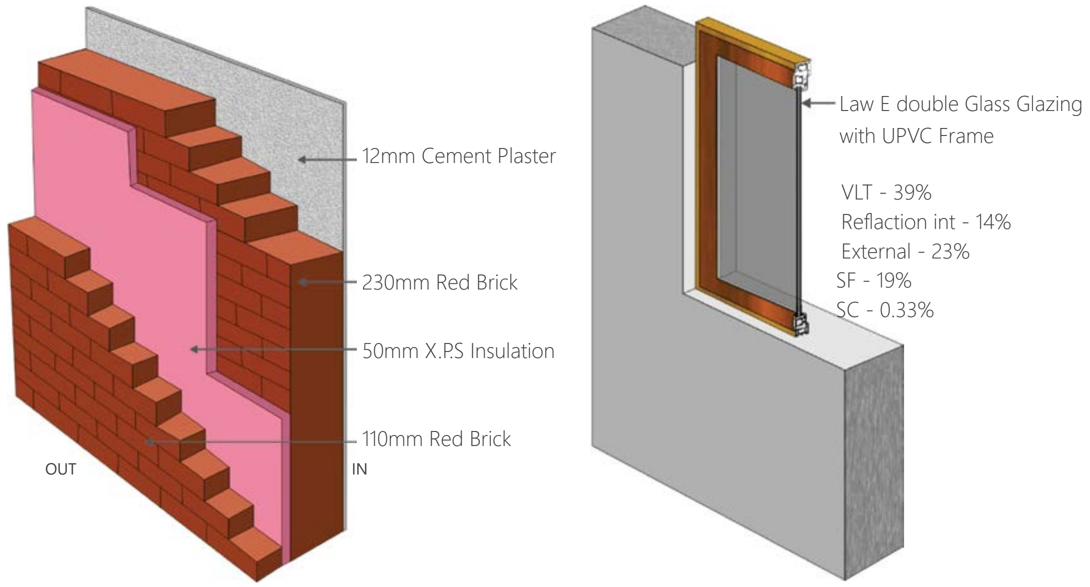
guarantee thermally comfortable spaces inside buildings for most part of the year in certain climates.

4.3 Role of ventilation

4.3.1 Operating buildings with comfort strategies

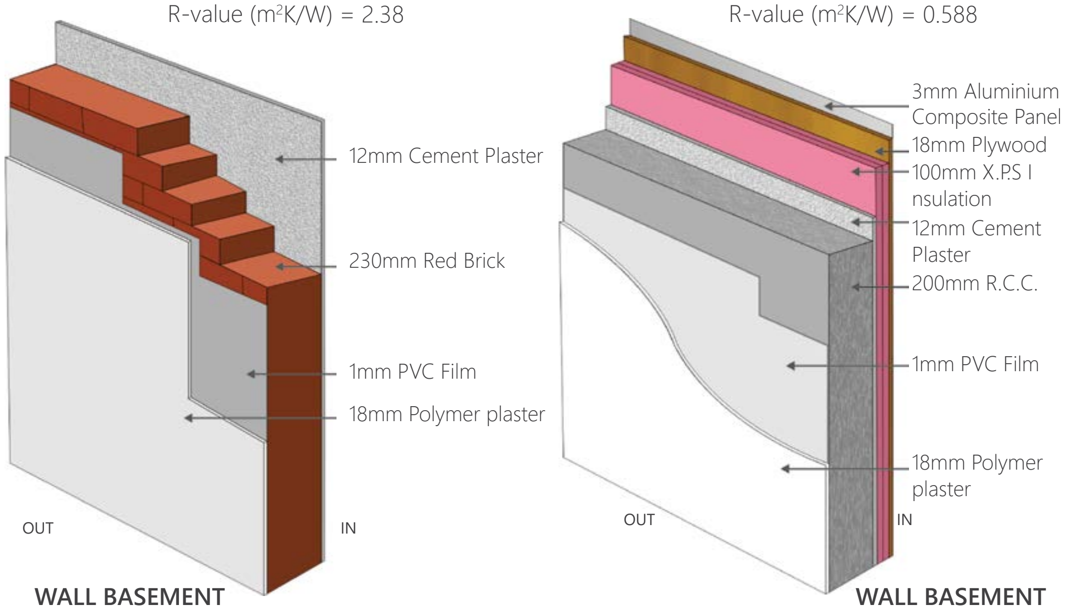
Using the weather data from the Indian Society of Heating, Refrigeration, and Air-conditioning Engineers (ISHRAE), the India Model for Adaptive Comfort (IMAC) model separates the outdoor conditions into nine categories based on outdoor temperature and humidity. It offers the most suitable building operation strategy for each of the nine categories, applicable across 56 Indian cities. Specifically developed for the Indian conditions based on thermal comfort surveys of Indian office buildings (Manu , Shukla , Rawal , Thomas , & Dear, 2016), the IMAC model has been integrated into the National Building Code of India (BIS, 2016). The nine operation modes with the corresponding outdoor conditions are listed in Table 16. Additionally, Figure 61 presents the percentage of comfort hours in a year for different building operation modes listed in IMAC-MM for twenty Indian cities located in three climate zones: warm–humid, hot–dry, and composite.

Effective operation of openable elements of the building envelopes such as windows, doors, and building appliances such as fans, provide the occupants with adaptive opportunities to alter their immediate environment (Cook, et al., 2020). Window operation is an effective adaptive measure in most Indian residences. Favourable outdoor thermal environmental conditions offer occupants the opportunity to open the windows and allow outdoor air to ventilate indoor spaces. Seasonal usage of blinds



WALL SUPER STRUCTURE
U-value (W/m²K) = 0.42
R-value (m²K/W) = 2.38

WINDOW
U-value (W/m²K) = 1.70
R-value (m²K/W) = 0.588



WALL BASEMENT
U-value (W/m²K) = 2.01
R-value (m²K/W) = 0.50

WALL BASEMENT
U-value (W/m²K) = 0.28
R-value (m²K/W) = 3.59

Figure 59: Wall, window, and basement assemblyexamples

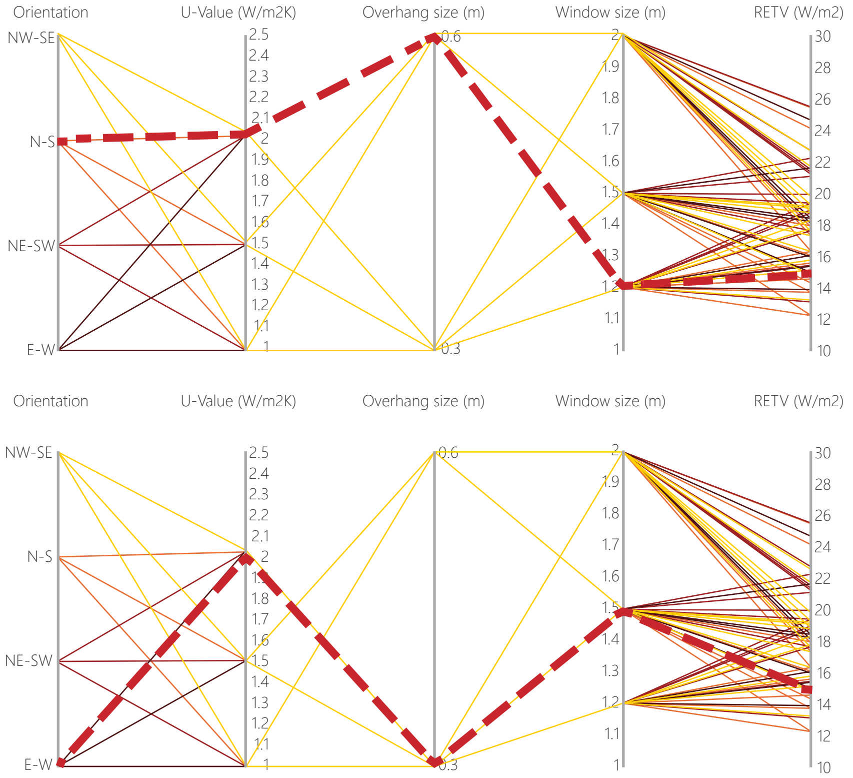


Figure 60: Multiple pathways to achieve RETV value of 15 W/m2 prescribed in ENS

made from material such as bamboo placed externally, can protect windows from direct solar radiation but allow natural ventilation in favourable outdoor temperatures.

From Figure 61, it can be observed that natural ventilation as a standalone strategy can provide comfort for around 35% of the total hours of the year in hot-dry, warm-humid, and composite climates. These hours include daytime and night-time ventilation. Consider the case of a residential building in Hyderabad. The IMAC model-based climate analysis graph shows that natural ventilation (NV) can be used to achieve nearly 42% of the total comfort hours in a year. Moreover, merely dehumidification of the indoor environment can elevate the percentage of comfort hours in a year to nearly 80% leaving only 20% of the comfort hours to require strategies that involve active cooling.

The analysis offers opportunity to compartmentalize the implementation of different strategies in achieving thermal comfort with minimal dependence on electrical energy. Natural ventilation, low energy cooling, and judicious use of refrigerant-based air-conditioning can together provide thermally comfortable indoor environments in a mixed-mode building operation strategy (Cook, et al., 2020).

4.3.2 Harnessing ventilation with windows

Natural ventilation is defined as provision of fresh air and removal of stale air using the naturally occurring forces of wind and buoyancy to drive airflow through purpose-provided openings in the building envelope(Cook, et al., 2020).

Theoretically, NV rate can be predicted for only constant conditions i.e., steady state ventilation even though the causes for natural ventilation are constantly changing. Understanding driving forces and their interactions leads to an understanding of the

Table 16: Conditions for operation modes per the temperature (based on the IMAC models) & RH thresholds. Source: Manu et. al. (2016).

Operation mode	Temperature thresholds	RH thresholds
Natural Ventilation	Within the 80% acceptability band	30% -70%
Heating	< Lower limit of 80% acceptability	30% -70%
Heating and Dehumidification	< Lower limit of 80% acceptability	>70%
Cooling	> Upper limit of 80% acceptability	30% -70%
Cooling and Dehumidification	> Upper limit of 80% acceptability	>70%
Dehumidification	Within the 80% acceptability band	>70%
Humidification	Within the 80% acceptability band	<30%
Heating and Humidification	< Lower limit of 80% acceptability	<30%
Cooling and Humidification	> Upper limit of 80% acceptability	<30%

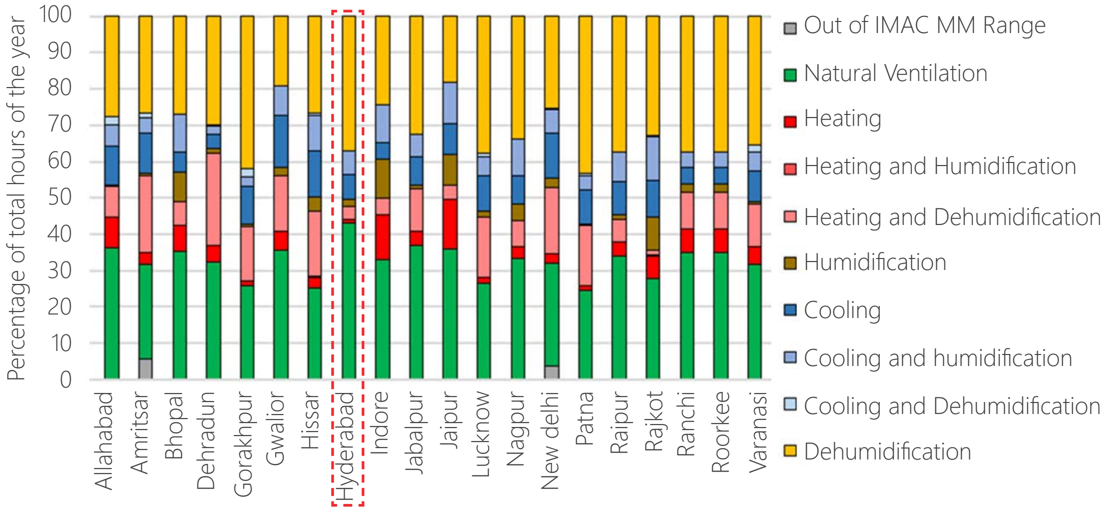


Figure 61: Percentage of comfort hours in a year for different building operation modes listed in IMAC-MM. Source: M., Shulka, Y., Rawal, R., Loveday, D., de Faria, L., Angelopoulos, C. (2020). Low Energy Cooling and Ventilation in Indian Residences Design Guide. CEPT Research & Development Foundation & Loughborough University. http://carbse.org/reports-and-articles/

natural air movements and airflow patterns. Natural ventilation is induced in the form of stack effect. This buoyancy force (stack effect) is a result of temperature differences between indoor and outdoor air. When outside and indoor temperatures are closer, these forces are small. Similarly, larger temperature differences between indoors and outdoors lead to significant stack effect. Understandably, designing appropriate ventilation strategies for times when the buoyancy forces are smaller is a greater challenge. Another factor at play is wind. Typically, NV systems are designed to ensure that buoyancy forces alone can provide adequate NV flow rates in absence of winds. Figure 62 shows the principles of buoyancy-driven NV.

Inside a space, warm air rises and forms a layer of buoyant air near the ceiling. Since there is lack of wind in the space, the buoyant air creates a hydrostatic pressure in the area. Compared to this pressure, the outside pressure at same height is lower. Hence, the buoyant force moves hot air outdoors from the inside space at heights near the ceiling. Closer to the floor, the openings at lower level allow cooler outside air to enter the space where the pressure balance is inverse to that near the ceiling.

The complex pressure distributions outside the buildings driven by wind forces are explained in Figure 63. Since moving air or wind is obstructed by the building, on the windward side, higher pressure is created. Further, as the air moves over and around the building towards the leeward side, the pressure gradually reduces and air speed increases. The pressure differences generated between indoors and outdoors because of non-uniform pressure distribution outside the building result in ventilation flow. Moreover, factors such as wind speed, direction, building form, shape and size affect the discussed pressure distribution and resulting pressure differences. This presents architects with an opportunity to design building elements such as fins and more that reorient pressure differences and drive natural ventilation in desirable manner. Additionally, the pressure on building exterior increases with height, allowing flexibility in design and adding scope for differences in fenestration details at various floors of the residential building . The sizing of ventilation openings to effectively deliver NV can be derived from design charts shown in Figure 65 through Figure 68. Their corresponding space ventilation illustrations are provided in Figure 64.

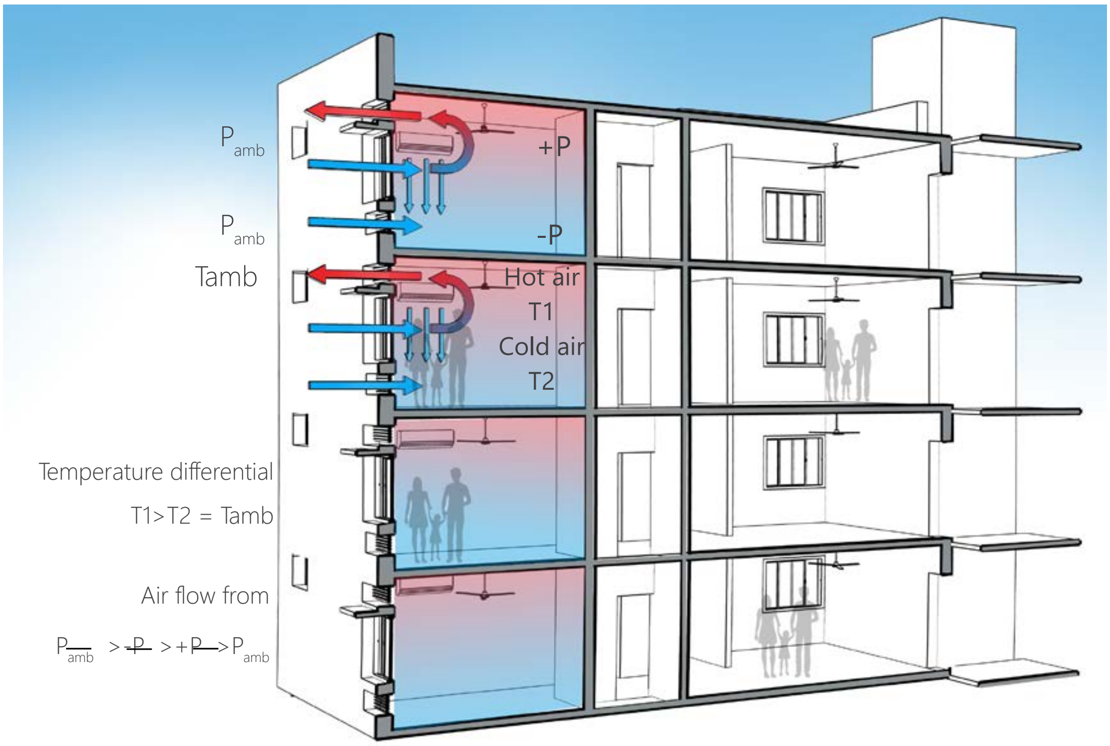


Figure 62: natural ventilation principles driven by buoyancy forces. +P denotes positive pressure regions and -P denotes negative pressure regions.
Source: (Cook, et al., 2020)

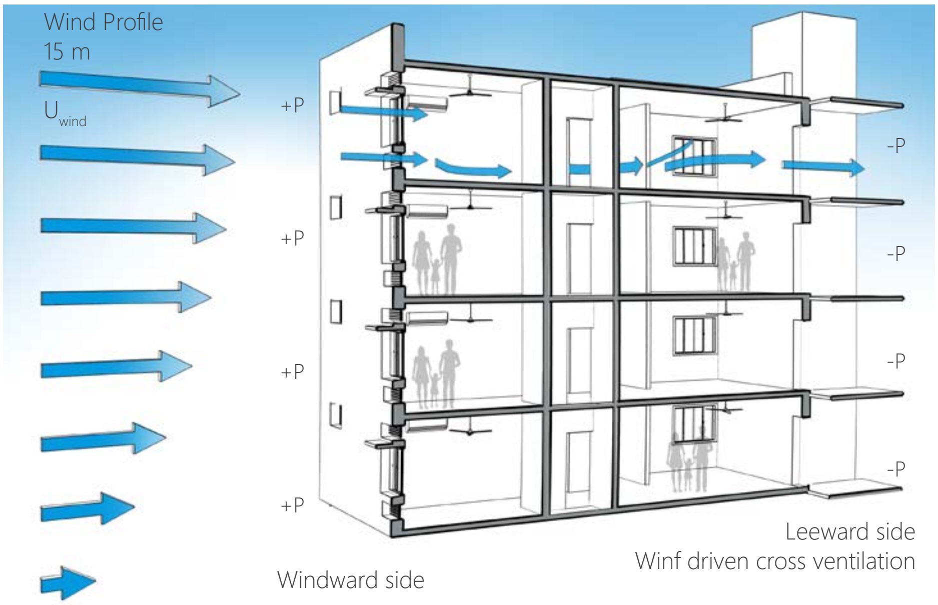


Figure 63: Pressure distribution outside a building and resultant ventilation flow.
Source: (Cook, et al., 2020)

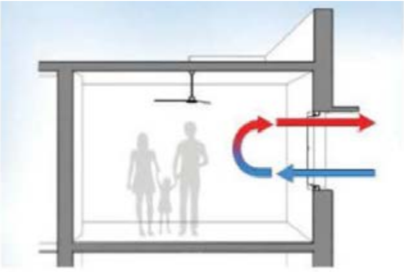


Figure 64a

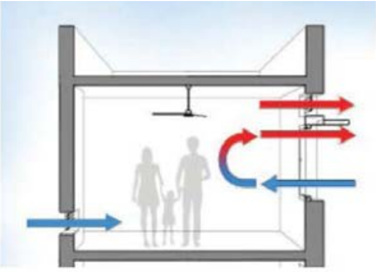


Figure 64b

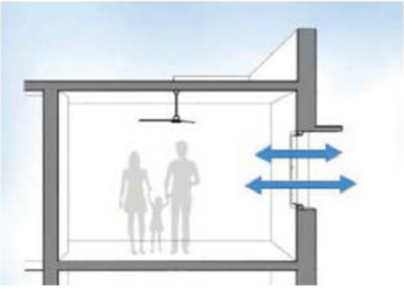


Figure 64c

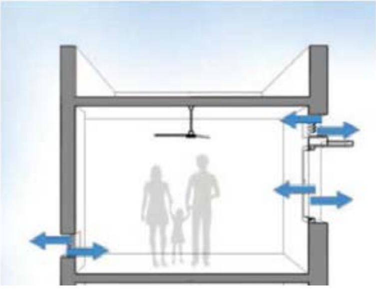


Figure 64d

Figure 64: Cross-section sketches of the driving forces for the naturalventilation systems presented in the four design charts.
Source: (de Faria, et al., 2018)

The four most common configurations in Indian residential buildings are presented in design charts.

- DC-01: buoyancy-driven flow; single-sided ventilation with one opening (Figure 65 and Figure 64a)
- DC-01: buoyancy-driven flow; cross ventilation with multiple openings (Figure 66 and Figure 64b)
- DC-01: wind-driven flow; single-sided ventilation with one opening (Figure 67 and Figure 64c)
- DC-01: wind-driven flow; cross ventilation with multiple openings (Figure 68 and Figure 64d)

Essentially, the design charts corelate air flow rate (designed or achieved) with geometrical free area (A_f) (Jones, Cook, Fitzgerald, & Iddon, 2016) for various air velocities. If desirable air velocity and air flow rate (i.e. volume of air to be displaced every second) is known, the charts can be used to obtain the geometrical free area of window openings required to deliver the air flow rate. Once the free area is known, it can be used to determine the effective area (A_{eff}) for windows, thus guiding window design for effective ventilation. A_f quantifies the total unobstructed cross-sectional area which is at right angles to direction of air flow. Considerations such as shape of the opening, air density, wind speed, and direction are characterized as discharge coefficient (C_d) to calculate A_{eff} based on Aeff = $C_d.A_f$.

Comfort through ventilation (natural or forced) happens due to removal of excess heat from the space. However, it requires ventilation design that is effective in most weather conditions and for maximum number of comfort hours. Maintaining comfort through NV operation based on the design charts is possible in all weather conditions for residential buildings in selected Indian climate zones. Using IMAC as the basis for thermal comfort evaluation in residences where Natural Ventilation (NV) and Mixed Mode (MM) situations prevail, ventilation rates can be predicted for an NV system. (Cook, et al., 2020).

Efficient ventilation demands better window designs. In addition to being openable, window systems should also be air-tight to avoid air leakage upon closing. Further,

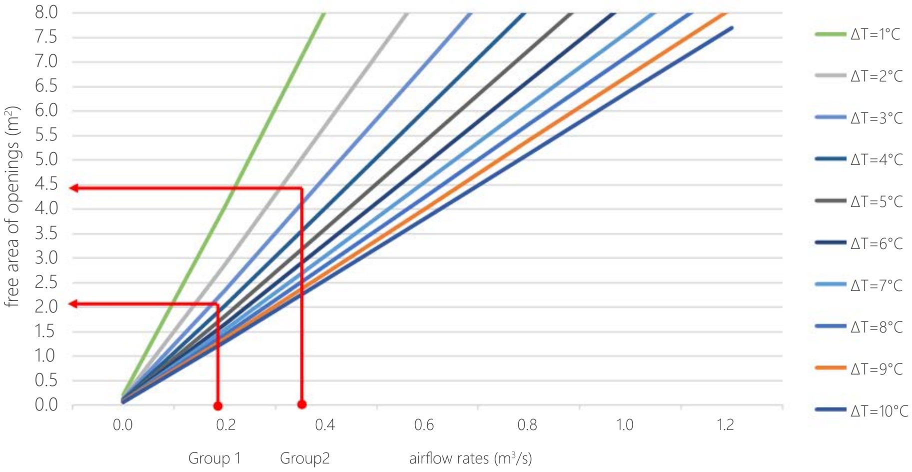


Figure 65: Design Chart DC-01 for single-sided single opening buoyancy-driven flow.
Source: (Cook, et al., 2020)

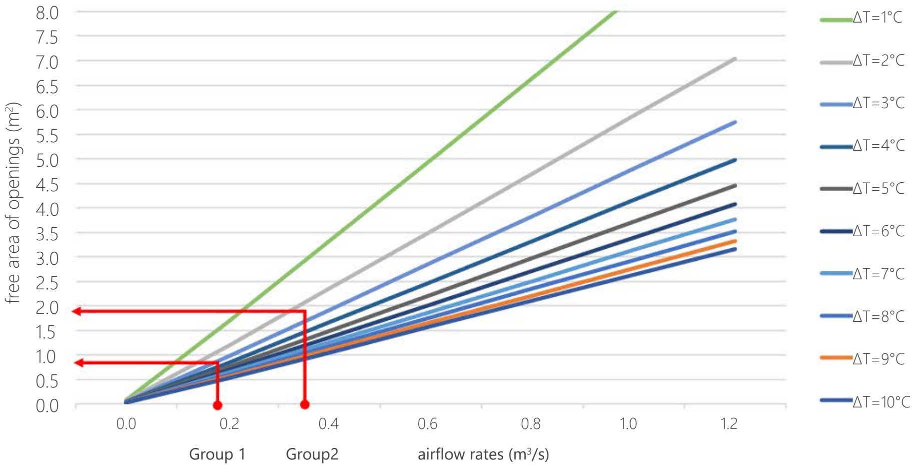


Figure 66: Design Chart DC-02 for multiple openings and buoyancy-driven flow.
Source: (Cook, et al., 2020)

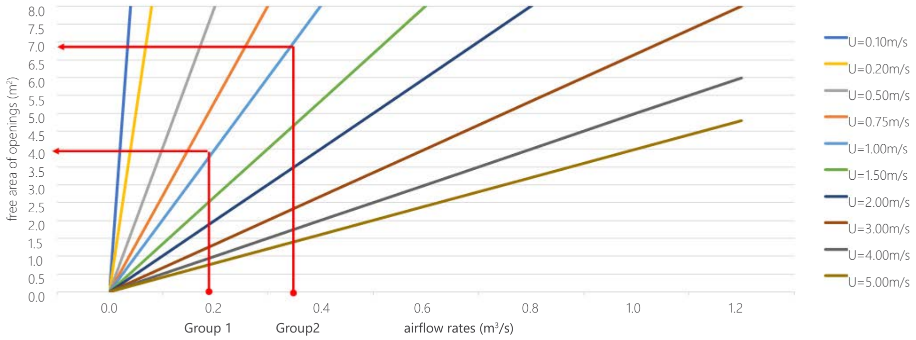


Figure 67: Design Chart DC-03 for single-sided single openings and wind-driven flow.
Source: (Cook, et al., 2020)

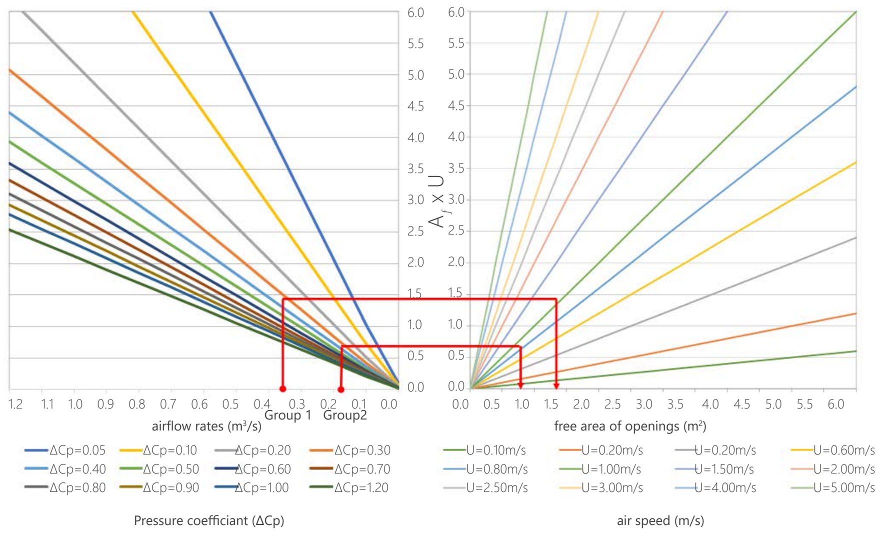


Figure 68: Design Chart DC-04 for multiple openings and wind-driven flow.
Source: (Cook, et al., 2020)

smaller ventilation openings above the windows allow warmer air to escape the space and generate ventilation air flows through pressure differences. Lastly, varying design of windows at different floor levels allows them to respond to the non-uniform pressure distributions outside the building and take advantage of the same for effective ventilation.

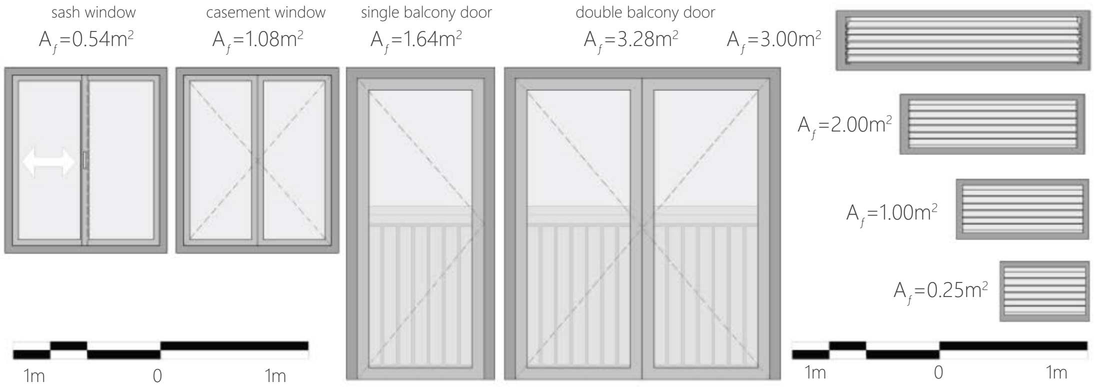


Figure 69: Geometrical Free Area (Af) for various door, window, and ventilation opening types.

4.4 Case Study- The Blessing House, Auroville, India

4.4.1 Background

Numerous studies have documented the thermal performance of passive design elements and naturally ventilated buildings in India. This section presents a case study (Doctor-Pingel, Vardhan, Manu, Brager, & Rawal, 2019) of a residential building in warm-humid climate experienced in Auroville, India. Table 17 presents relevant details pertaining to the naturally ventilated Blessing House studied for its indoor thermal parameters.

Table 17: Details of the Blessings House in Auroville, India

Building	Blessing House (AV)
Storeys and rooms	G+1 with 2 rooms and a mezzanine
Function	Private Residence and Workplace
Built-up Area (m^2)	107
Zone under study (m^2)	24
Hours Occupied/ Unoccupied	Always Occupied
No. of Occupants	2-3
Zones/Features Studied	Bedroom, Aerocon Insulated Roof Assembly, Balcony (Night Flushing)
Monitoring Period	SEP 2013-AUG 2014

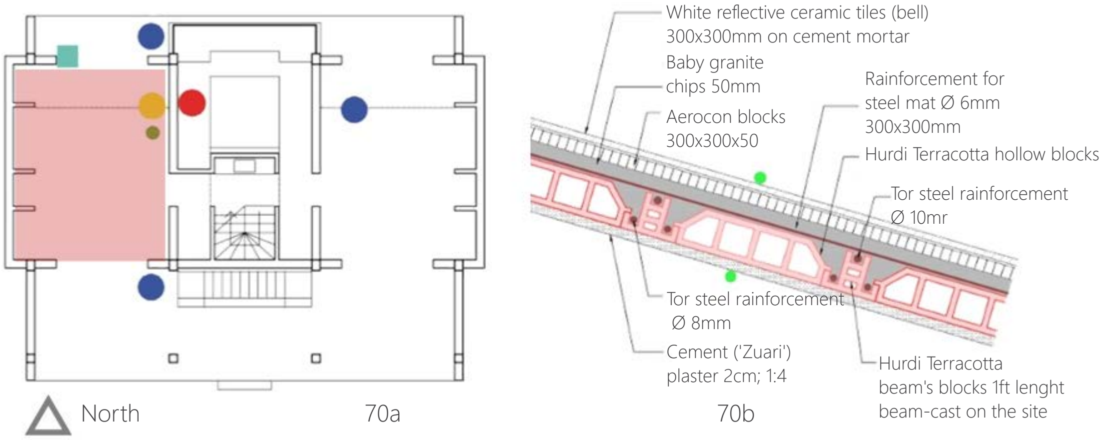
4.4.2 Passive design measures

As indicated in Table 17, the Blessing House is a two-story residential building with a home office located in Auroville, India. The design and construction of the house involves multiple passive design strategies.One of them is the roof assembly shown in Figure 70b. Moving from indoors to outdoors, the roof assembly consists of hurdi terracotta hollow blocks with reinforcement, a layer of cement concrete followed by

AAC blocks and finished with white reflective ceramic tiles on top. The inside surface is finished with cement plaster.

Another prominent construction material-based passive design feature of the house is the walling assembly consisting of compressed earth blocks shown in Figure 71. Moving towards outdoors, the compressed earth block layer is followed by a layer of Aerocon blocks, also known as AAC (Aerated Autoclaved Concrete) blocks. Both inside and outside surfaces of the assembly are finished with cement plaster. The compressed stabilized earth blocks layer (CSEB) renders high thermal mass to the assembly preventing the loss of indoor coolth through walls. Additionally, AAC blocks offer better insulation; thus, preventing heat from outdoors to enter the house.

On top of the passive design strategies, the occupants of the Blessing House utilize night-time natural ventilation strategy. By opening the windows at night and closing them in the morning, they condition the thermal environment of the house naturally at desirable levels. This pre-cooled environment is then maintained throughout the day by the walling assembly.



70a 70b

Figure 70: Blessing house architectural and monitoring details;70a- Position of HOBO loggers for monitoring the occupied zone; Yellow dot- HOBO Logger A(RH/Tair/lux), Red dot- HOBO Logger B 2ch(RH/ Tair),Blue dot- HOBO Logger D(RH, T), Green dot- Surface temperature sensor; Green square- logger to record open/close state of balcony window; 70b- Roof construction detail;
Source: (Doctor-Pingel & Vardhan, Blessing House: Post Occupancy Analysis, 2017);

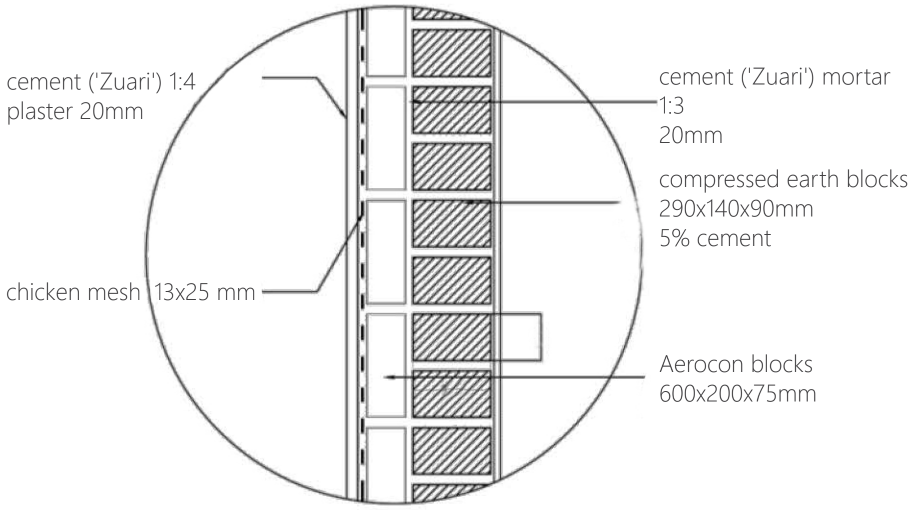


Figure 71: Walling assembly in Blessing House located in Auroville, India

The monitoring of the thermal parameters of the house included measuring the air temperatures and relative humidity using installed HOBO data loggers as well as measuring instantaneous air velocity through hand-held devices. Refer to chapter 7 for ways to measure parameters of the thermal environment.

4.4.3 Results and Analysis

Air Temperature (T_a) and Relative Humidity (RH)

Figure 72a and Figure 72b indicate the variation of hourly averaged Ta and RH trends for the hottest and coldest months of June and January for the occupied bedroom zone (Doctor-Pingel, Vardhan, Manu, Brager, & Rawal, 2019). The occupant controlled natural ventilation during the morning and evening, small fenestration size and use of blinds to blocks excess sunlight maintained indoor temperatures within a range of 1.3°C and 1.2°C for June and January respectively. The use of insulated Aerocon blocks on south and east facades also contributed in moderating the temperatures of the occupied space.

Roof Temperature

Figure 72c shows the variation of hourly averaged Ts for the sloping hollow block roof during the month of June. The air cavities in the hollow blocks contributed to lower thermal transmittance, while the white reflective tiles helped in reducing absorption of solar radiation. Additionally, sloping of the roof against the angle of the summer sun resulted in reduced normal radiation absorption.

Passive Design Strategy: Night Flushing

Figure 72d shows the variation of hourly averaged Ta for the indoor zone and balcony for June and January. It can be observed that the indoor temperatures remain lower and within a relatively smaller range as compared to the air temperatures in the balcony

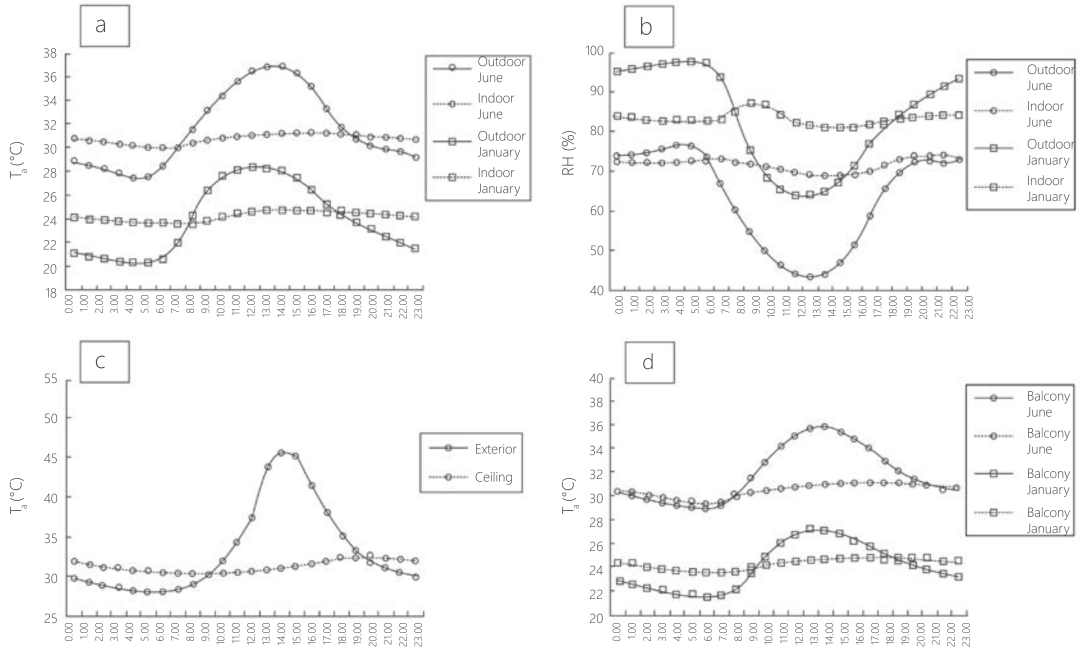


Figure 72: Variation of hourly averaged 72(a). Indoor Ta for the hottest and coldest months. 72(b). RH for the hottest and coldest months. 72(c). T_s across the roof assembly for the hottest month. 72(d). T_a across the balcony and indoor zone showing the temperature difference due to night flushing for the hottest and coldest months.

for both June and January months. This can be attributed to the natural ventilation at night time strategy where warm indoor air was allowed to be replaced by cool ambient air. The HOBO logger readings were used to determine the average window opening and closing times. For the first three weeks of June- the hottest month, the windows were closed at 07h00 and opened at 18h32 on an average. To accommodate for seasonal variations in outdoor temperatures, the average operation times were changed to 07h33 and 20h34 in the month of January with 8 instances of deviation from designated pattern. Additionally, it was found that the 'night-flushing' strategy maintained indoor temperatures at 4.9°C lower than the air temperature of the balcony zone during the hottest summer hour.

Key takeaways from the case study:

- Identifying the most efficient design-based and construction material based passive design measures for given building and climate is crucial to achieve maximum performance.
- Ensuring design details such as effective area of window openings and ventilation flow rates provides opportunity for the strategies to perform with efficiency
- In addition to designing and building with passive design strategies, it is equally relevant to operate buildings, specifically for ventilation-based strategies in accordance with the design measures.

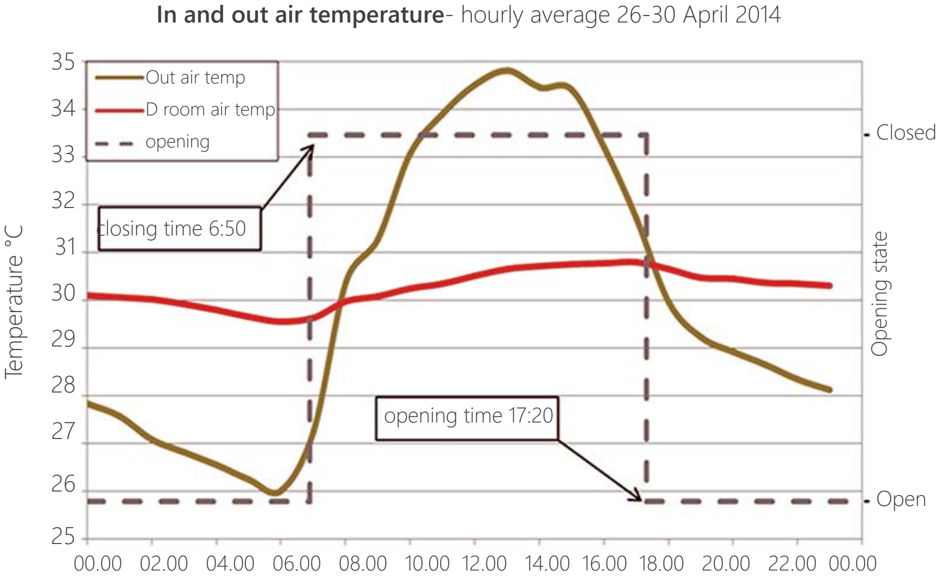
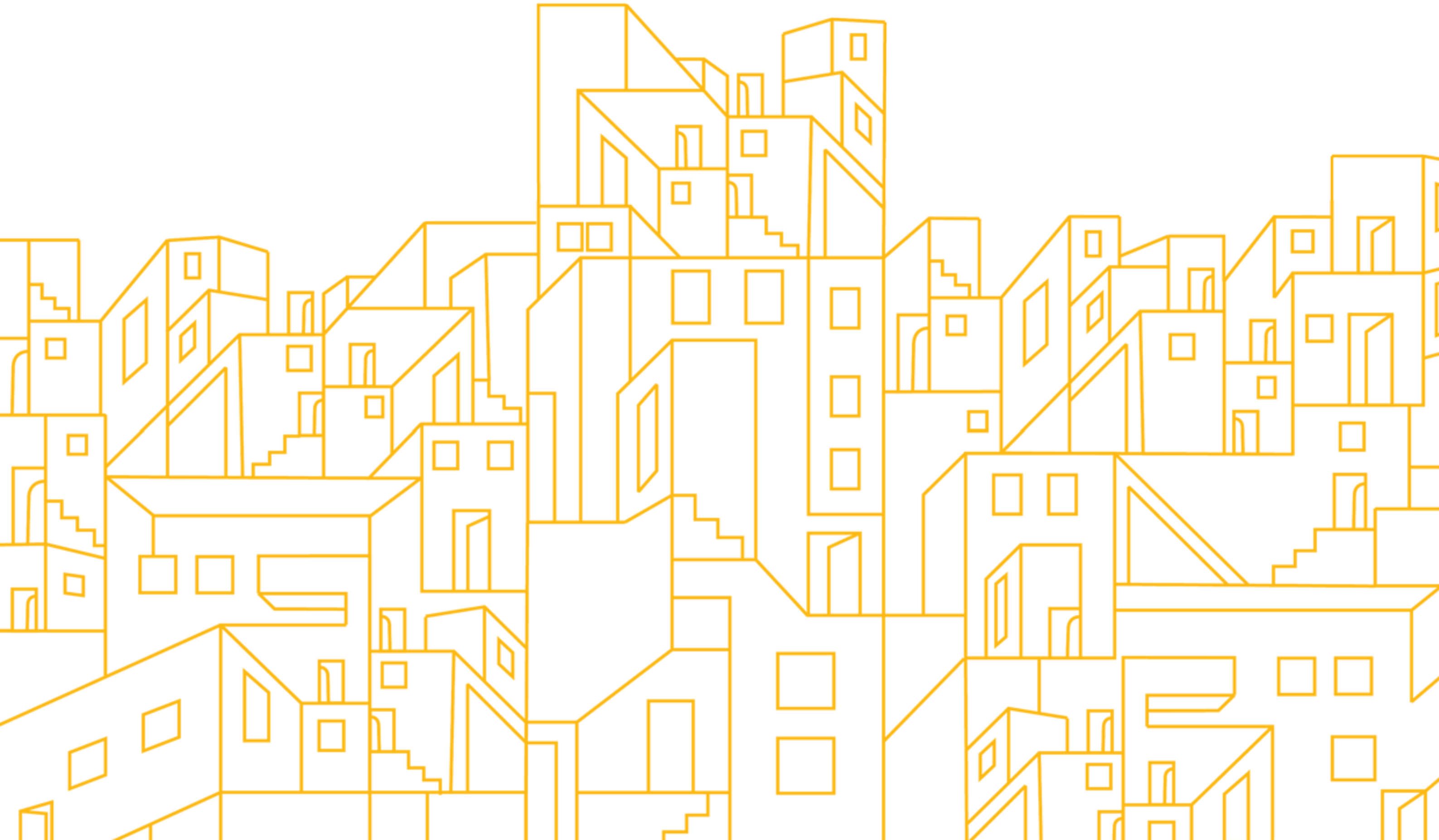


Figure 73: Daytime closing and nighttime opening of windows prevents excessive temperature rise indoors in the Blessing House.
Source: (Doctor-Pingel, Vardhan, Manu, Brager, & Rawal, 2019)

5

INNOVATIVE BUILDING MATERIALS AND NEW METHODS OF CONSTRUCTION FOR AFFORDABLE HOUSING



5.1 Introduction

This chapter extensively cover concepts focusing on building envelope components- external walls, windows, and roof. Beginning with individual concepts of thermal insulation, thermal mass, thermal bridging, the chapter extends the subject to link these concepts with design of various layers of a wall assembly. Concluding this section with the relation between U-value and internal surface temperature, the chapter proceeds to present information on various walling materials and technologies in the Indian construction landscape. Following the walls, the chapter focusses on windows with glazing and its metrics for heat gains. This section also addresses thermal bridging in window frames. Subsequently, the chapter highlights important metrices surrounding heat gains through roof. The chapter concludes with a section on the current Light House Project Technologies under PMAY-U and GHTC.

5.1.1 Thermal insulation and thermal mass

Thermal insulation in building envelope components restricts the heat exchange between indoor and outdoor temperatures. Thermal insulation in building envelope components can be used for a combination of following purposes- **Energy conservation, economizing envelope thickness, condensation control, noise control and/ or fire safety.**

Thermal behaviour of a material refers to its capacities to absorb heat and to conduct heat. Lower capacity to conduct heat (such as in EPS sheets), means less heat can flow through the material and hence, its insulation capacity is greater. Thus, thermal insulation due to low thermal conductivity can be understood as material's tendency to reflect maximum amount of heat incident on it. As shown in Figure 74a, during the day, outside surface temperature of a wall is much higher than inside surface temperature. Hence, the wall insulates the inside space by allowing less amount of heat to flow through itself. At night, the direction of heat flow reverses and insulation contains the heat inside.

However, materials also have capacity to absorb some part of the incident heat. This is quantified as the specific heat capacity of the material. High specific heat of the

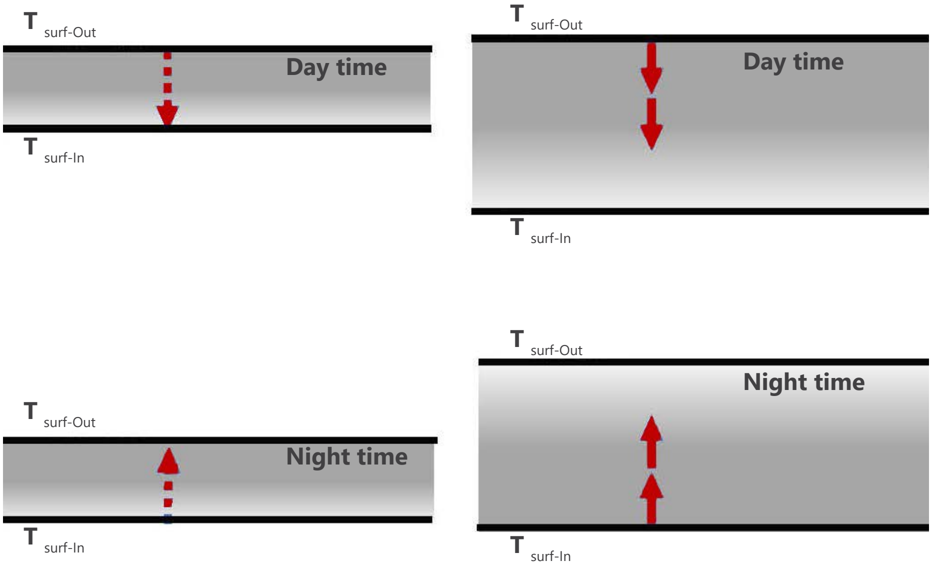


Figure 74: Thermal insulation; 74a- thermal insulation through thermal conductivity; 74b- thermal insulation through thermal mass

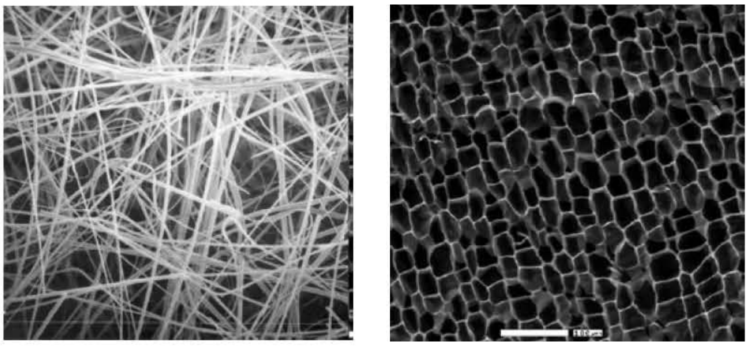


Figure 75: Left- Microscopic images of insulating materials.
Information and Image Courtesy: Prof. Cloude Roulet, EMPA,Switzerland, Indo Swiss BEEP project, BEE, India;
Right- Relation between density and apparent thermal conductivity for common insulating materials.

material also known as high thermal mass, results in more amount of heat storage within the material and consequently less transmission. The resulting effect of high thermal mass is similar to that of low thermal conductivity i.e., better thermal insulation performance of the material. During the day, walling materials with high thermal mass store heat that is trying to flow towards indoors. However, during night, the direction of heat flow inverses and the stored heat is gradually lost to the outdoor environment. Depending upon the climate, thermal requirement of the space i.e., prevention of heat gain or prevention of loss of coolth, appropriate mechanisms should be deployed.

For homogenous materials, thermal conductivity is normally considered an intrinsic property. However, in porous materials, the presence of air renders the material non-homogenous. Heat flow in such materials occurs through a combination of conduction, convection, and radiation causing dependencies on orientation and/or direction. In non-homogenous materials, the measured capacity of heat transfer is termed as apparent thermal conductivity and accompanied with test condition specifications such as sample thickness, orientation, etc (ASHRAE, 2021).

The most commonly known insulating material is air. This property of air is used in various aspects of building materials and construction technologies to improve thermal environment of spaces. Starting with the insulation materials- air is encapsulated inside materials such as rockwool, XPS sheets, bubble reflective foil (layer of bubble wrap sandwiched between two reflective aluminium sheets), fibrous materials and so on, which imparts insulating properties to these materials. At the walling material level, walling units such as hollow AAC blocks use the insulating property of air. Lastly at the walling assembly level, maintaining a layer of air between two masonry walls, termed as cavity walls helps to restrict heat transfer between indoors and outdoors.

The strong correlation between density and thermal conductivity of a material can be explained through their porosity level or the presence of air between their molecules. Materials with low density have larger amount of air present between their molecules. Thermal insulation materials have porosities typically exceeding 90% (ASHRAE, 2021) and hence, heat is transmitted through mainly radiation and gas conduction in pores while normal conduction through solid parts of the material.

5.1.2 Thermal conductivity and thermal bridge

Some of the most common building materials and their thermal conductivities are presented in Figure 76. The thermal properties of these materials can be used to device

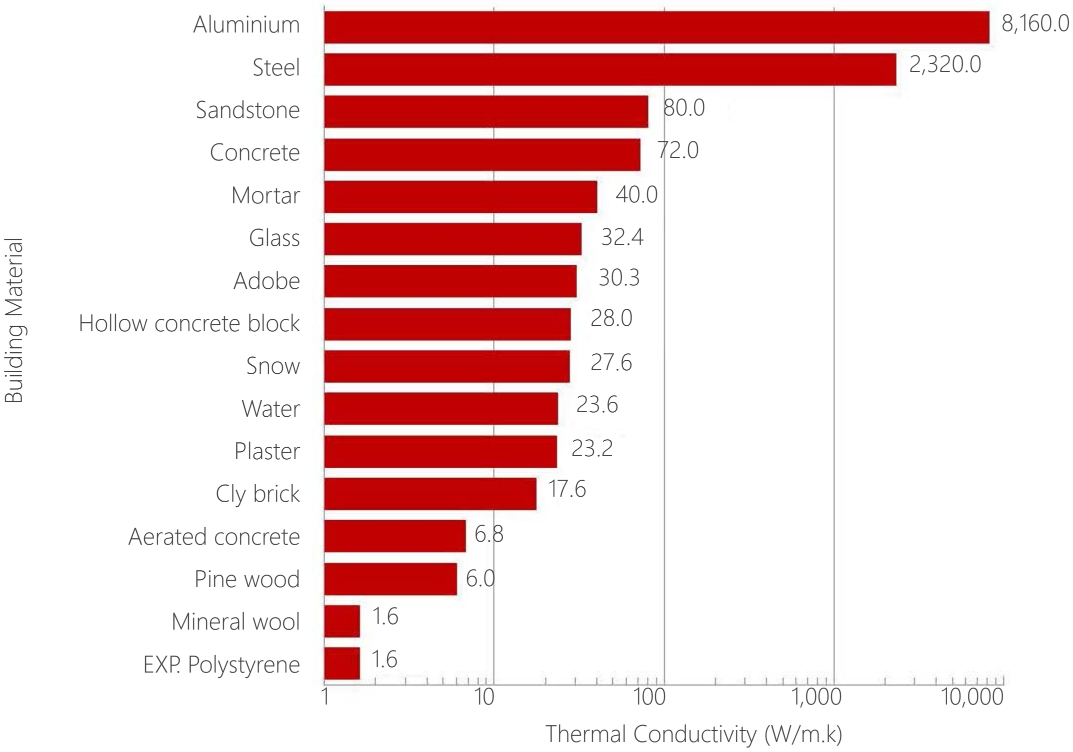


Figure 76: Thermal conductivities of common building materials.
Information and Image Courtesy: Prof. Cloude Roulet, EMPA, Switzerland, Indo Swiss BEEP project, BEE, India

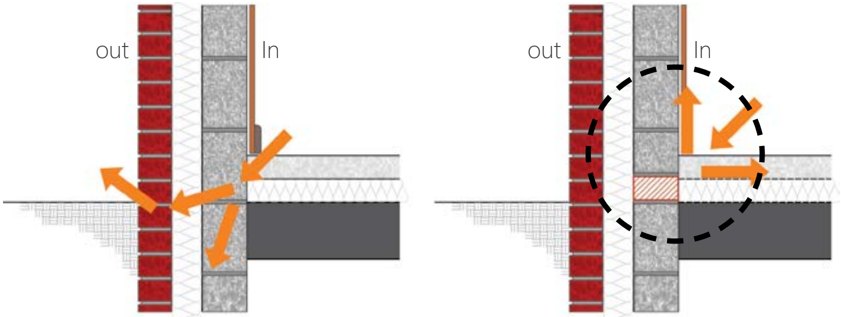


Figure 77: Walling assemblies and thermal bridging.
Information and Image Courtesy: Prof. Cloude Roulet, EMPA, Switzerland, Indo Swiss BEEP project, BEE, India

feasible assemblies of required thermal performance. Often , assembling the layers of walling or roofing technology or inserting window frames in walling assemblies can result in thermal bridges. A thermal bridge is a part of the assembly (such as metal screws or nails) that allows direct heat transfer between indoors and outdoors due to interruptions in insulation. Typically, 0.0002 sq.m. of aluminium acting as a thermal bridge can negate the thermal insulation provided by 1 sq. m. if insulating material. Thermography images of wall sections captured using infrared camera help to detect thermal bridges in an envelope.

5.1.3 Material thickness and location in walling assemblies

Pragmatically, designers or architects are required to balance the thermal performance of walling and roofing assemblies with their total thickness so as to not reduce inhabitable carpet area in dense urban cities. More importantly, the quantity and availability of materials for the designed assemblies also drive project costs. A suitable approach to address this is to allow design of walling assemblies or technologies to be guided by the thermal conductivities of different thicknesses of the individual components.

The thermal conductivities of various walling assemblies shown in Figure 78 are less than 0.40 W/m2K. However, due to varying thermal conductivities of individual materials, the thickness of these materials required in achieving a total U-value less than 0.40 W/m2K is different in each case. This provides flexibility to designers in choosing various layers of a walling assembly suitable to their needs.

In addition to material thicknesses, the location of each material in the assembly also affects the surface temperature values and other functioning of the assembly. This can be understood by developing temperature profile across the wall section. Illustrative images of the same can be referred in Figure 79.

Figure 79 shows illustrations of temperature profile across wall sections with various indoor and outdoor conditions in different weathers. The layering sequence of different materials allows for variations in temperature profile even if the U-value of assemblies in each case remains same. Note that in all cases, the surface temperature of layer directly exposed to outside environment is higher than its adjacent air temperature (i.e., outside air temperature) due to the direct solar radiation incident on the surface.

Case 1: Steady state indoors and variable outdoors on hot-sunny day: On a hot and sunny day, the outside air temperature is high while a constant comfortable indoor temperature is maintained. Hence direction of heat flow is from outdoors to indoors.

- **Case 1a- Insulation is placed closer to outdoors and finished with plaster.** In this case, the insulation prevents maximum absorption of heat allowing the

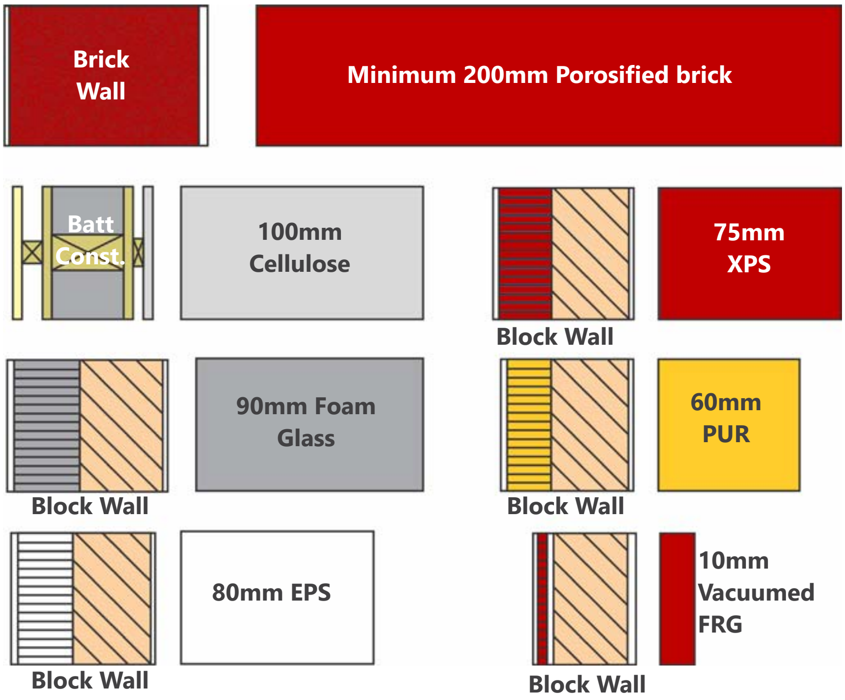


Figure 78: Minimum thickness needed to achieve U value < 0.4W/m^{2}K.
Information and Image Courtesy: Prof. Cloude Roulet, EMPA, Switzerland, Indo Swiss BEEP project, BEE, India

temperature drop to be steep across its exterior and interior surfaces. The slope of temperature gradient may allude to the time taken for heat exchange between indoors and outdoors. In climates such as hot and dry, maximizing the time lag helps to maintain cooler indoor temperatures throughout the day.

- **Case 1b- Insulation is placed closer to indoors.** In this case, the outermost layer of the wall allows for some thermal transmittance. Hence although the temperature gradient across the insulating layer is high, it is still lower compared to that in case 1a.
- **Case 1c- insulation is absent and wall with high thermal mass is used.** To maintain the indoor environment at a constant temperature, the thickness of the building material required when thermal mass is responsible for insulation may be greater than an assembly containing insulation. This can prove to disadvantageous in terms of material costs incurred and space availability.

Case 2: Steady state indoors and variable outdoors on cold-sunny day: In this condition, the higher indoor air temperature dictates the direction of heat flow from indoors to outdoors.

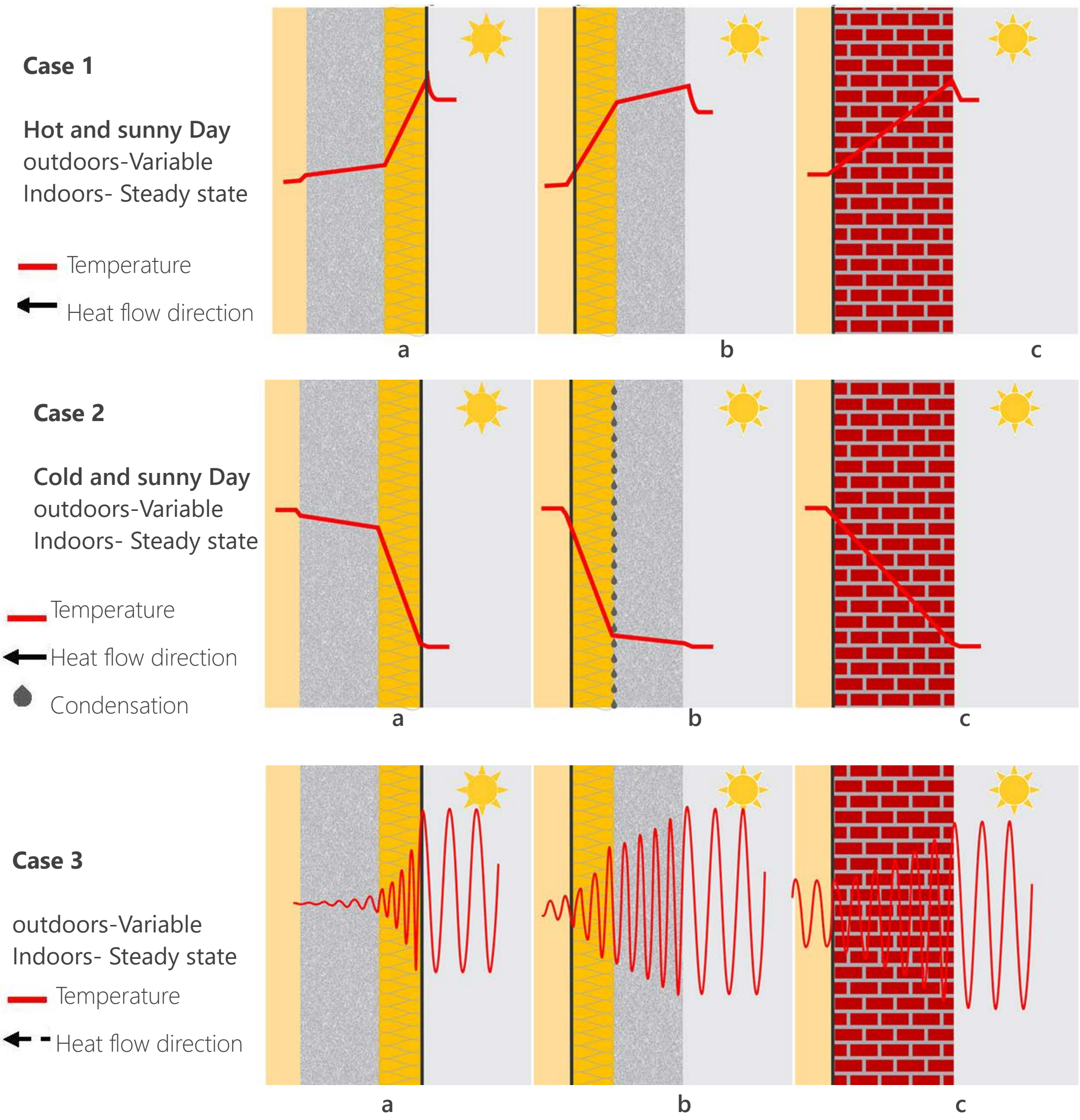


Figure 79: Temperature profile illustrations for various indoor and outdoor conditions
Information and Image Courtesy: Prof. Cloude Roulet, EMPA, Switzerland, Indo Swiss BEEP project, BEE, India

- The placement of insulation in a situation where indoor air temperature is higher than outdoor air temperature, is essential. In case 2b, the temperature profile across insulating layer is steep. This can allow for storage of moisture towards the cooler surface of the layer giving rise to the possibility of condensation where the insulating layers meets RCC wall.
- The issue of condensation can be resolved through the introduction of a vapour barrier layer between the insulating layer and concrete wall. This is a suitable approach as placing insulation closer to indoor space helps to retain the comfortable temperature and thus reduces dependence on cooling system to maintain constant temperature.

Case 3: variable indoor and variable outdoors on hot-sunny day: In this case, the direction of heat flow changes depending on the outside and inside air temperatures.

- Placing insulation towards the outdoors reduces the temperature modulations around the RCC layer which has heat storage capacity. Hence the indoor temperature fluctuations are lower in this case compared to material mass being located towards outdoors.
- Moreover, since insulation through thermal mass depends on heat storage capacity of the material, the performance of walls with high thermal mass in this case may be poor compared to assembly with insulation layer.

5.1.4 U-value and surface temperature

The temperature gradient across the wall section can be measured in field and lab environments to understand their true performance. Figure 80 shows the temperature gradients across wall sections of six different buildings studied in field (Manu, Brager, Rawal, Geronazzo, & Kumar, 2018). The temperature gradient lines in the graph represent temperature data from every three hours (12:00 A.M. to 9:00 P.M.) for a

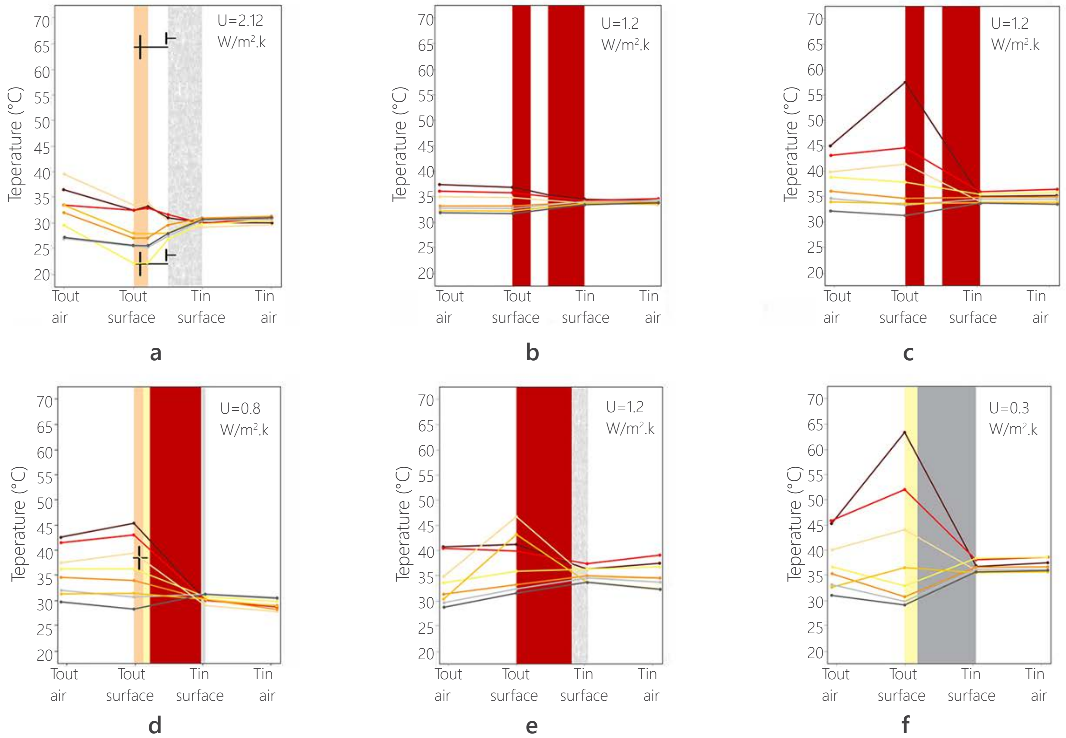


Figure 80: Temperature gradients across wall sections for an extreme summer day.
Source: (Manu, Brager, Rawal, Geronazzo, & Kumar, 2018)

single day in an extreme summer week when the outdoor temperatures ranged from 27-45 °C in all locations.

Interestingly, it can be observed in the figure that irrespective of the swings in the outdoor air temperatures, all assemblies maintained the internal wall surface in a narrow band of no more than 5°C and this band shifted as the construction and assembly details of the wall changed. The U-values indicated on the graph were calculated using the CARBSE Assembly U-factor Calculator (CARBSE, 2013). It is noteworthy that while the U-value of case a is higher, the internal surface temperature band is still lower on the temperature scale when compared to case f. Same temperature band observation was made between cases c and e where the U-value was same for both walls. The study suggested that a detached skin layer shading the external wall (identified in case a), or a ventilated cavity wall can reduce heat gains and add to the thermal mass that contributes to lower internal surface temperatures. Internal surface temperatures are worthy of attention as they ultimately impact thermal comfort of a space by influencing the Mean Radiant Temperature (MRT).

5.2. Walling Materials and Units

Literature review has shown the existence of a national database for walling materials and their thermophysical properties in the context of India. (Rawal, et al., 2021). The thermal performance of selected walling materials included measurements of thermal conductivity, specific heat capacity, dry/ bulk density, water absorption capacity and compressive strength according to established standards as shown in Table 18. The samples were sourced from various manufacturing facilities around the country and tagged for record-keeping. Measurements for thermal parameters were taken for larger sample size and averaged to obtain the thermophysical properties shown in Table 20, Table 21, and Table 22. Sample tags for other bricks and blocks are explained in Table 19. Additionally, the testing samples accounted for variations due to manufacturing processes, raw material sourced in various manufacturing facilities and other such factors. For ease of analysis, the materials were segregated into three categories:

- Fired clay bricks (hand-moulded, extruded, soft mud-moulded, water-struck moulded)

Table 18: Measured properties and corresponding testing standards & instruments used

S/N	Testing parameter	Instrument	Applicable Testing Standard
1	Thermal Conductivity and Specific heat	Thermal Constants Analyser	ISO/DIS 22007-2:2015 (for both bricks and blocks) (ISO, 2008)
2	Dry density	Precision Weighing Scale, Inert Gas Oven, Water Bath	ASTM C20 (for both bricks and blocks) (ASTM, 2015)
3	Water Absorption	Precision Weighing Scale, Inert Gas Oven, Water Bath	IS 3495 (for bricks) (BIS, 1992b) IS 2185 (for blocks) (BIS, 2005)
4	Compressive Strength	Compression Testing Machine	IS 3495 (for bricks) IS 2185 (for blocks)

Table 19: Reference tags for other bricks and blocks

EC: Expanded Clay Aggregate	AB: AAC blocks	CC: Concrete block
CD: Construction & Demolition Waste Brick	EB: CSEB	CB: Concrete brick
CS: Calcium Silicate blocks	CL: CLC blocks	SB: Surkhi Brick

Table 20: Average value of measured properties of fired clay samples.
Source: (Rawal, et al., 2021)

S/N	Sample	Dry density ρ (kg/m^3)	Thermal conductivity λ (W/m.K)	Specific heat C_p (KJ/kg.K)	Compressive strength (MPa)	Water absorption (%)
Hand-moulding (Phase I)						
1	RB01	1599	0.48	0.907	14.83	21
2	RB02	1777	0.60	0.921	16.54	15
3	RB04	1654	0.57	0.917	23.08	19
4	RB06	1887	0.76	0.927	20.23	12
5	RB07	1738	0.53	0.960	7.21	16
6	RB09	1604	0.39	0.909	6.10	23
7	RB10	1512	0.42	0.926	5.32	26
8	RB11	1447	0.50	0.936	10.01	24
9	RB14	1503	0.42	0.935	4.88	26
10	RB15	1264	0.38	0.927	4.16	32
11	RB20	1780	0.55	0.952	18.68	15
12	RB21	1716	0.54	0.923	17.8	17
13	RB23	1819	0.74	0.978	25.8	13
Hand-moulding (Phase II)						
1	RB01	1801	0.57	0.927	21.76	12
2	RB02	1723	0.58	0.891	5.84	12
3	RB03	1493	0.41	0.910	5.22	20
Extrusion						
1	RB03	2119	0.97	0.916	58.21	7
2	RB05	2028	1.12	0.955	54	10
3	RB12	1975	0.80	0.928	26.83	12
4	RB18	1895	0.58	0.924	19.82	14
5	RB19	1958	0.65	0.947	10.79	13
Soft mud moulding						
1	RB13	1807	0.59	0.934	13.48	17
2	RB16	1657	0.42	0.940	7.51	19
3	RB17	1648	0.41	0.927	5.71	20
4	RB22	1798	0.64	0.918	26.17	14
Water-struck moulding						
1	RB08	1737	0.51	0.946	7.76	16

Table 21: Average value of measured properties of cured fly ash samples.
Source: (Rawal, et al., 2021)

S/N	Sample	Dry density ρ (kg/m³)	Thermal conductivity λ (W/m.K)	Specific heat C_p (KJ/kg.K)	Compressive strength (MPa)	Water absorption (%)
Phase I						
1	FB01	1878	0.86	0.938	19.98	12
2	FB02	1844	0.80	0.924	12.43	16
3	FB03	1475	0.53	0.962	9.02	23
4	FB04	1299	0.39	0.924	11.44	27
5	FB05	1807	0.50	0.961	10.64	15
6	FB06	1543	0.36	0.908	5.05	27
7	FB07	2048	0.67	0.976	15.16	12
8	FB08	1682	0.52	0.936	10.14	19
9	FB09	1989	0.65	0.929	8.87	13
10	FB10	1722	0.50	0.925	3.6	20
Phase II						
1	FB01	1878	1.05	0.918	15.72	10
2	FB02	1779	0.84	0.935	18.72	15
3	FB03	1716	0.56	0.891	12.07	17
4	FB04	1606	0.67	0.954	9.97	19
5	FB05	1627	0.69	0.954	8.57	18
6	FB06	1774	0.97	0.879	10.33	15
7	FB07	1734	0.79	0.972	8.75	18
8	FB08	1694	0.75	0.646	15.16	20

Table 22: Average value of measured properties of other bricks and blocks samples.
Source: (Rawal, et al., 2021)

S/N	Sample	Dry density ρ (kg/m³)	Thermal conductivity λ (W/m.K)	Specific heat C_p (KJ/kg.K)	Compressive strength (MPa)	Water absorption (%)
Phase I						
1	AB01	608	0.17	0.875	2.7	72
2	AB02	623	0.19	0.831	3.4	73
3	EB01	1630	0.59	0.908	1.76	22
4	EB02	1773	0.75	0.934	13.05	16
5	CC01	2032	0.81	0.912	10.04	9
6	CC02	1961	0.66	0.928	6.8	13
7	CB01	2122	1.55	0.920	29.6	7
8	CS01	2071	0.71	0.969	18.79	12

S/N	Sample	Dry density ρ (kg/m³)	Thermal conductivity λ (W/m.K)	Specific heat C_p (KJ/kg.K)	Compressive strength (MPa)	Water absorption (%)
9	CL01	693	0.19	0.932	1.12	78
Phase II						
1	CC01	2057	0.20	0.886	6.6	9
2	CC02	2141	0.49	0.907	10.2	9
3	CC03	2092	0.70	0.868	11.59	11
4	CD01	1537	0.54	0.956	6.63	23
5	CL01	760	0.20	1.048	2.63	37
6	CL02	744	0.21	0.892	2.86	44
7	EB01	1993	0.97	1.040	2.91	12
8	EC01	613	0.19	1.032	2.77	30
9	SB01	1423	0.46	0.525	5.96	28

- Cured Fly ash bricks
- Other bricks and blocks

The other bricks and blocks category included Autoclaved Aerated Concrete (AAC), Compressed Stabilized Earth Blocks (CSEB), Concrete Block, Calcium Silicate blocks, Cellular Lightweight Concrete blocks (CLC), Expanded Clay Aggregate blocks, Construction & Demolition waste bricks, and Surkhi bricks .

Thermal Conductivity:

The corelation between dry density and thermal conductivity for each category was analysed as shown in Figure 81, Figure 82, and Figure 83. Goodness of fit (R^2=0.70) shows that dry density is a major factor that governs thermal conductivity of solid fired

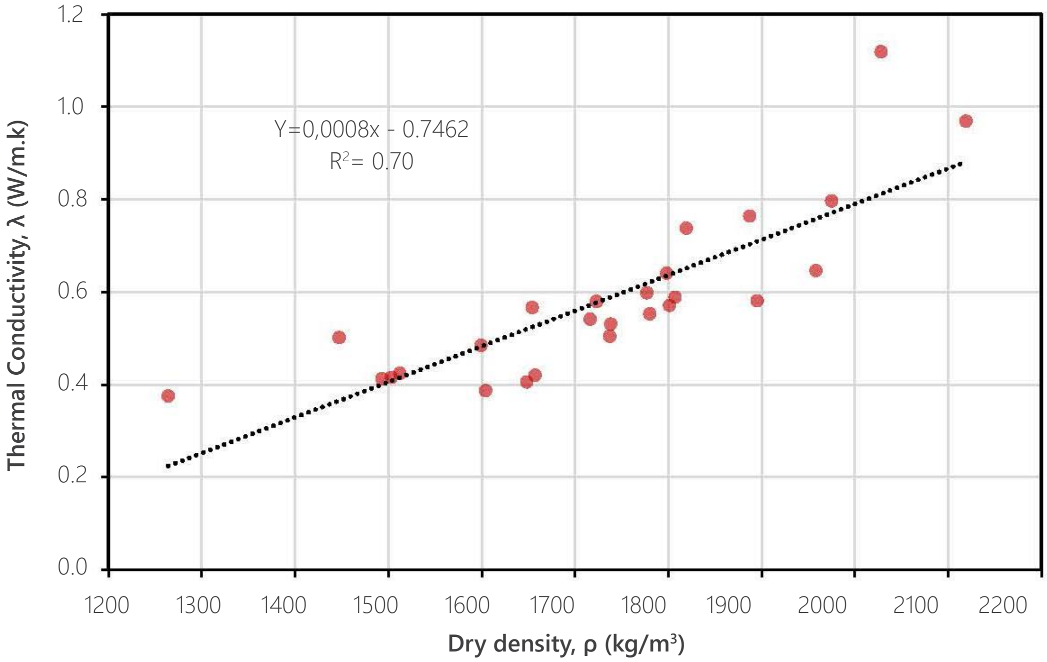


Figure 81: Thermal conductivity as a function of dry density for fired-clay bricks.
Source: (Rawal, et al., 2021)

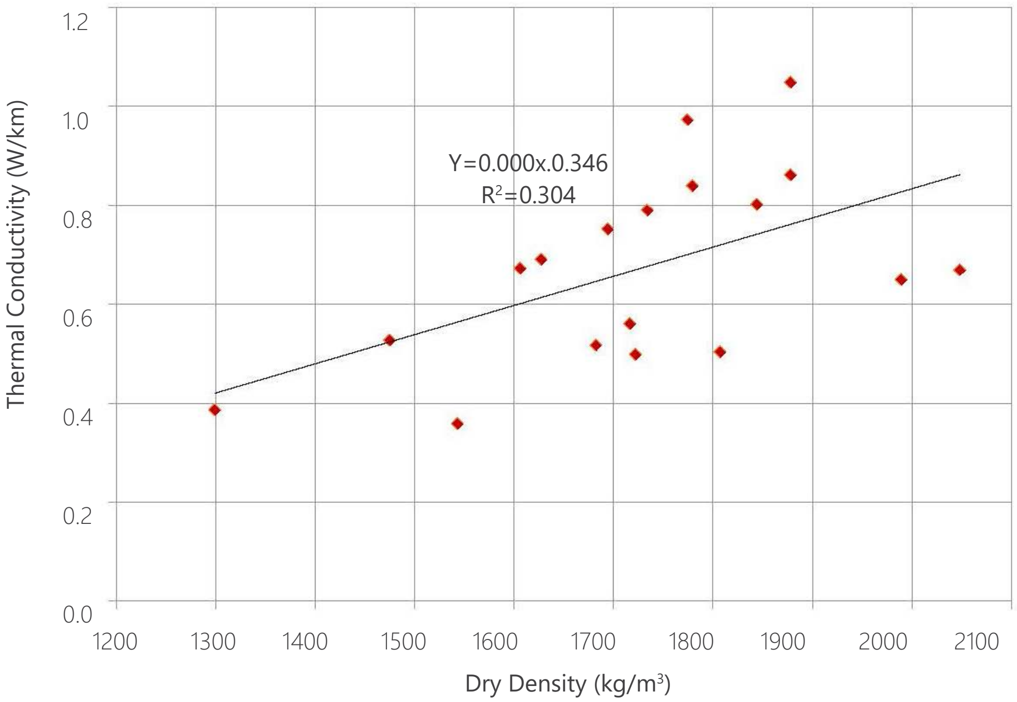


Figure 82: Thermal conductivity as a function of dry density for non-fired fly ash bricks. Source: (Rawal, et al., 2021)

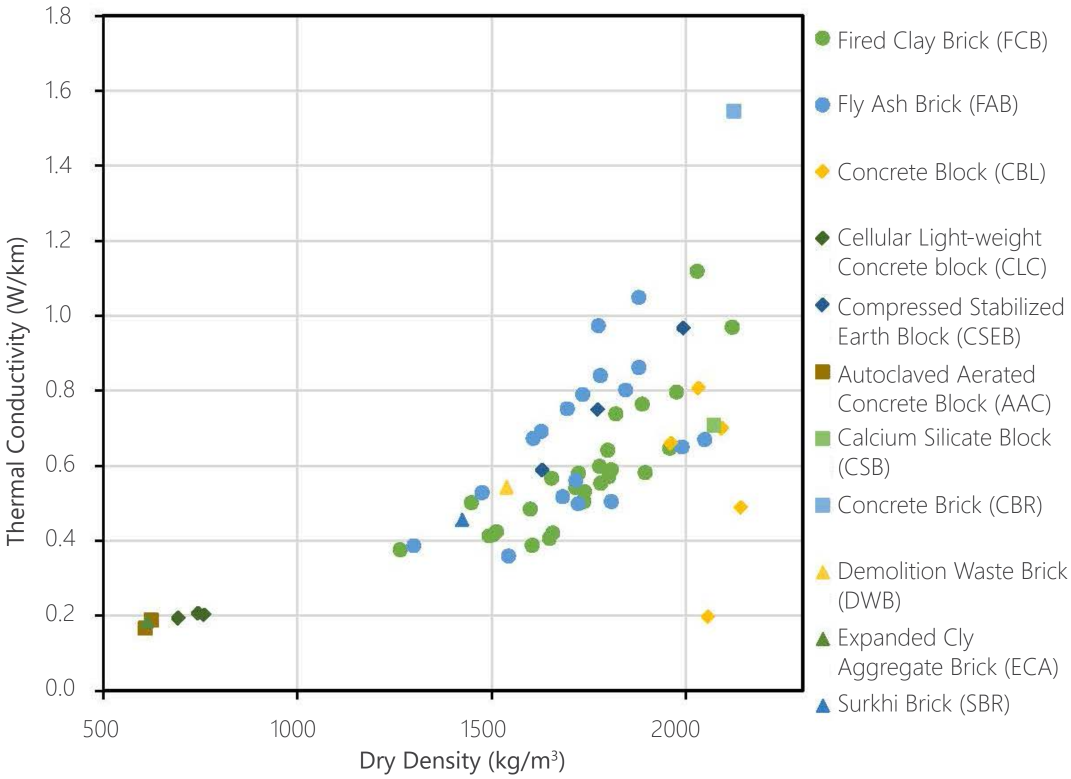


Figure 83: Variation of thermal conductivity with dry density for other non-fired bricks. Source: (Rawal, et al., 2021)

clay bricks. Similarly, for cured fly ash brick the goodness of fit ($R^2=0.3045$) indicates a strong correlation between the two parameters. Thus, for a given value of dry density ρ (kg/m^3), the following equations can be used to make an estimation of thermal conductivity λ (W/m.K) for the two categories:

Fired Clay bricks: $\lambda=0.0008\rho - 0.7462$
Non-fired, cured fly ash bricks: $\lambda=0.0006\rho-0.3466$

The range and mean of thermal conductivities of commonly used walling materials is shown in Figure 84. The graph shows lowest thermal conductivity for light weight concrete blocks (AAC and CLC), while solid concrete blocks exhibit the highest thermal conductivity. Additionally, the mean thermal conductivity value of the hand-moulded fired clay bricks is 18% lower compared to that of fly ash bricks. However, the range of thermal conductivity is large for fired clay bricks, fly ash bricks, concrete blocks and CSEB blocks.

Bulk Density:
Figure 85 shows that the three most used solid bricks/blocks – fired clay, fly ash and

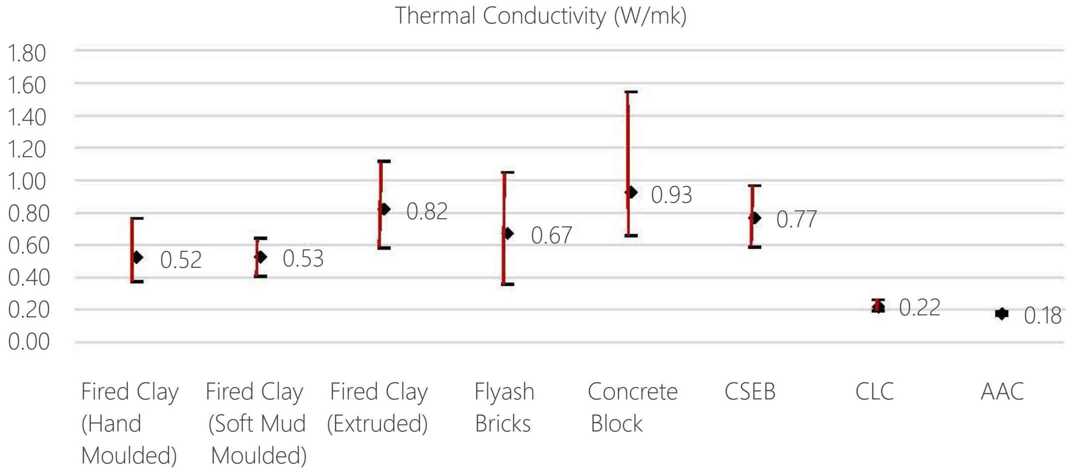


Figure 84: Comparison of thermal conductivity of various walling materials
Source: (Rawal, et al., 2021)

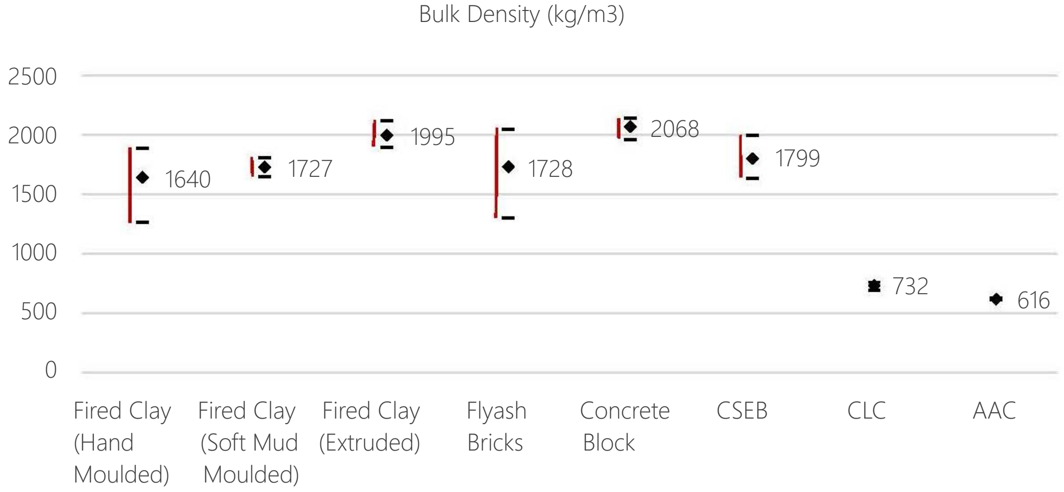


Figure 85: Comparison of bulk density of various walling materials
Source: (Rawal, et al., 2021)

solid concrete have significant variations in their bulk densities. This can be attributed to the variations in the raw material properties (composition, particle size, etc) and the manufacturing process employed (e.g. the amount of pressure employed while shaping). Amongst these, extruded clay fired bricks and concrete blocks exhibit highest bulk densities.

Water Absorption:

The water absorption capacity of nearly all walling materials exhibited a large variation with the highest being in CLC blocks. Additionally, CLC and AAC blocks were observed to have very high water absorption due to their porous nature.

Compressive Strength:

Figure 87 shows fired clay bricks manufactured through extrusion have the largest variation in compressive strength, while the AAC and CLC blocks exhibit the lowest compressive strength.

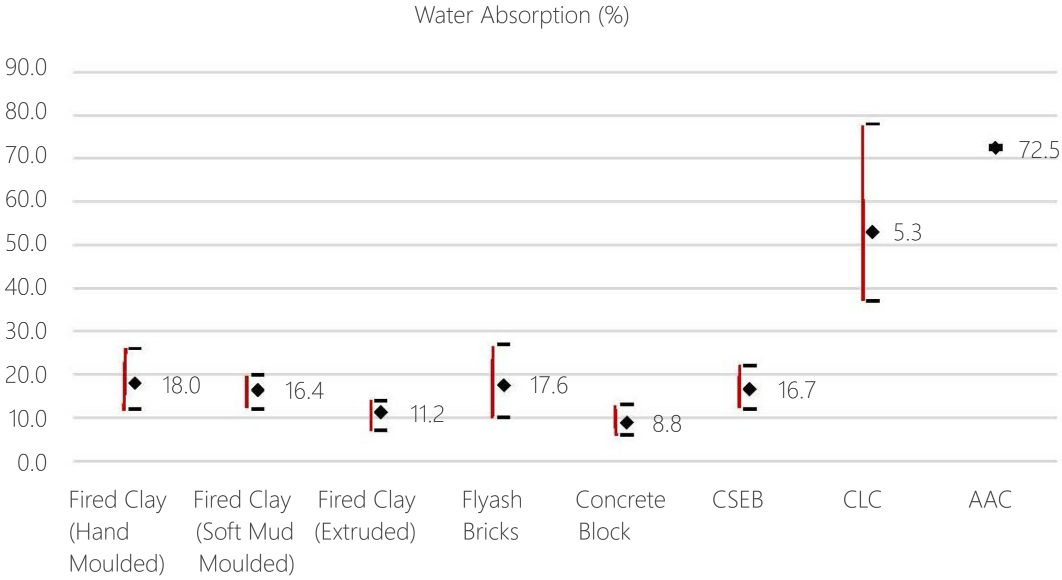


Figure 86: Comparison of water absorption of various walling materials

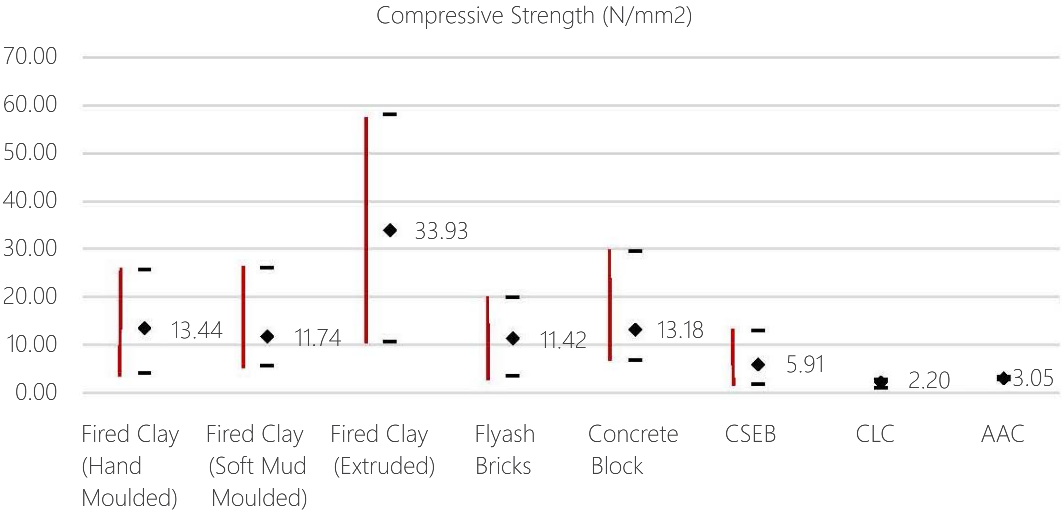


Figure 87: Comparison of compressive strength of various walling materials

Specific Heat :
A comparison of the Specific Heat capacity of various walling materials is shown in Figure 88. The mean specific heat capacity of all the materials were found to vary between a narrow range of 853 -961 J/kg.K.

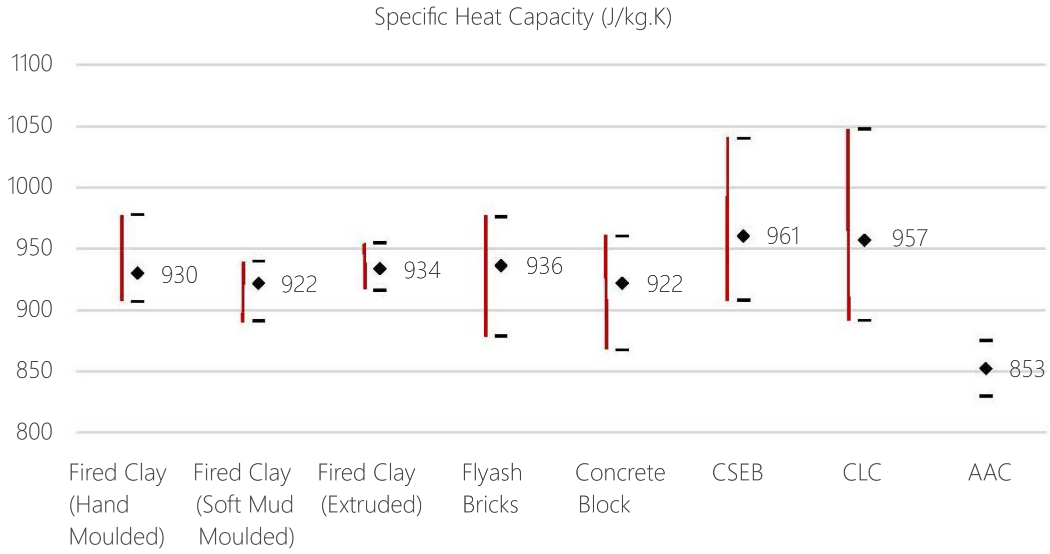


Figure 88: Comparison of specific heat capacity of various walling materials

RETV

Impact of walling material on RETV was studied by calculating u-values and RETV for each walling material considering a 200 mm thick wall with 15 mm plaster on both sides for a dwelling unit of 26.6 sq. m. (Rawal, et al., 2021). Figure 89 represents the site plan and typical floor plan of the selected project. Additionally, assumptions for the study included casement windows that are either fully (glass) or partially (PVC) glazed. Table 23presents the calculated u-values and Figure 90 shows the corresponding RETV values arranged in descending order. The study presented following conclusions:

- The choice of brick to construct external wall (U-value ranging between 0.7 W/m^{2}K to 2.93 W/m^{2}K) has a large impact on the RETV value. The maximum value of RETV for Smart GHAR-3 is 19.65 W/m^2, which is more than double the minimum RETV of 9.13 W/m^2 for the given sample set.
- AAC and CLC blocks have the lowest U value and lowest RETV value.
- Solid concrete and calcium silicate bricks exhibit high U value and RETV, generally exceeding the threshold of 15 W/m^2.
- Commonly available hand moulded fired clay (excluding extruded bricks) and fly ash bricks exhibit moderate U value and in majority of cases meet the RETV threshold of 15 W/m^2 specified in ENS.

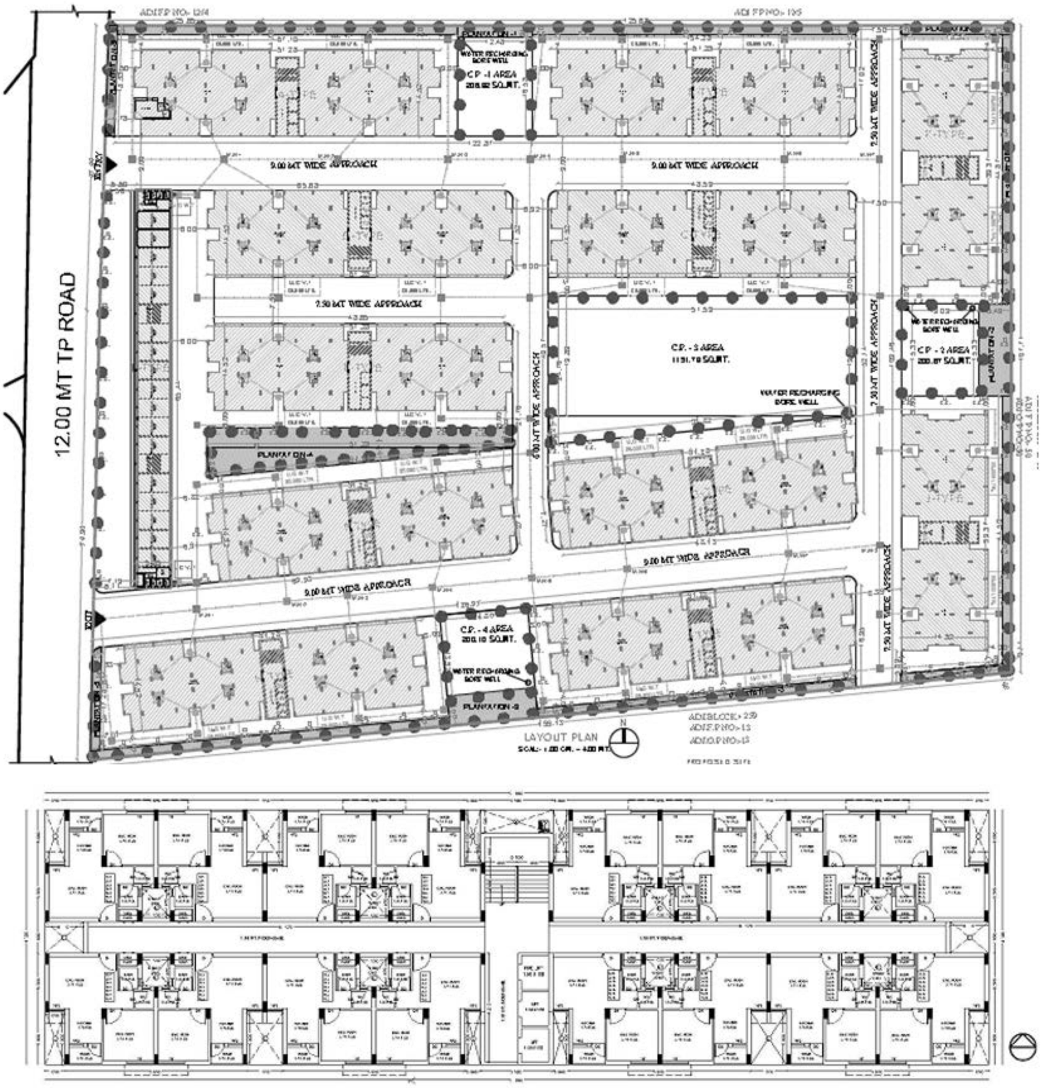


Figure 89: Site plan and typical unit plan of SMARTGHAR-III project, Rajkot
Source: (Rawal, et al., 2021)

Table 23: U-values for different walling material samples

S/N	Sample	Sample type	Thermal Transmittance Coefficient (U-value)(W/(m².K)) of 200 mm thick wall with 15 mm plaster on both sides
1	RB01	Fired clay brick	1.60
2	RB02	Fired clay brick	1.83
3	RB03	Fired clay brick	2.39
4	RB04	Fired clay brick	1.77
5	RB05	Fired clay brick	2.56
6	RB06	Fired clay brick	2.11
7	RB07	Fired clay brick	1.70
8	RB08	Fired clay brick	1.64
9	RB09	Fired clay brick	1.37
10	RB10	Fired clay brick	1.46

S/N	Sample	Sample type	Thermal Transmittance Coefficient (U-value)(W/(m².K)) of 200 mm thick wall with 15 mm plaster on both sides
11	RB11	Fired clay brick	1.63
12	RB12	Fired clay brick	2.16
13	RB13	Fired clay brick	1.81
14	RB14	Fired clay brick	1.44
15	RB15	Fired clay brick	1.34
16	RB16	Fired clay brick	1.45
17	RB17	Fired clay brick	1.42
18	RB18	Fired clay brick	1.80
19	RB19	Fired clay brick	1.92
20	RB20	Fired clay brick	1.74
21	RB21	Fired clay brick	1.72
22	RB22	Fired clay brick	1.91
23	RB23	Fired clay brick	2.07
24	FB01	Fly ash brick	2.25
25	FB02	Fly ash brick	2.16
26	FB03	Fly ash brick	1.69
27	FB04	Fly ash brick	1.37
28	FB05	Fly ash brick	1.64
29	FB06	Fly ash brick	1.30
30	FB07	Fly ash brick	1.96
31	FB08	Fly ash brick	1.67
32	FB09	Fly ash brick	1.92
33	FB10	Fly ash brick	1.63
34	AB01	AAC block	0.70
35	AB02	AAC block	0.70
36	EB01	CSEB	1.81
37	EB02	CSEB	2.08
38	CC01	Concrete block	2.17
39	CC02	Concrete block	1.94
40	CB01	Concrete brick	2.93
41	CS01	Calcium silicate blocks	2.02
42	CL01	CLC block	0.80

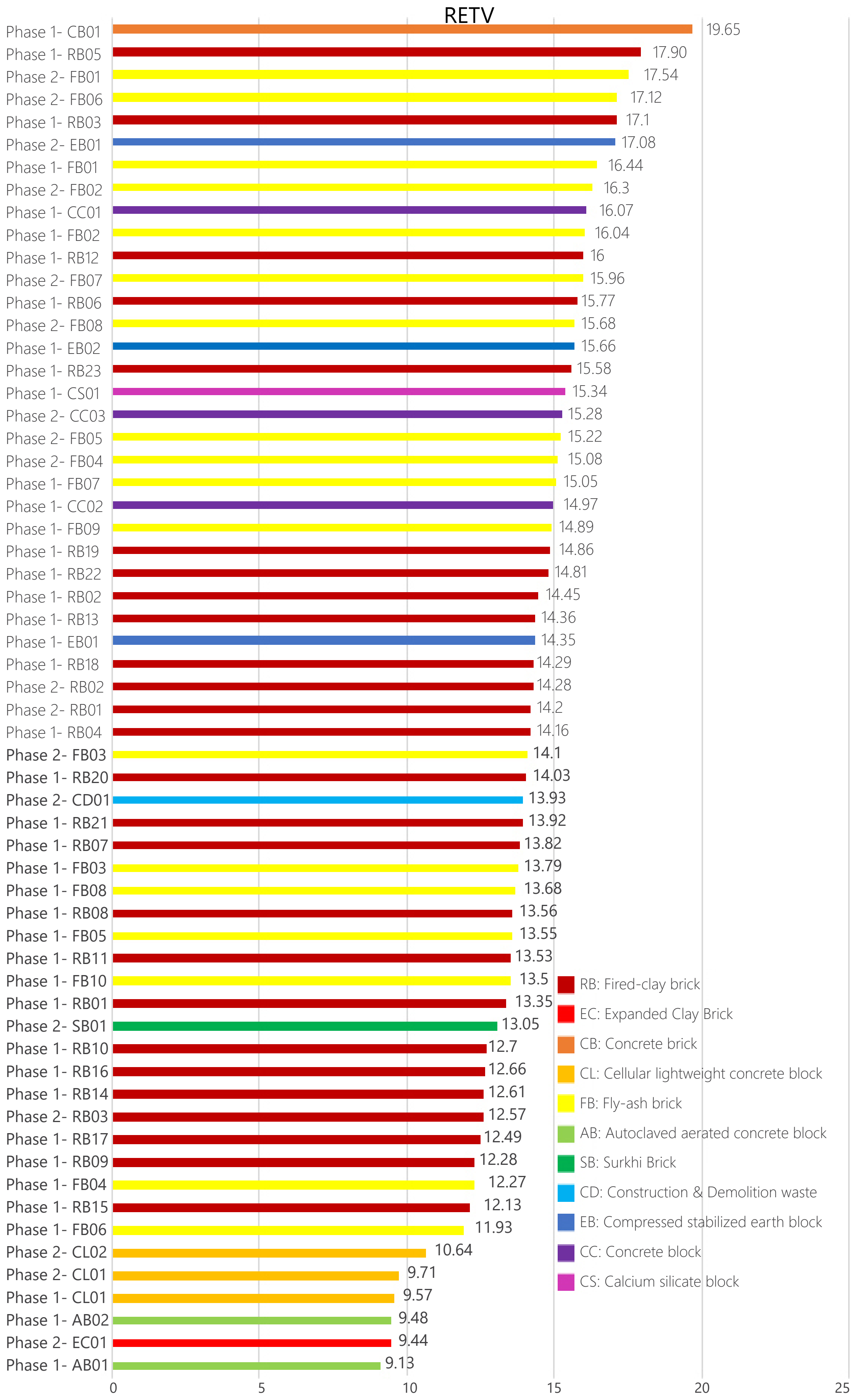


Figure 90: RETV values corresponding to various walling materials for a sample envelope

5.3 Walling Technologies

Table 24 shows the U-values of twenty-four tested wall assemblies and Figure 91 shows comparative graph of their thermal performance (Rawal, et al., 2021). These assemblies were tested at Center for Advanced Building Science and Energy (CARBSE), CEPT University in a Guarded Hot Box (GHB). The assemblies presented are a mix of commonly used traditional systems and emerging technologies in the Indian context. It can be observed from the figure that assemblies with insulation such as EPS, insulated panels have lower U-values and hence, can help in reducing heat gains through wall.

5.4 Glazing Materials and Glazing Assemblies

Choice of glazing for windows, when guided by desirable SHGC and VLT levels can

Table 24: U-value database of all selected walling assemblies and technologies

S/N	Test Phase	Wall types	Thickness (in mm)	U value (W/m².K)
1	1	Base case: Burnt Clay Brick Wall	250	2.41
2	1	Rattrap bond wall	250	2.11
3	1	Light Gauge framed steel structure with EPS	136	1.37
4	1	Light Gauge framed steel structure with PPGI Sheet	150	2.12
5	1	Reinforced EPS core Panel system	150	0.56
6	1	Glass fibre reinforced Gypsum Panel -Unfilled	124	2.06
7	1	Glass fibre reinforced Gypsum Panel -with RCC & non-structural filling	124	2.12
8	1	Glass fibre reinforced Gypsum Panel -with partial RCC filling	124	2.13
9	1	Structural stay-in-place formwork system (Coffor) – Insulated panel	230	0.44
10	2	Bamboo Crete	65	2.71
11	2	Wattle and Daub	45	3.61
12	2	Stabilized Adobe	230	2.11
13	2	Laterite Block Wall	205	2.17
14	2	Unstabilized Adobe	230	2.05
15	2	CSEB	230	2.79
16	2	Unstabilized CEB	230	2.74

S/N	Test Phase	Wall types	Thickness (in mm)	U value (W/m².K)
17	2	AAC Block Wall with Perlite based Cement Plaster	230	0.76
18	2	Unstabilized Rammed Earth	230	2.13
19	2	Stabilized Rammed Earth	230	2.09
20	2	AAC Block Wall with Cement Mortar and Cement Plaster	230	0.78
21	2	AAC Block Wall with Lime mortar and Lime Plaster	220	0.82
22	2	Burnt Clay Brick with Lime Mortar and Lime Plaster	250	2.31
23	2	Limestone with Lime Mortar and Lime Plaster	224	2.84
24	2	Limestone with Cement Mortar and Cement Plaster	230	2.82
25	3	Hollow Clay Brick (100 mm thick) with Cement Plaster	130	2.71
26	3	Hollow Clay Brick (100 mm thick) with Cement Plaster and XPS (25 mm)	158	0.89
27	3	Hollow Clay Brick (200 mm thick) with Rockwool and Cement Plaster	230	1.28
28	3	Hollow Clay Brick (200 mm thick) with Cement Plaster	230	1.83
29	3	Hollow Clay Brick (200 mm thick) with Cement Plaster and XPS (25 mm)	258	0.75
30	3	RCC Wall (100mm thick)	100	3.59
31	3	RCC Wall (100mm thick) + EPS (50 mm thick)	150	0.58
32	3	RCC Wall (100mm thick) + Styrofoam (24 mm thick) at both sides	154	0.65
33	3	RCC Wall (100mm thick) + PVC panel (6mm thick) at both sides	112	2.62
34	3	RCC Wall (100mm thick) + PVC panel (6mm thick) at both sides + EPS Board (50 mm thick) at one side	165	0.52

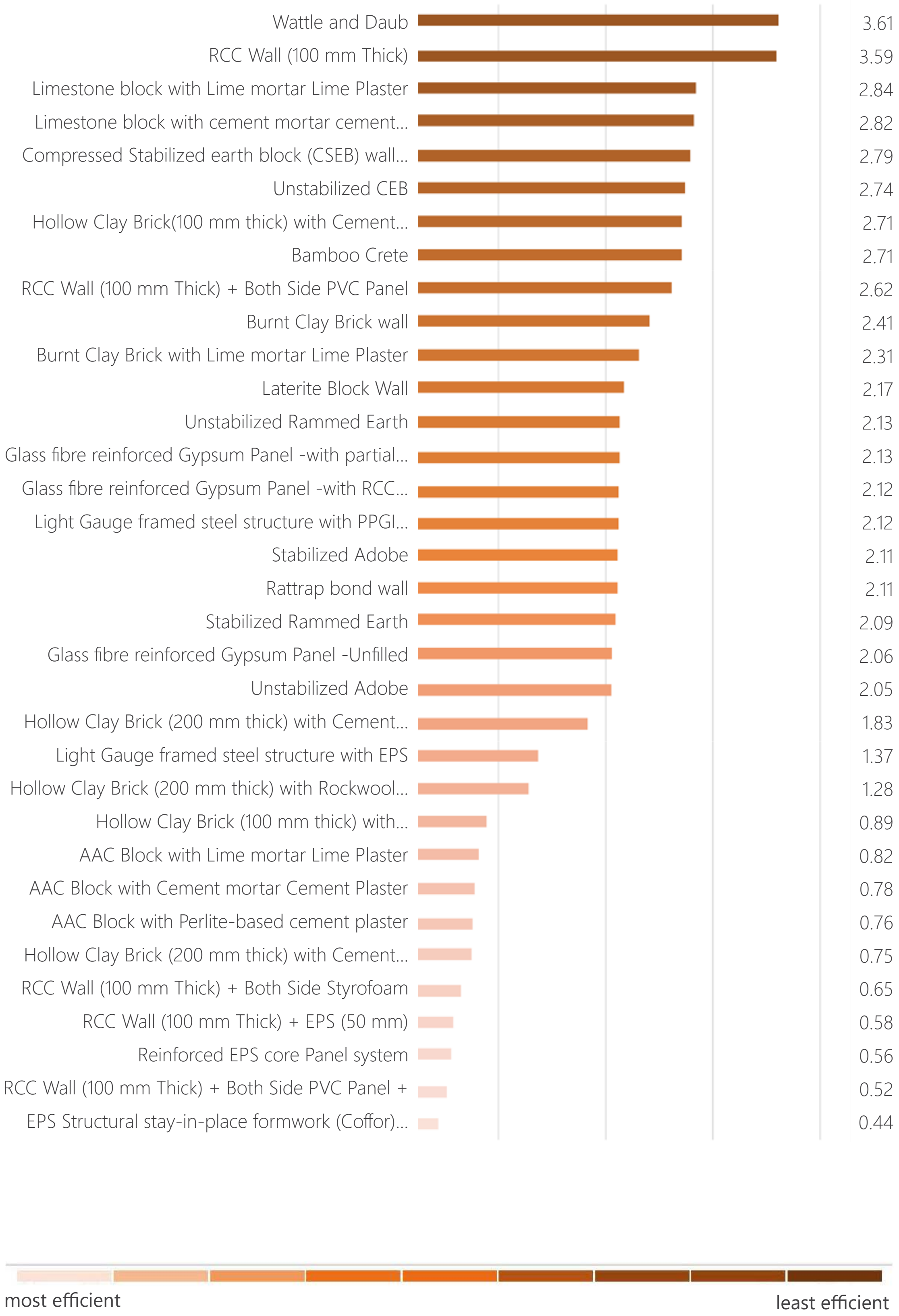


Figure 91: Thermal performance evaluation of the selected wall assemblies

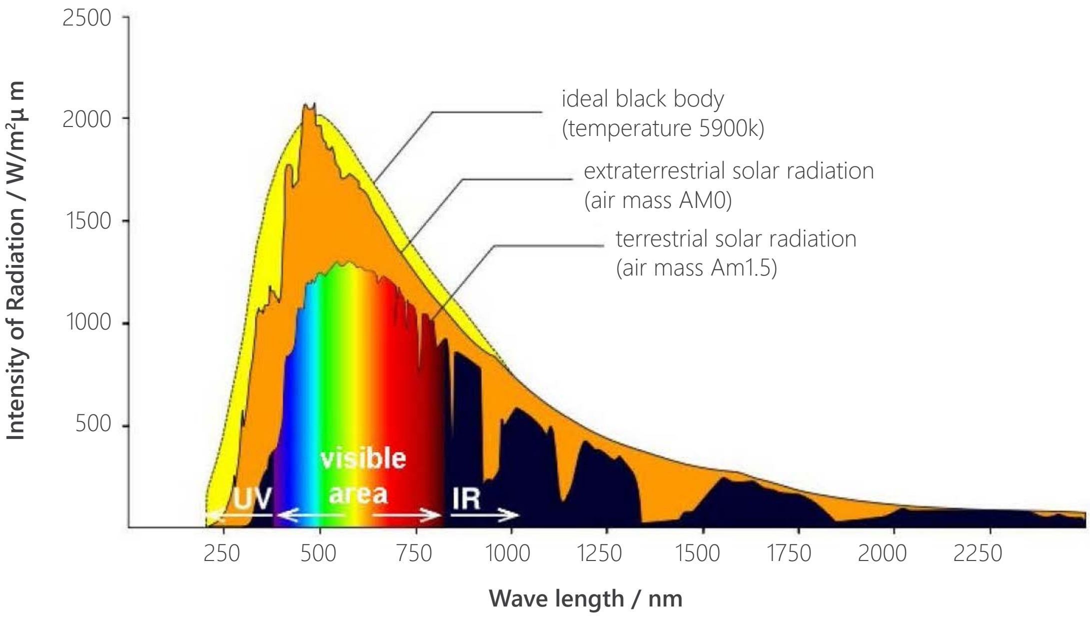


Figure 92: Variation in intensity of solar radiation due to air mass

provide optimized daylighting with minimum heat gains in cooling dominated climates. Additionally, material of the window frame can also be selected to minimize heat transfer through conduction .

The solar radiation incident on earth's surface has a wide spectrum. Figure 92 explains the change in intensity of solar radiation as it passes through different mediums-vacuum in space and earth's atmosphere. The intensity of ideal black body radiation for different wavelengths at a temperature of 5900 K is shown in yellow in the graph. For an ideal black body, $\alpha=1$, $\tau=0$ and $\rho=0$. The intensity profile of solar radiation, across the wavelengths, closely resembles that of the ideal black body at 5900 K when the radiation is travelling in space where air mass is zero (extraterrestrial radiation). As the radiation enters Earth's atmosphere, it experiences scattering and diffusion. The measure of scattering depends upon the distance travelled by the radiation in earth's atmosphere which is in turn, dependent upon the incident angle of the radiation (refer chapter 2). This is quantified as air mass. Air mass is defined as the proportion of atmosphere travelled by the radiation before striking Earth relative to its overhead path length. Hence for radiation incident at 90°, air mass is 1 and it subsequently increases as the incident angle changes.

As can be seen in the graph, air mass lowers the intensity of the solar radiation. The solar radiation moving within Earth's atmosphere (terrestrial solar radiation) has much lower intensity than extra-terrestrial radiation due to higher air mass. Within this spectrum of wavelengths, the visible light lies from around 380-400 nm to 760-780 nm. Although there are no sharp boundaries, wavelengths below this range spanning from 100-400nm belong to the ultraviolet spectrum. Similarly, beyond visible light range, 780mm to 1mm wavelengths belong to the infrared category.

5.4.1 Visible light transmittance and solar heat gains

Figure 93(top) shows the variation in transmission levels of different types of glasses at different wavelengths within the visible light spectrum. It can be observed that the extra clear glass transmits nearly 90% of visible light, closely followed by Indian planilux or clear glass with 80-90% visible light transmissions while blue and green tinted glasses provide VLT levels in the range of 35% to 80%.

While high transmission levels can contribute to greater daylighting in spaces, they

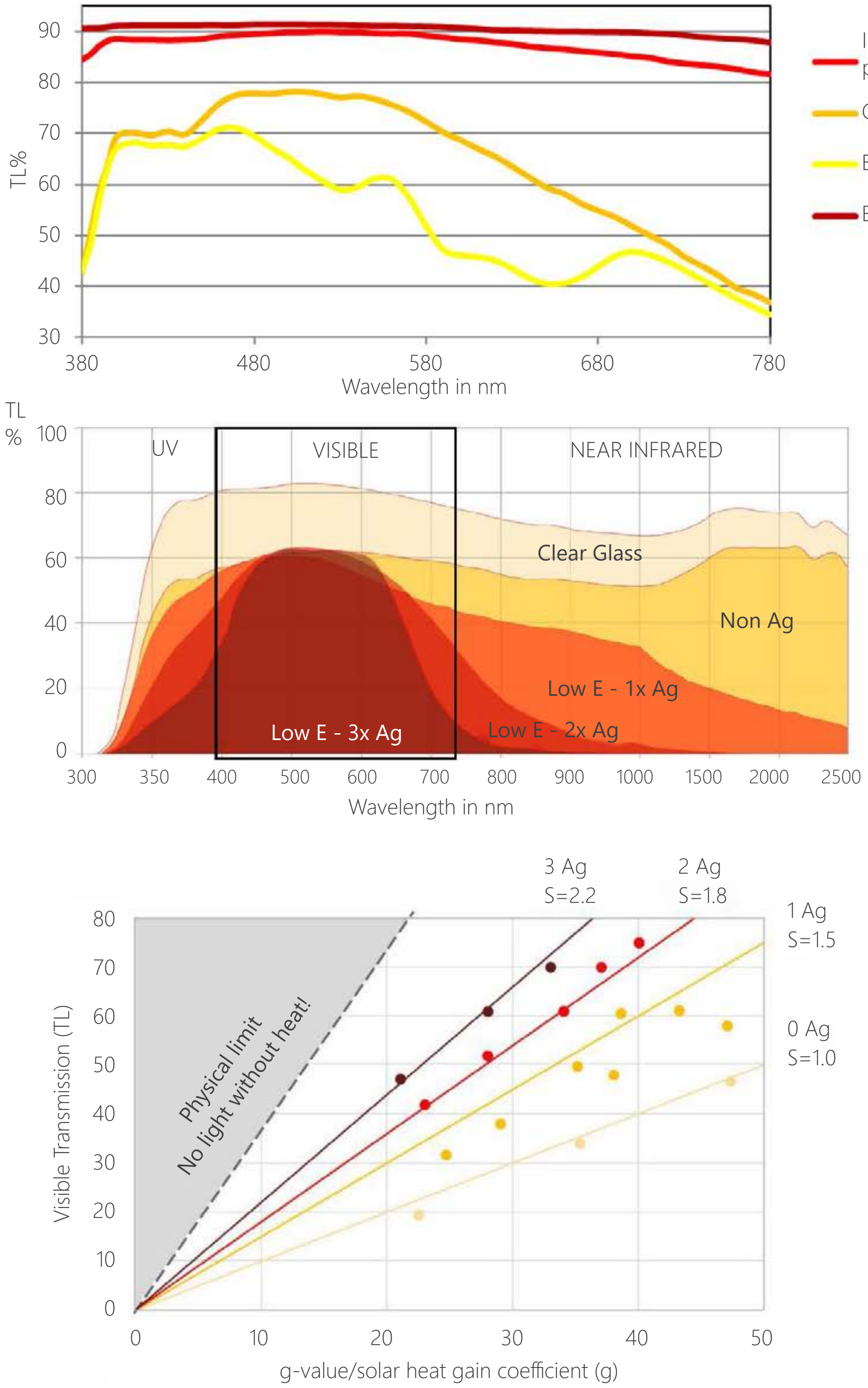


Figure 93: Top- VLT for different types of glasses; Middle- performance of different low-e coating combinations in UV, visible light, and IR spectrums. Bottom- selectivity, solar heat gain coefficient and visible light transmission of different low e-coating combinations
Information and Image Courtesy: A.R Unnikrishnan, Saint Gobain Glass

may also give rise to visual issues such as glare. Further, the performance of glass in IR and UV spectrum should also be modulated. High absorptivity or transmissivity in UV and IR wavelengths can lead to heating of indoor spaces. Glazing units engineered with microscopically thin coatings that render low emissivity properties (Low e-coatings) can cut transmission of IR and UV radiations without any interference to visible light transmission. Refer section 5.4.1 for further details on emissivity. Figure 93 (middle) presents the difference in performance of simple clear glass and advanced glazing systems with coatings- clear glass, Double Glazed Unit (DGU) with no coating (indicated as non Ag), DGU with one low e-coating, DGU with two low e-coatings, and DGU with three low e-coatings.

Silver (Ag) based low e-coatings have maximum selectivity and hence are often preferred. The metric solar control or selectivity indicates the performance of glazing unit with respect to daylighting and heat transmission. It is defined as the ratio of visible light transmission to solar heat gains.

$$Selectivity = \frac{T.L.}{g} \quad \left(i.e., \frac{Light}{Heat}\right)$$

Figure 93 (bottom) shows comparison between the solar heat gain coefficients of clear glass without any silver-based low e-coatings with that containing different number of coatings along with their transmission levels of visible light. It also shows the theoretical limit of optimizing heat gain coefficient and VLT in a glazing material. Technological advancements such as low e-coatings make minimizing solar heat gains possible while higher amount of daylight is experienced by the buildings.

Architects/ designers can utilize these graphs to determine the most suitable options in their projects. By knowing the maximum limit of solar heat gains permissible in the building, a cap on solar heat gain coefficient can be decided. Simultaneously exploring options with high VLT in the acceptable solar heat gain coefficient range, few glazing options can be shortlisted. Alternative approach is deciding upon a desirable selectivity range to eliminate unsuitable options.

5.4.2 Solar Gains and cooling load

The use of optimized glazing units can significantly reduce solar heat gains through fenestrations. The reduction in cooling loads and solar heat gains are dependent on multiple factors including window to wall area ratio and orientation. Assuming a fixed WWR in standard sized affordable housing, Figure 94 presents the cooling load reduction associated with glazing units of varying performances. Additionally, Figure 95 shows the percentage of reduction in solar gains from windows for each of these glazing units. It can be observed that product E can reduce the solar heat gains experienced in clear DGU by 83.2%. This translates to a 40% reduction in the cooling loads of the assumed space. Specification of products are shown in Table 25.

5.4.3 Window Frame

In addition to the glazed part, heat exchanges happening across the frame of the glazing unit must also be considered for their impact on solar heat gains. Combination of high weather resistance, lightweight, and structural stability make aluminium an attractive material in window frames within modern construction. Contemporary window frames made of aluminium, a metal with high thermal conductivity, provide thermal breaks in the form of air gaps and insulating foam to eliminate thermal bridging and the

Table 25: Properties of glazing assemblies

Product	VLT (%)	External Reflection (%)	Internal Reflection (%)	Solar Factor	Shading coefficient	U-value
A	80	15	15	0.76	0.87	2.6
B	46	16	18	0.22	0.25	1.5
C	46	20	22	0.47	0.54	2.8
D	51	18	22	0.28	0.33	1.5
E	47	17	11	0.38	0.43	1.9

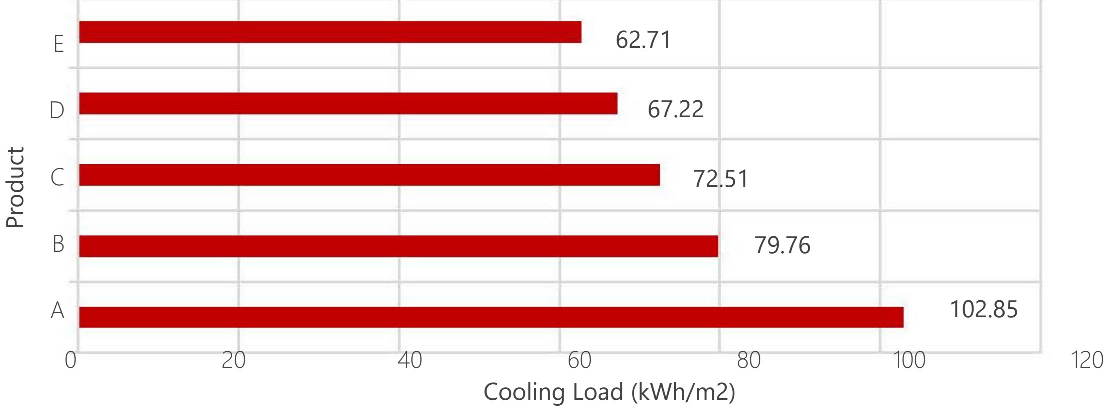


Figure 94: Cooling loads associated with different glazing units.
Information and Image Courtesy: A.R Unnikrishnan, Saint Gobain Glass

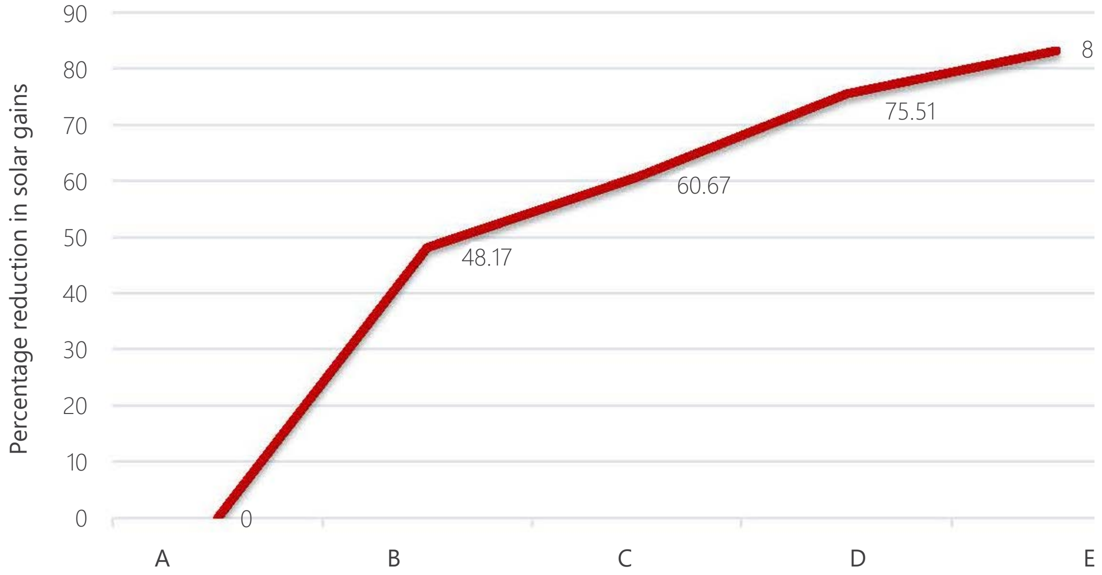


Figure 95: Reduction in solar gains associated with different glazing units.
Information and Image Courtesy: A.R Unnikrishnan, Saint Gobain Glass

resulting heat exchanges. Considering different glazing configurations for aluminium frame, a comparative graph of the U-values of different window assemblies is shown in Figure 97 (left). Additionally, Figure 97 (right) depicts that changing angle with the horizontal affects the U-value of the assembly, due to different air patterns caused by gravity in each case .

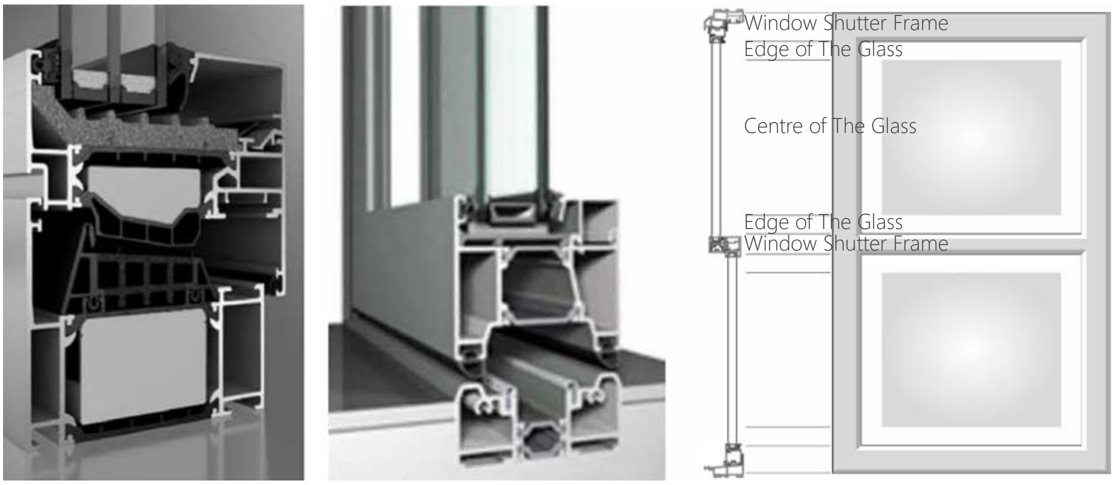


Figure 96: Window frame construction details
Source: Neuffer. (n.d.). Schüco Aws 90. Neuffer. Retrieved from http://192.169.1.1:8090/httpclient.html Grabex. (n.d.). Sliding-Folding Doors For Your Space. Grabex. Retrieved from https://grabex.co.uk/doors/bi-fold-doors/cf68-bi-fold-doors/

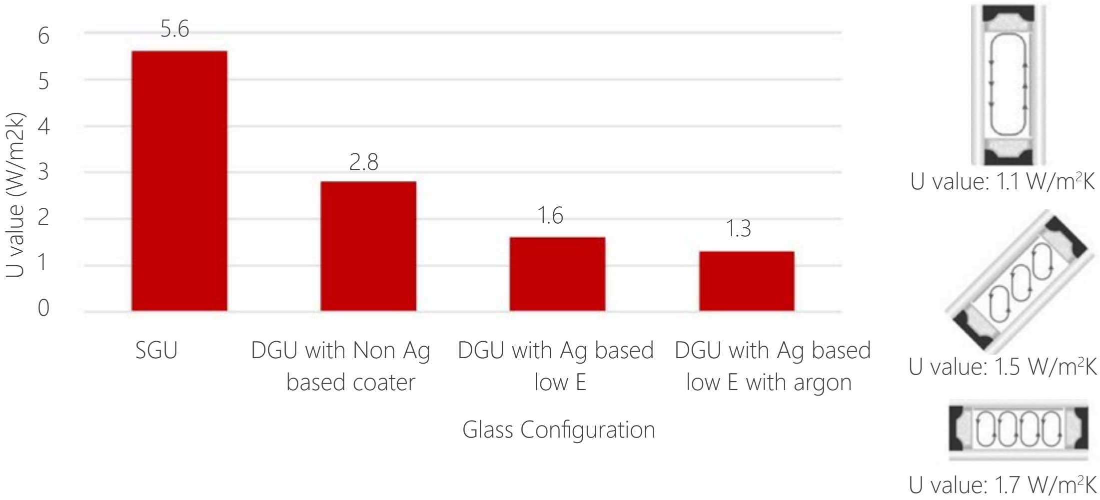


Figure 97: U value based on glass & frame configuration; Right- Orientation of assembly with respect to horizontal affects U-value

5.5 Roofing Coating Materials

5.5.1 Reflectance, Emittance, Emissivity

As previously explained in chapter 2, heat transfer by radiation depends on the reflectance (ρ), transmittance (τ), and absorptance (α) of a material and according to law of conservation of energy, $\alpha + \rho + \tau = 1$. The absorbed heat may cause an increase in the temperature of the surface and object. Additionally, part of the absorbed heat may also be re-emitted by the surface (refer Figure 98). This property of the material is known as its thermal emissivity. Thermal emissivity is the ratio of radiant flux emitted by a surface to that emitted by a black surface at the same temperature (For a blackbody or black surface has $\alpha = 1$). Emissivity refers to intrinsic properties of a material's surface and is defined only for a specimen of the material that is thick enough to be completely opaque and has an optically smooth surface. Emissivity is a function of the material, its surface condition, and its surface temperature (ASHRAE, 2021).

Out of all the components of a building envelope, the roof experience maximum quantity of solar radiation incident on a building. Due to the absorptance property of roofing finishes, their surface temperatures tend to be significantly higher than surrounding air temperatures in hot countries like India. Some of this heat absorbed by the roof surface may be lost to the outdoor air through convective heat transfer occurring from winds. However, prioritizing the removal of remaining heat will avoid its transfer to indoors through conduction. This can be achieved by using roofing and/ or roof coating materials with high emissivity values. Roof coating materials such as paints, tiles, sheets with high reflectance and emittance values are available. They are usually termed as products with high Solar Reflective Index (SRI) values. SRI is explained in the next section.

On the interior side of roofs, the aim should be to retain the coolth created in the indoor space. Therefore, finishes with low emissivity will not raise the mean radiant temperature (MRT) of the interiors.

5.5.2 SRI and its aging

Solar Reflective Index (SRI) value is a combined metric used to indicate the reflectance and emissivity values of roofing materials. High SRI value corelates to desirable combination of high reflectance and emissivity in the context of cooling-dominated Indian climates, especially hot and dry. Figure 99 explains that higher solar reflectance (R_{sol}) reduces solar heat gain and higher emissivity (E) enhances thermal radiative cooling.

Figure 100 explains the reflectance levels of cool roof or white roof and other standard roof coating paints in the UV, visible light, and near IR ranges of solar irradiance (incident solar radiation). It can be observed that white roof can reflect nearly 82% of the solar irradiance in visible light range while its reflectivity decreases as wavelength of near IR spectrum increases. Compared to that, a dark gray roof is not capable of reflecting more than 30% of the solar irradiance in visible light and IR spectrums. Practicing cool roof (white roof) in Indian climates is an affordable strategy to reduce heat gains through the roof. Additionally, emerging generation of paints have been developed to offer color independent reflectance within cool roof paints allowing higher degree of aesthetical freedom to buildings.

Solar reflectance of coatings such as paints with high SRI is subject to degradation from collection of dust and particulate matters as well as development of unwanted vegetation on the surface among other reasons. It is critical to design considering the

Figure 98: Interaction of roofing materials and surfaces with incident solar radiation.
Source (left): ASC Building Products. (2020). Energy-Efficient Cool Colors in Today's Metal Roofing. ASC Building Products. Retrieved from https://www.ascbp.com/cool-colors-and-energy-savings/.

actual delivered SRI values as ageing happens. International ASTM standards specify that the roof product's aged solar reflectance index shall be computed from three-year aged values of solar reflectance and thermal emittance determined in accordance with ASTM E 1980.

Figure 100 (left) shows the difference in SRI of new and four-year aged white coat observed in experimental research in Italy (Paolini, Zani, Poli, & Zinzi, 2017). The experimental observations were used to develop simulations that indicated the impact of the paint on a typical building throughout the year over a period of four years. Figure 100 (right) displays the surface temperature of the southern façade of the simulated building on a typical summer day in following four conditions:

- Insulated wall with aged paint (INS aged)
- Insulated wall with fresh paint (INS new)
- Non- Insulated wall with aged paint (Non-INSaged)
- Insulated wall with aged paint (INS aged)

It is important to note that simulation-based estimations of degradation in SRI of a cool roof may not be exactly experienced in actual application. Since the weather and atmospheric conditions that determine weathering of a building material vary regionally, the SRI performance will also vary for similar buildings in different locations. Contemporary research on ageing properties of the coatings in Indian context includes development of accelerated ageing tests to understand and account for the same during design phase of buildings.

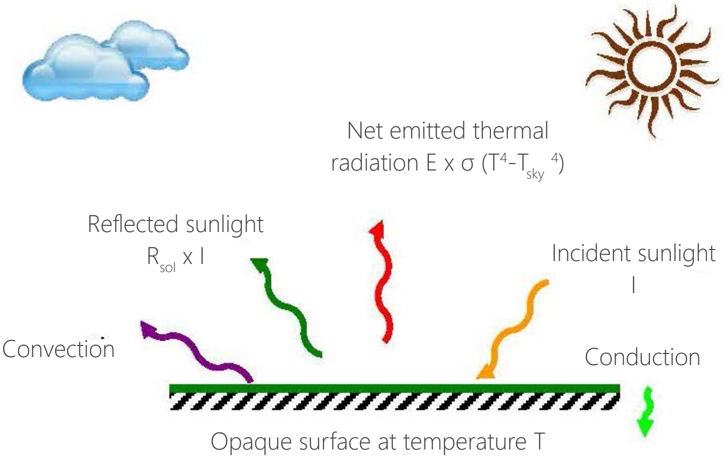


Figure 99: Factors affecting surface temperature of roof and/or roof coating materials

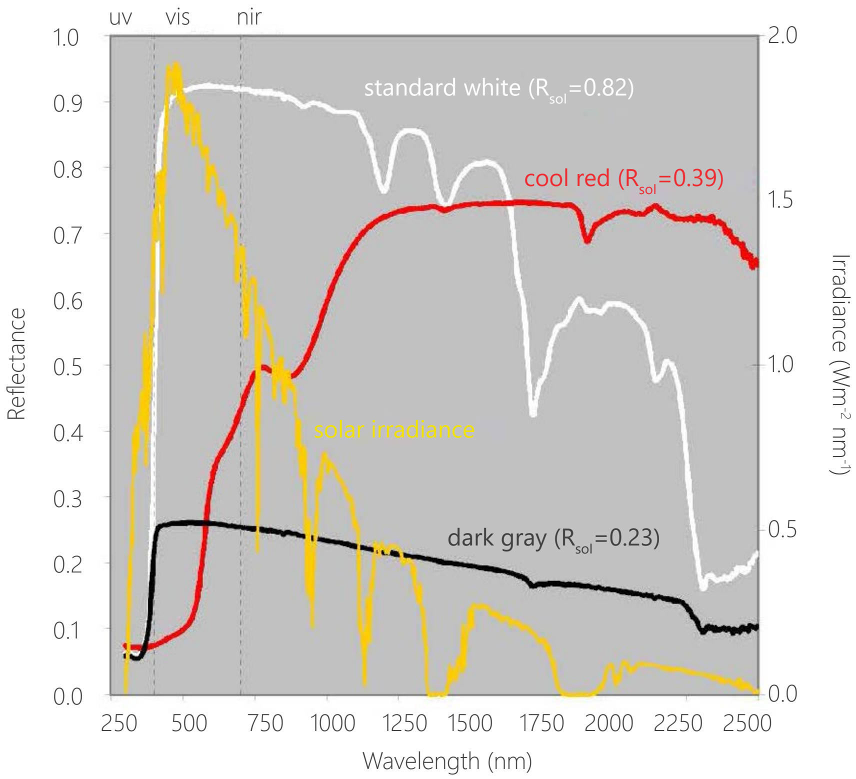


Figure 100: Reflectance of different roof paint colors for different wavelengths

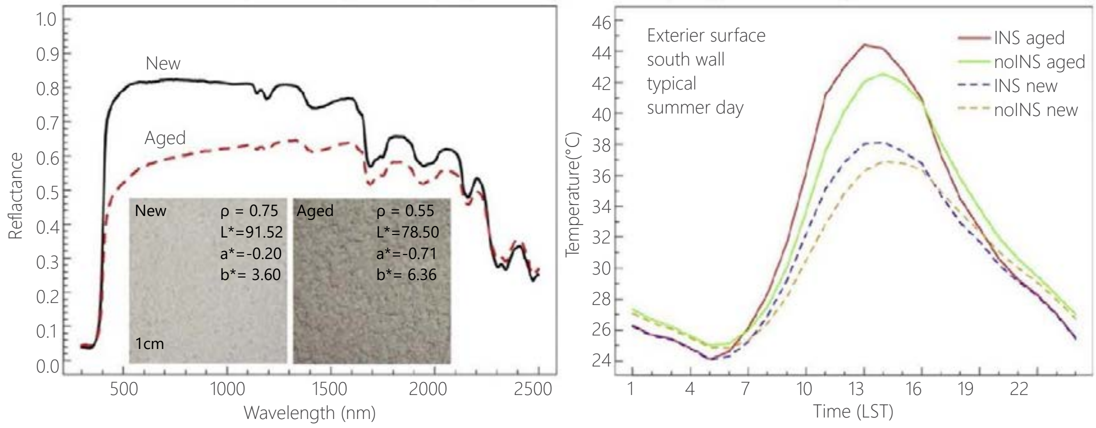


Figure 101: Ageing of high SRI coatings;
Source: (Paolini, Zani, Poli, & Zinzi, 2017)

5.6 Light House Projects (LHP)

For introduction to LHP and GHTC initiatives, refer section 6.1.2.

LHP – Agartala (Light Gauge Framed Steel Structure – Infill Concrete Panel)

Light Gauge Steel Framed Structure with Infill Concrete Panels (LGSFS-ICP) Technology uses factory-made cold-rolled Light Gauge Steel Framed Structure (LGSFS) in combination with light weight concrete and precast panels to form walls and roof structures. Produced by computerized roll-forming machine, the LGS frame is a “C” cross-section with built in notch, dimpling, slots, service holes etc. These frames are assembled using metal screws and provisions for doors, windows, ventilators, and other cut-outs in the case of walls are required to be incorporated in the LGSFS.

Once manufactured and assembled in to LGSF wall structures, they are transported to the construction site to begin wall by wall erection on a pre-built concrete floor as per the designed floor plan. Consequently, steel reinforced concrete panels (800mm X300mm X20mm) manufactured at factory are transported to the site. These panels are fixed on either side of the LGSFS wall using self-drilling/tapping screws to act as outer and inner faces of the wall leaving a gap between them. Electrical and plumbing pipes/ conduits are provided in the service holes of the LGSFS before concreting is done. Self-compacting concrete is mixed and pumped into the gaps between two panels. The concrete flows and fills the gap and provides adequate cover to the LGS frames and joints. After curing, LGSFS with in-fill concrete and panels (LGSFS-ICP) forms a monolithic sandwich composite wall structure. The staircase, chajjas, and parapet walls of the building are also constructed using LGSFS-ICP Technology.
Salient features:

- Weight of the LGSFS-ICP building is about 20-30% lighter

Additional details regarding the technology can be accessed at the GHTC website (MoHUA, GoI, 2021).

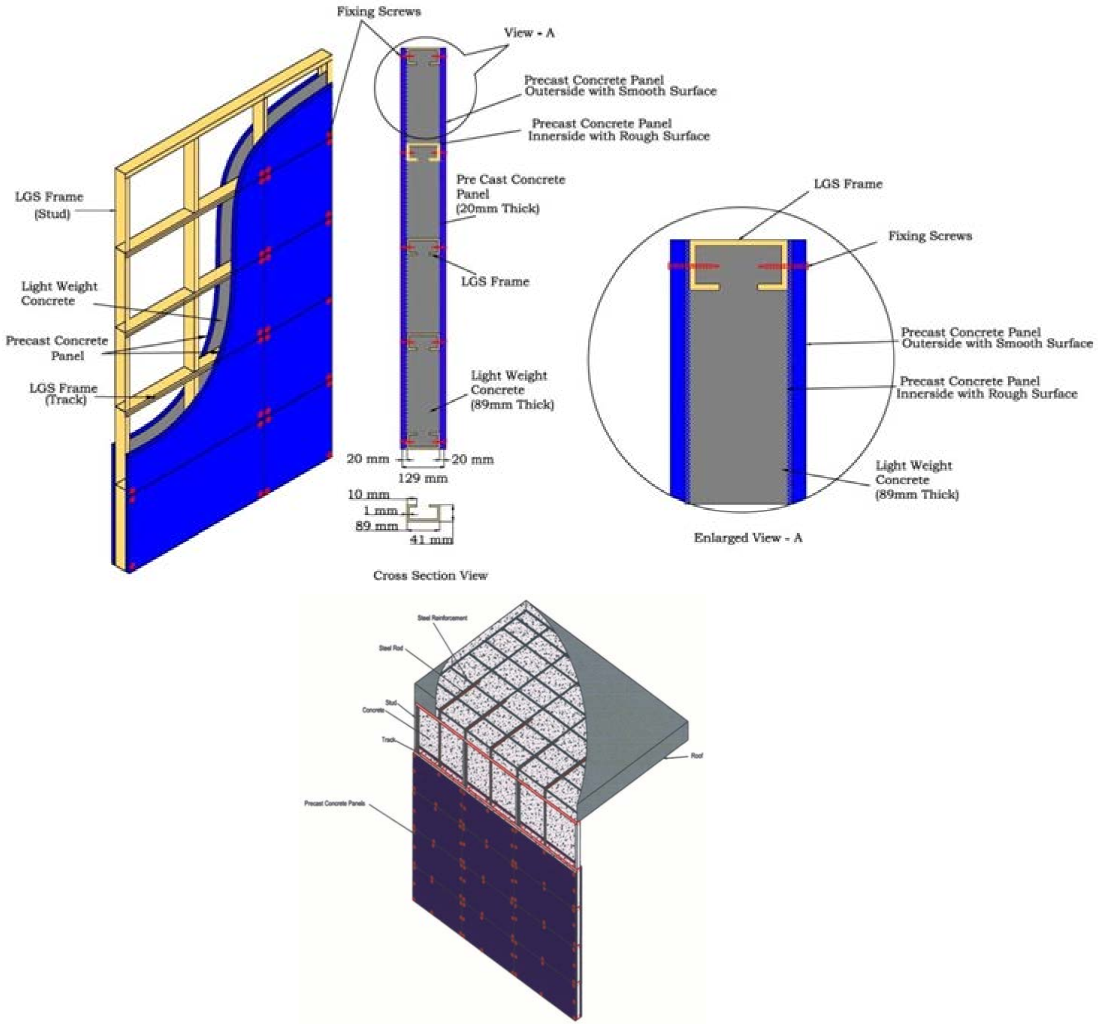


Figure 102: Structural Details of LGSFS-Infill Concrete Wall.
Source: (MoHUA, GoI, 2021)

LHP- Chennai (Precast Concrete Construction System)

3S system incorporates precast dense reinforced cement concrete hollow core columns, structural RCC shear walls (as per design demand), T/L/Rectangular shaped beams, stairs, solid precast RCC slabs for floor/ roof, lintels, parapets and chajjas. AAC blocks are used for partition walls. Hollow core columns are erected above substructure, over which beams are integrated in the column notches. This is followed by erection of slabs. Wet jointing using dowel bars/ continuity reinforcement placed at connections and filling the in-situ self-compacting concrete in hollow cores of columns provides structural stability . All the connections and jointing of various structural framing components is accomplished through in-situ self-compacting concrete/ micro concrete/ non-shrink grout as per design demand along with secured embedded reinforcement of appropriate diameter, length, and configuration to ensure monolithic and durable behaviour.

All the structural components are pre-engineered and manufactured in factories/site factories with objective quality control resulting into dimensional accuracy, correctness in spacing of reinforcement, uniform protective cover, full maturity of components and assurance on design strength due to use of design mix concrete having minimal water-cement ratio which ultimately results into durable structure.

Salient features

- Precast dense reinforced cement concrete hollow core columns, structural RCC shear walls, T/L/Rectangular shaped beams, stairs, floor/roof solid.
- AAC blocks are used for partition walls

Additional details regarding the technology can be accessed at the BMTPC website (GOI, 2021).

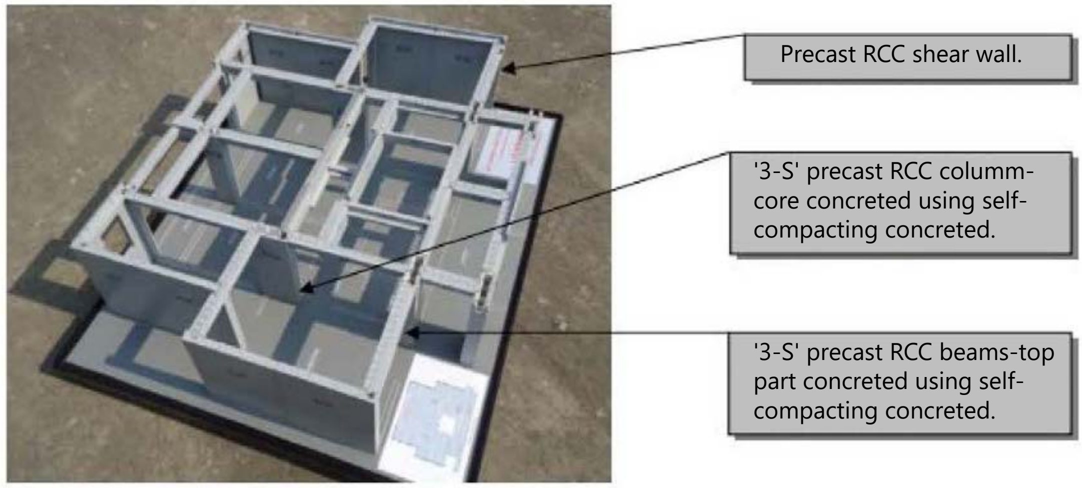


Figure 103: Construction details of LHP Chennai.
Source: (MoHUA, GoI, 2021)

LHP- Indore (Prefabricated Sandwich Panel System)

Prefabricated Sandwich Panels are lightweight composite wall, floor, and roof sandwich panels. They are made of thin fiber cement/calcium silicate board acting as face covered boards with the core material as a mix of EPS granule balls, adhesive, cement, sand, flyash, and other bonding materials in mortar form. The core material is pushed under pressure into preset molds in a slurry state. Upon setting, it is cured until ready for use with RCC or steel support structure beams and columns. Mostly used as walling material, these panels are also suitable for use as floor and roof panels. Typically, these panels are non-load bearing and should be used with a structural support frame only. However, if used in G+1 structures, these can be used as load bearing panels.

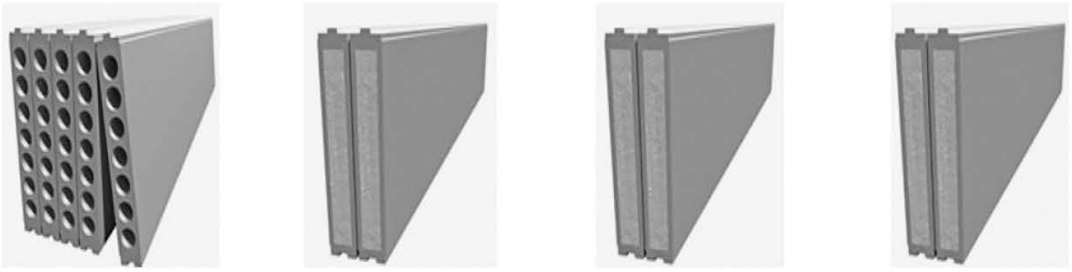
Typical panel size manufactured in factories is

- Length: 2440 mm (may be increased up to 3000 mm)
- Width: 610 mm (may be altered as per requirement but should not be too wide since handling of the panels become difficult)
- Thickness: 50-250 mm.

The design of panels can include perforations based on application requirements. Solid heart type may be used as walling material in any type of construction while pole, rod and block hole may be used where different types of inserts are used like iron rods or wires for security (Refer Figure 104).
Salient features:

- Facilitate quick and cost-effective construction
- EPS granule balls used as core material make the board lightweight

Additional details regarding the technology can be accessed at the GHTC website (MoHUA, GoI, 2021).



Pole Holes Solid Heart Rod Holes Block Holes

Figure 104: (From left to right) Four types of prefabricated sandwich panel systems.
Source: (MoHUA, GoI, 2021)

LHP- Lucknow (PVC Stay-in-place formwork)

Stay-in-place formwork refers to an innovative formwork system made of rigid polyvinyl chloride (PVC) that acts as durable finished formwork for concrete walls. It has slide and interlock technology for the extruded components to create continuous formwork. The two faces of the wall are connected by continuous web members to form hollow rectangular components. Additionally, the web members are punched with oval-shaped cores to allow easy flow of the poured concrete between the components.

The hollow wall components are erected and filled with concrete, in situ, to provide a monolithic concrete wall. This wall has enhanced curing capacity due to water entrapment. Typically, with only top surface of the wall exposed to potential drying, there are chances of non-uniform drying of concrete. This is avoided by the polymer encasement. It also provides vertical and horizontal crack control for the concrete and acts as vertical tension reinforcement.

To anchor the wall to the concrete foundation, steel dowels are required. This system is suitable for both low and high-rise residential or commercial buildings. LHP Lucknow uses the composite structure with Pre-Engineered Steel Structural System as structural members to achieve speedier construction, strength, and resource efficiency. The PVC wall forms have been developed in various cross-sectional sizes as per project requirement. The common sizes are 64mm, 126mm, 166mm & 206mm.
Salient features:

- Rigid polyvinyl chloride (PVC) based formwork system serves as a permanent stay-in-place durable finished formwork for concrete walls
- The PVC extrusions consist of the substrate (inner) and modifier (outer). The two layers are co-extruded during the manufacturing process to create a solid profile.

Additional details regarding the technology can be accessed at the GHTC website (MoHUA. GoI, 2021).

Figure 105: On-site construction using PVC Stay-in-place formwork system.
Source: (MoHUA. GoI, 2021)

LHP- Rajkot (Monolithic concrete construction with tunnel formwork)

LHP Rajkot utilized tunnel formwork as the innovative construction technology which uses customized engineering formwork replacing the conventional steel/plywood shuttering system. Tunnel formwork is used cellular structures. It is based on two half shells which are placed together to form a room or cell and several cells constitute an apartment. This technology allows walls and slab to be cast in a single day by dividing the structure into phases. Each phase consists of a section of the structure that can be cast in a single day. The program of the project i.e., quantity, nature and layout of spaces together with the amount of floor area that can be poured in a day determine the phasing. Every construction day, the form work is set up and positioning of reinforcements and services takes place. This is followed by pouring of concrete for walls and slabs in single operation. The following day, formwork is first stripped and positioned for reuse in the next phase.

Being room size formworks that allow walls and floors to be caste in a single pour, modular tunnel forms provide opportunity to cast the entire floor of a building in a single pour using more than one forms. However, as they are slipped out and lifted for use on the next floor, they require sufficient space for movement around the actual building footprint. This Tunnel form consists of inverted L-shaped half tunnels (one vertical panel and one horizontal panel) joined together to create a single tunnel. The horizontal and vertical panels are braced by struts that allow adjustment of the horizontal level of the slab to simplify the stripping of the formwork. The additional horizontal infill panel dimensions can be modified to accommodate a range of spans. The vertical panel is equipped with adjustable jacking devices and a triangular stability

Figure 106: Modular Tunnel formwork hoisted in air.
Source: (MoHUA, GoI, 2021)

system. Both devices are on wheels. Staggers and offsets in the wall layout and different wall thickness are possible in this technology due to the distribution of horizontal beams on the vertical planks. The half-tunnels are equipped with back panels to cast perpendicular shear walls or corridor walls.

In addition to modular tunnel forms, temporary mods known as walls forms can also be used to build structural walls, columns and more. Being adaptable to both repetitive and non-repetitive tasks provides more freedom in design. However, unlike modular formwork, they can be used to cast only walls, columns, and other vertical structures.

Moreover, kicker forms and box out forms are two additional formworks used for specific purposes. Kicker forms are fixed to tunnel forms before concrete is poured to guide the walls of the upper floor precisely above the walls of the floor below, and box out forms such as window box out, door box out and slab box out are mounted on the tunnel in each phase using a magnetized system to allow openings for windows, walls, etc.

Characteristics of the system:

- Maximum span between walls shall be 5.60 m without accessory units and 7.00 m with accessory units.
- Height of the formwork – Typically, the forms are designed for a floor to ceiling height of at least 2.51 m.However, it can be increased by using the leg jacks or movable panels.
- Appearances of the faces after form removal – The joints connecting the units may have fins which should be sanded off and smoothed with paint filler. Remaining surfaces allow direct application of finishing paint or wallpaper.
- Working rhythm using the system – Under average temperature conditions, the normal rhythm is two days per cycle with one day and two nights for drying and setting the concrete, given ordinary cement is used.
- Time period required for execution of the process – The time required for execution varies according to the cell plan. For a cell consisting of two formed wall surfaces and a floor surface, the average time is less than 1-1.5 hours per square meter of building. This time includes the form removal, oiling, displacement of the units, formwork, and adjustment.

Additional details regarding the technology can be accessed at the GHTC website (MoHUA, GoI, 2021).

LHP-Ranchi (Pre-cast concrete construction- 3D Volumetric)

3D Volumetric concrete construction involves construction with solid precast concrete structural modules like room, toilet, kitchen, bathroom, stairs etc. & any combination of these. The modules are cast monolithically either at a plant or a casting yard in a controlled condition. Termed as Magic Pods, they are transported, erected, installed, and integrated in the form of complete building unit using cranes and push-pull jacks. Hence, use of technology for different building heights is subject to the hoisting capacity of these machinery. The indicative manufacturing, construction, and installation process of the Magic Pods is presented below:

- 3D Steel moulds suitable to various sizes of building units are created.
- High strength steel is placed inside 3D moulds for structural reinforcements.

- Electrical and plumbing lines, block outs for doors and windows are simultaneously set up.
- The pods are cast into their final shape using high-performance concrete.
- Stringent quality checks are taken before they are packed for shipping, to ensure that the construction project adheres to strict quality standards.
- The pods are then loaded and shipped in the sequence of erection at the site.
- Factory finished building units/modules are installed with the help of tower cranes on site. Gable end walls are positioned to terminate the sides of building.
- This is followed by installation of prestressed slabs as flooring elements. Rebar mesh is finally placed for structural screed thereby connecting all the elements together.

Salient features:

- About 90 % of the building work including finishing is complete in the plant/casting yard resulting in significant reduction in construction and occupancy time
- The required concrete can be designed using industrial by-products such as Fly Ash, Ground granulated blast furnace slag (GGBS), Micro silica etc. resulting in improved workability
- Minimal shutter and scaffolding

Additional details regarding the technology can be accessed at the GHTC website (MoHUA, GoI, 2021).

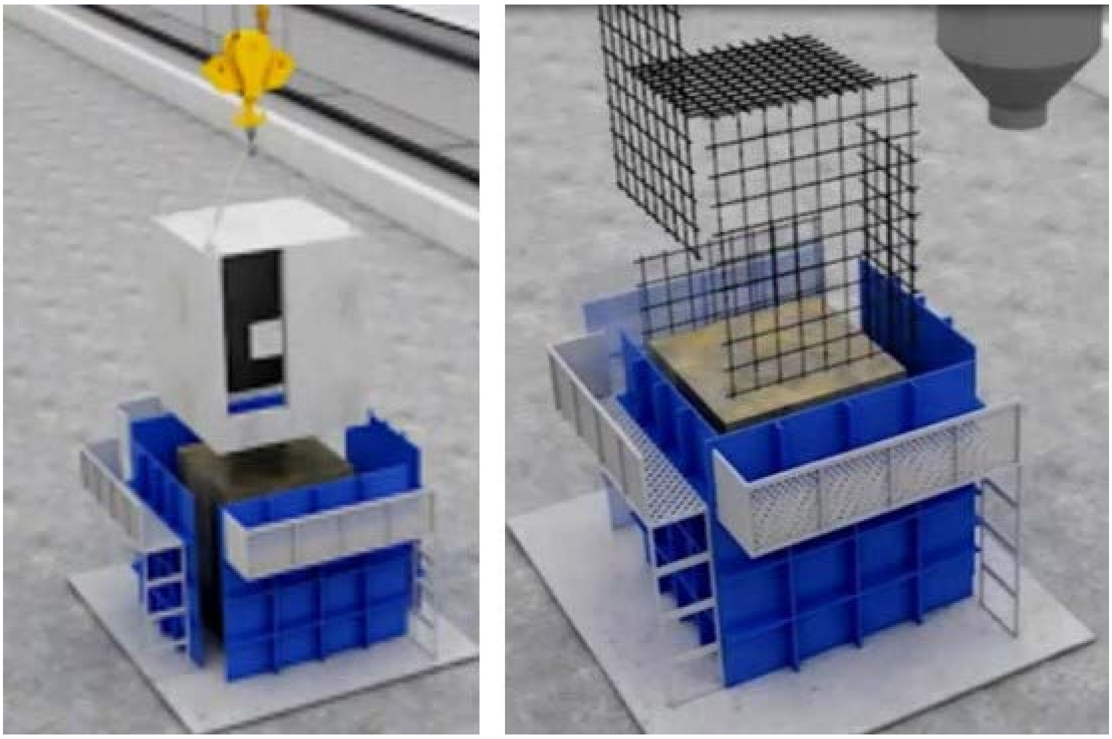
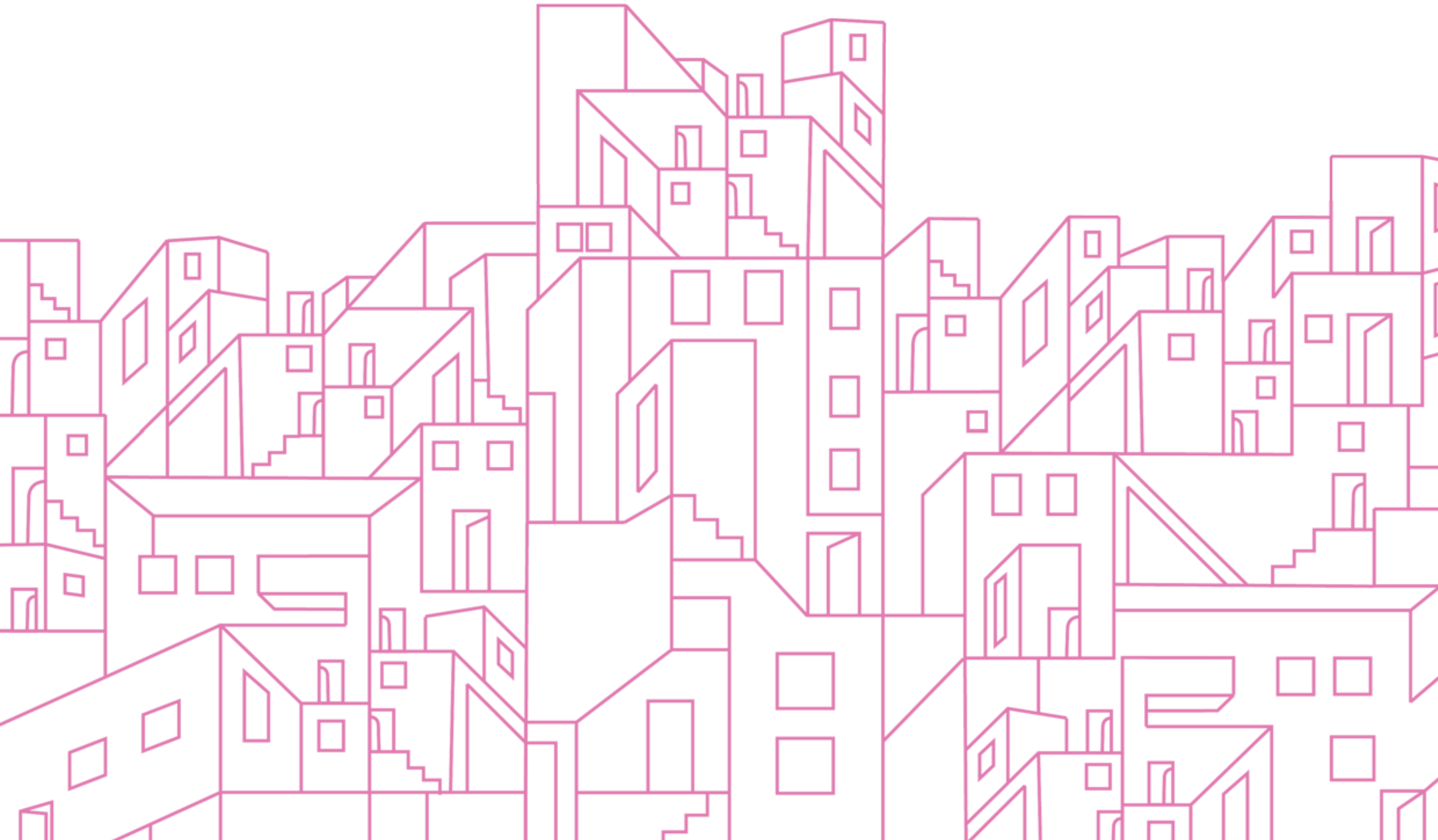


Figure 107: Illustration of construction and installation process of Magic Pods.
Source: (MoHUA, GoI, 2021)

6

BUILDING CODES, AFFORDABLE HOUSING AND THERMAL COMFORT



6.1 Introduction

This chapter deals with the contemporary codes pertaining to thermally comfortable affordable housing in India. The chapter explains the ongoing national initiatives for affordable housing and sets the context for existing codes through explanation of different terms- standards, guidelines, codes and more. Further it explains the ENS -I component of the code and its requirements in detail. This is followed by a description of the RETV formula and its individual components. Lastly, through an example, the chapter delineates the process of checking for code compliance in a project using the ENS compliance check tool.

6.1.1 Energy consumption in residential buildings

The energy consumption in residential sector in India was found to be 255 TWh in 2017 (Ministry of Statistics and Programme Implementation, GOI, 2019) . Projections for energy consumption in 2030 show an increase of 3.5 times to 850 TWh. This increase is largely attributed to the residential stock build-up (estimated to double in the next 1.5-2 decades) and increased ownership of room air-conditioners, subsequently leading to higher usage. This will ensure that by 2030, residential sector surpasses the industrial sector as the largest consumer of electricity by contributing to nearly 38% of the total electricity consumption of the country. Thus, it is important to promptly implement strategies and guidelines developed at the local, state, and national levels to ensure construction and operation of energy efficient building stock, including affordable housing.

Affordable Housing is defined in terms of the project size, dwelling unit area and occupant income. An affordable housing project can be a mix of houses for different categories – Economically Weaker Section (EWS) or Lower Income Group (LIG), satisfying the following criteria (Ministry of Housing & Urban Affairs, GOI, 2021):

- Carpet Area of Dwelling Units shall be between 21 m2 to 27 m^2 for EWS category and 28 m2 to 60 m2 for LIG category.
- Projects using at least 60 percent of the Floor Space Index (FSI) for dwelling units of Carpet Area not more than 60 sqm. will be considered as Affordable housing projects. In addition, 35 percent of the total number of dwelling units constructed should be of carpet area 21-27 sqm for EWS category.
- At least 250 DUs

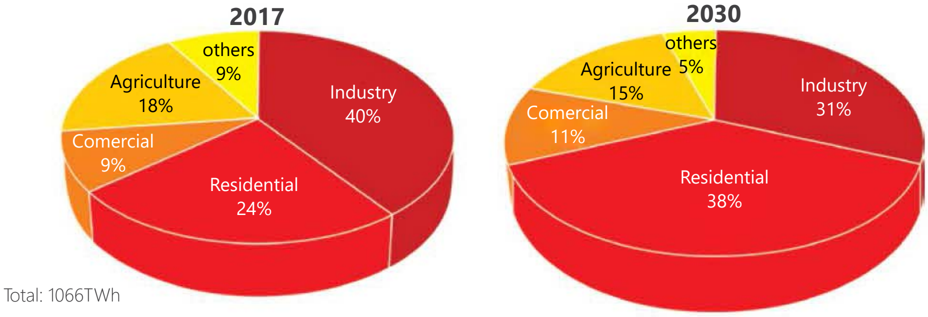


Figure 108: Sector-wise energy consumption statistics and projections.
Source: MOSPI, GOI

- For EWS DUs, the qualifying annual household income is up to INR 1 lakh and for LIG, the corresponding value is between INR 1 to 2 lakhs.

6.1.2 Affordable housing programmes in India

The Government of India has been implementing its flagship programme- Pradhan Mantri Awas Yojana- Urban (PMAY-U) since 2015. PMAY-U aims to fulfil the vision of 'Housing for All'. Under the Mission, Ministry of Housing and Urban Affairs (MoHUA), provides Central Assistance to implementing agencies through States and Union Territories for providing houses to all eligible families/beneficiaries within the stipulated time.

As an outcome of PMAY-U, 11.23 million houses are being constructed within the Mission period. The houses built under the Mission will last at least 50-60 years and thus have a potential to impact resource usage during their life span. Further, the decisions taken during implementation have an impact on the level of comfort that these dwellings provide to its occupants, thus impacting their energy use and costs and the associated carbon emissions over the lifetime of the buildings. A significant portion of the projected electricity demand is expected to come from increased appliance ownership and cooling needs arising from enhanced access to housing, thus making thermal comfort an imperative concept to be considered while designing and building homes.

Additionally, MoHUA has also initiated a sub-scheme- Affordable Rental Housing Complexes (ARHCs) under PMAY-U as a significant step for urban migrants/ poor in the industrial and non-formal urban economy sectors. Two models have been identified for provision of the dignified affordable rental housing near workplaces with civic amenities in close proximities:

1. Utilizing existing Government funded vacant houses in cities by converting them into ARHCs under Public Private Partnership (PPP) mode or by public agencies as a Centrally Sponsored Scheme,
2. Construction, Operation and Maintenance of ARHCs by Public/ Private Entities on their own available vacant land.

Additionally, MoHUA has initiated the Global Housing Technology Challenge - India (GHTC-India). The purpose of the initiative is to identify and mainstream innovative construction technologies from across the globe to enable more sustainable, eco-friendly, and disaster-resilient housing. The primary goal of challenge is to meet the current housing demand through faster speed of construction while ensuring affordability, functional needs, and quality of construction.

Construction Technology India: Global Expo-cum-Conference was inaugurated by Hon'ble Prime Minister on 2-3 March 2019 at New Delhi to promote 60 exhibitors with 54 proven technologies from 25 countries. Out of these, 6 distinct innovative technologies were shortlisted for implementation in the ongoing Light House Projects (LHP) detailed in chapter 5.

The mission also intends to support future technologies through an environment of research and development in the country. Affordable Sustainable Housing Accelerators-India (ASHA-India) initiative offers incubation and acceleration support to currently 72 potential future technologies identified through GHTC challenge. These potential future technologies are at various stages of development- either not yet market ready (pre-prototype applicants) or are market ready (post prototype applicants). Development of design guidelines, construction manuals and other necessary guidelines for effective use of such technologies in the region will also be supported under ASHA-India.

6.2 Context

With majority of Indian population living in warm – humid and composite climates, followed by hot and dry, the need for thermally comfortable housing is evident. In residential buildings designed without adequate planning for thermal comfort, indoor temperatures have been observed reach anywhere between 36.5°C to 42°C during peak summers.

The implementation of appropriate spatial design and construction material/ technology-based strategies discussed in previous chapters can help to lower the peak indoor temperatures to 30°C - 35°C. Some of the most effective strategies for this goal utilize reduction of heat ingress and calibrated natural ventilation as explained in previous chapters.

However, effective implementation of the strategies requires guidance for designers, builders, and other building industry professionals at urban, state, and national levels. This guidance can be manifested within the community in various formats- Standards, guidelines, codes, laws and rules are tools for formalization of the strategies and encourage the community towards strategic adoption of these measures in the built environment industry.

6.2.1 Standards, guidelines, codes, laws, and rules

Standards: A Standard is a technical specification that defines conditions, criteria, and associated performance metrics. An internationally accepted ISO Standard

Figure 109: Intended outcomes of the PMAY-U initiative by Government of India

Guidelines: Guidelines consists of implementation principles based on best practice cases or empirical evidence. They differ from standards in their voluntary nature.

Codes: A set of guidelines or standards that are most useful to initiate mass implementation. They may or may not include pathways to best-in-class performance standards. However, they are structure in a language suitable for translation into laws at a later stage. Codes are meant to drive a bulk of the market towards a certain efficiency standard.

Laws: When codes are adopted by the state or national governments, they turn into laws. Further, upon incorporation into municipal byelaws, they are implemented city-wide with the force of law.

Rules: A system of legal regulations that defines enforcement mechanisms, penalties, and occasionally incentives for implementation of the laws. They can be understood as legal instructions on carrying out the implementation of the law at all ends- public and government.

Figure 110: Tools to formalize strategies and encourage their implementation

6.2.2 Types of codes

There are different categories of building energy codes depending upon their definition of technical standards. These categories also vary in the set performance goals and degrees of flexibility offered to designers, developers, and construction industry professionals in meeting the goals. They may also recommend different pathways to meet the standards.

- Prescriptive codes: The current residential and commercial codes in India are partially prescriptive as they specify requirements with key building components. They have performance standards for building envelope elements such as U-value of walls, roof etc (based on typical construction details) that must be adhered for code compliance. It is relatively easier to design and assess buildings for code compliance if the codes are prescriptive in nature.
- Trade-off codes: When codes allow minor trade-offs between similar building to acknowledge the possibility that meeting all the performance criteria may not be feasible or architecturally desirable in every project, they are categorized as trade-off codes. By offering alternative pathways for achieving or offsetting the difficult performance criterion, they provide flexibility in building material choices, construction systems and architectural designs. This allows trade-off codes to make code-compliance easier, ultimately leading to a bigger energy efficient and thermally comfortable building stock.
- Performance codes: Performance code allow maximum flexibility in design if energy consumption of the whole building is ensured as per code specifications. These codes require whole building energy simulations to be carried out in advance. The building simulations must explain energy performance of the building over its

lifespan in comparison with a baseline scenario detailed in the code. These codes are preferred when the building industry has a mature knowledge of efficiency related design parameters.

- Outcome-based codes: Whole building simulations may not account for all the complexities involved in actual building operation. Hence, actual building performance may not fully match the intended design. Outcome-based codes take this into consideration and hence, require performance measurements during the design as well as operational phase of the buildings. This means that code compliance happens at least 1-2 years post occupancy. This makes outcome-based codes most effective in ensuring building energy efficiency and thermal comfort provisions to occupants. At the same time, code compliance becomes more complex.

The Energy Conservation Building Code- Residential (ECBC-R) in India comprises of ENS-I (building envelope) and ENS-II (electro-mechanical systems). ECBC 2017 is the first commercial code of India. It offers three levels to choose compliance with – ECBC, ECBC+, Super ECBC. Both ECBC- R and ECBC 2017 consist of prescriptive and performance features.The codes prescribe the desirable performance of the building in relevant metrices rather than suggesting pathways of approach. This system allows the codes to remain technologically unbiased and offer freedom for economic viability to plethora of projects seeking compliance.

6.3 Eco Niwas Samhita

Often also referred to as ECBC – R, Eco Niwas Samhita-I deals with three parameters that contribute to a more energy efficient and thermally comfortable housing (refer Figure 111).

- Reducing heat gains/ losses through building envelope
- Improving natural ventilation
- Improving daylighting

India is classified as a cooling-dominated country (Cook, et al., 2020). The building envelope contributes to conductive and radiative heat gains; walling, glazing, and roofing materials transfer heat from outdoors to indoors across the thickness of the assembly and non-opaque surfaces add heat through radiation. Hence, code provisions aim to reduce heat gain by capping the Residential Envelope Transmittance Value of building envelope for multi-family buildings. RETV is a specialized derivation of Overall Thermal Transfer Value (OTTV) introduced by ASHRAE Standard 90- 1975 and first used as standard in building code by Singapore. (Jeyasingh, 2010)

Further, natural ventilation related building performance is quantified as Window-to-Floor area ratio (WFR_{op}). Additionally, meeting minimum WFRop values contributes to minimizing cooling energy and improving thermal comfort (Bureau of Energy Efficiency, 2018).

Lastly, the daylight performance of buildings can be assessed by the metric Visible Light Transmittance (VLT) of the glazing in combination with Window-to-Wall Area ratio. Together, these indicate the potential of utilizing daylight inside buildings and reducing lighting loads.

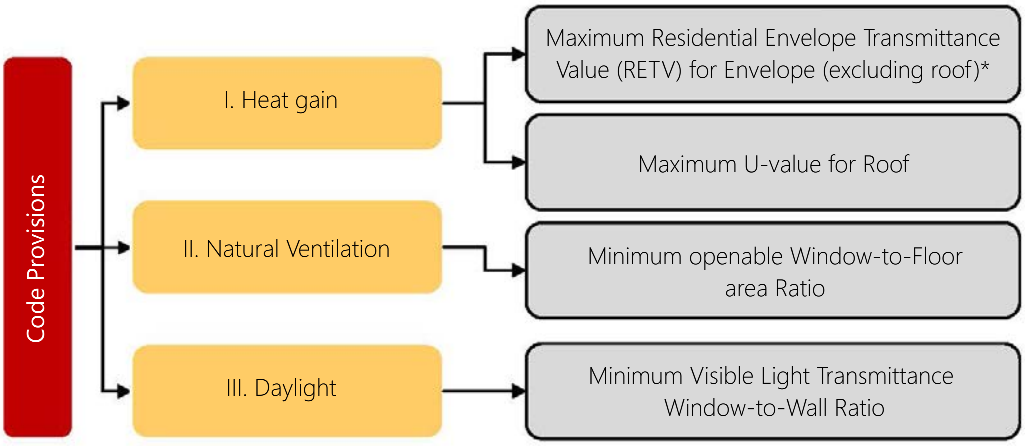


Figure 111: Metrics for various parameters mentioned in ENS-I

6.4 Code Provisions

6.4.1 Heat Gain- RETV

The heat gains through building envelope excluding roof are defined by the metric Residential Envelope Transmittance Value (RETV) for multi-family buildings. It is the ratio of net heat gain rate (over the cooling period) through the building envelope, excluding roof (i.e. windows and walls) to the area of the building envelope (excluding roof). RETV is measured in W/m^2. The code specifies a threshold value for RETV for building envelope in all climates except the cold climate as 15 W/m^2. The unit W/m^2 indicates the quantification of heat gain as proxy to electrical energy consumption indicated in Energy Performance Index (EPI). Low RETV indicates less heat gain and higher thermal comfort. Subsequently, it also translates to lower energy consumption and higher savings compared to BAU scenarios. Further, defining in terms of building area, similar to EPI, offers scalability in application to various residential building sizes. However, this value excludes from consideration the heat gains from the roof

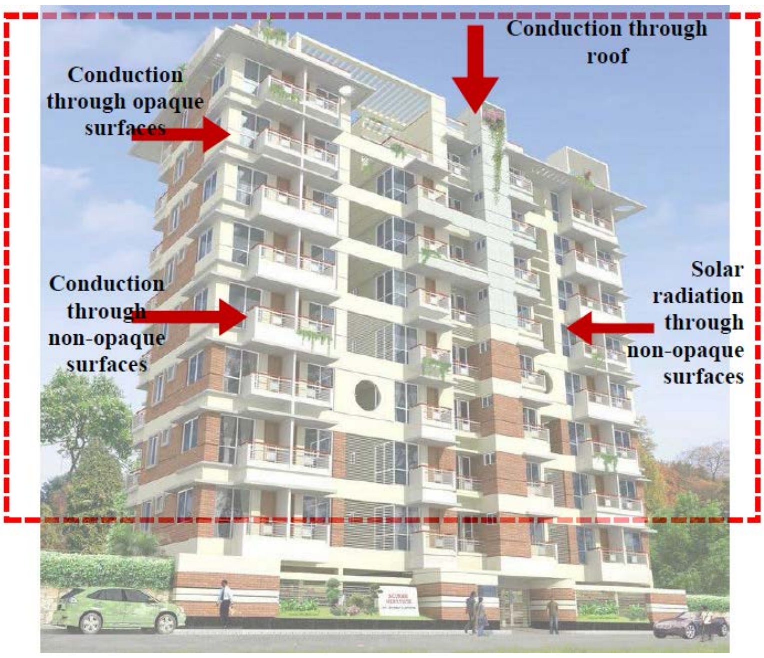


Figure 112: Sources and type of heat gain in multi-family residential building

and its area. This is to allow for the possibility of looking at individual dwelling unit performance in a multi-family building, if needed. For roofs, the maximum acceptable thermal transmittance value for code compliance is set at 1.2 W/m^{2}k, applicable to all climate zones in India.

RETV Influencing factors

RETV is determined by certain spatial design decisions that dictate the total amount of solar radiation falling on various elements of the envelope. Additionally, construction materials and assemblies also affect RETV calculation due to varying capacities of heat conduction. A brief list of the design and construction based influencing factors is presented below.

- Spatial design
    - Window to wall ratio
    - Shading factor of openings
    - Orientation of wall/ windows
- Construction material and assembly
    - U-value of glass
    - SHGC of glass
    - U-value of walls

Example: Spatial Design - Orientation

As seen from Figure 113, the incident solar radiation stays below 1 W/m2 for walls of a dwelling unit facing true north in a building located in the northern hemisphere. As the orientation of wall changes towards east or west, the amount of incident solar radiation increases. For walls oriented towards south, solar radiation is less than east or west-facing walls as the sun is at the highest altitude allowing maximum solar radiation to fall on the roof as opposed to walls. Further, Figure 113 shows that incident solar radiation is nearly double for walls facing southwest in comparison to north oriented walls. Greater the incident radiation, larger is the amount of heat transfer by a material of given thickness through conduction. Conclusively, the impact of orientation on heat gains inside a building is significant. This can be addressed in either of the following ways or a combination of both.

- Selecting building orientation option that minimizes incident solar radiation under given site conditions
- Addressing heat gains from the facades having most incident solar radiation through material choices.

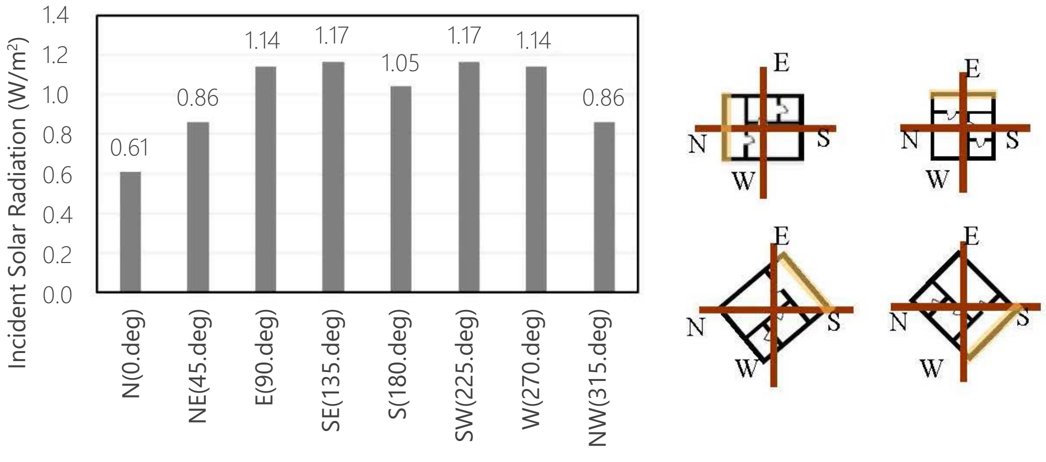


Figure 113: Impact of orientation on incident solar radiation and heat gains

RETV formula and calculations (Bhanware, Sunger, & Maithel, 2020)
RETV of the envelope (excluding roof) can be calculated by the following formula:

$$RETV = \frac{1}{A_{envelope}} \times \left[\left\{ a \times \sum_{i=1}^{n} \left(A_{opaque\ i} \times U_{opaque\ i} \times \omega_i \right) \right\} + \left\{ b \times \sum_{i=1}^{n} \left(A_{non-opaque\ i} \times U_{non-opaque\ i} \times \omega_i \right) \right\} + \left\{ c \times \sum_{i=1}^{n} \left(A_{non-opaqu\ e_i} \times SHGC_{eq_i} \times \omega_i \right) \right\} \right]$$

Equation 7: RETV formula

$A_{envelope}$: envelope area (excluding roof) of dwelling units (m^2).
$A_{opaque i}$: areas of different opaque building envelope components (m^2)
$U_{opaque i}$: thermal transmittance values of different opaque building envelope components ($W/m^2.K$)
$A_{non-opaque i}$: areas of different non-opaque building envelope components (m^2)
$U_{non-opaque i}$: thermal transmittance values of different non-opaque building envelope components ($W/m^2.K$)
$SHGC_{eq i}$: equivalent solar heat gain coefficient values of different non-opaque building envelope components.
ω_i: orientation factor of respective opaque and non-opaque building envelope components; it is a measure of the amount of direct and diffused solar radiation that is received on the vertical surface in a specific orientation. The values of orientation factor for latitudes higher or lower than 23.5 N are presented in Table 26.

Firstly, the $\frac{1}{A_{envelope}}$ component establishes the value of net heat gain rate in terms of area of the envelope i.e., per sq. m. Each building block is independently evaluated for RETV value for code compliance.

Table 26: Orientation factor values and reference chart for walls oriented in different directions. (Bureau of Energy Efficiency, 2018)

	Orientation Factor (ω_i)	
Orientation	**Latitude ≥ 23.5° N**	**Latitude < 23.5° N**
North (337.6°–22.5°)	0.550	0.659
North-east (22.6°–67.5°)	0.829	0.906
East (67.6°–112.5°)	1.155	1.155
South-east (112.6°–157.5°)	1.211	1.125
South (157.6°–202.5°)	1.089	0.966
South-west (202.6°–247.5°)	1.202	1.124
West (247.6°–292.5°)	1.143	1.156
North-west (292.6°–337.5°)	0.821	0.908

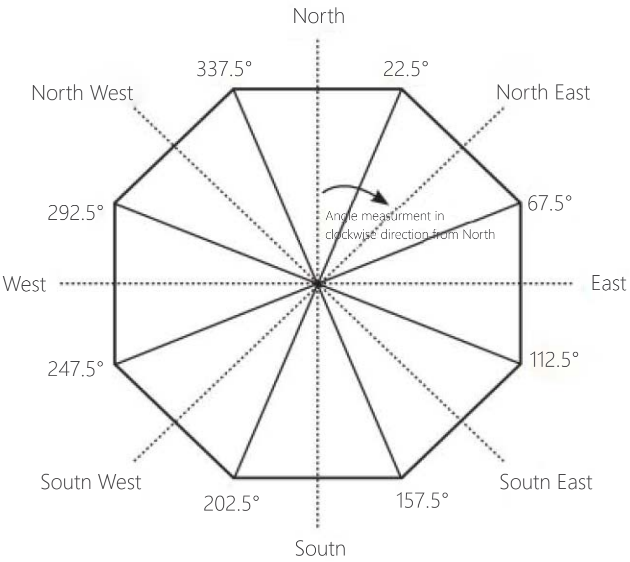


Figure 114: Primary orientations for determining the orientation factor.
Bureau of Energy Efficiency, 2018)

Next, the component $\{a \times \sum_{i=1}^{n}(A_{opaque_i} \times U_{opaque_i} \times \omega_i)\}$ calculates the heat gains due to conduction through opaque surfaces i.e., walls and doors. The remaining two key components of the equation calculate the heat gains through the glazed part of the envelope.

- $\{a \times \sum_{i=1}^{n}(A_{non-opaque_i} \times U_{non-opaque_i} \times \omega_i)\}$ This component is similar to that of opaque surfaces and gives conductive heat gains through windows.
- $\{a \times \sum_{i=1}^{n}(A_{non-opaque_i} \times SHGC_{eq_i} \times \omega_i)\}$ accounts for the radiative heat gains through window glass by means of Specific Heat Gain Coefficient (SHGC).

a', 'b', 'c' are climate coefficients that determine the quantitative contribution of heat gain value of each component towards the final net heat gain rate in each climate zone. Table 27 shows the climate coefficient values are much higher for 'c' i.e., the component dealing with radiative heat gains through the glazing accounted for by SHGC when compared to 'a' and 'b'. This holds true for all climate zones. Additionally, the values of 'a', 'b', and 'c' for each climate zone vary and hence establish the contribution of climate zone in determining heat gains in a building.

Table 27: Coefficients 'a', 'b', and 'c' for RETV formula.
(Bureau of Energy Efficiency, 2018)

Climate Zone	a	b	c
Composite	6.06	1.85	68.99
Hot – Dry	6.06	1.85	68.99
Warm – Humid	5.15	1.31	65.21
Temperate	3.38	0.37	63.69

6.4.2 Natural Ventilation

ENS Part - I requires that natural ventilation potential of a building be expressed in openable window-to-floor area ratio (WFRop) calculated by following formula.

$$WFR_{op} = \frac{A_{openable}}{A_{carpet}}$$

Equation 8: Window to Floor Area Ratio (WFR) formula

Here $A_{openable}$ refers to the openable area of all windows and ventilators, opening directly to external air. It also includes areas of open balcony, 'verandah', corridor, or shaft. In case the open balcony is accessed directly through an operable door, the openable areas of doors must be included. External doors on the ground floor such as back-yard doors and doors opening into corridors should be excluded from the term. The term is expressed in m^2.

The term A_{carpet} refers to the carpet area of dwelling units. It is the net usable floor area of an apartment, excluding the area covered by the external walls, areas under services shafts, exclusive balcony or verandah area and exclusive open terrace area, but includes the area covered by the internal partition walls of the apartment (Rajya Sabha, 2016)

The minimum values for WFR_{op} (expressed as %) in each climate zone to comply with ENS code are presented in Table 28 (BIS, 2016). It can be observed that the warm and humid climate requires higher threshold of minimum WFR as compared to other climates. This is because, as previously explained, sufficient ventilation is a necessity to aid the cooling effect needed to experience thermal comfort in this climate.

Table 28: Minimum WFR values for different climate zones of India

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

6.5 ENS Compliance Tool

6.5.1 Project overview

To understand the methodology of calculating RETV and checking code compliance for a project, an example is presented. Figure 115 (left) shows the site plan of the selected project. It consists of 32 building blocks with 12 blocks oriented East–West, 8 blocks oriented North–South, and 12 blocks oriented North-East–South-West. Figure 116 shows a typical floor plate with dimensions in mm of one of the east-west oriented towers which is explored in this example. The tower has a dedicated parking with G+14 storeys. A typical affordable dwelling unit layout with carpet area of 22.98 sq. m. is shown in Figure 115 (right).

6.5.2 ENS Tool operation

Although compliance with code can be checked by manually calculating RETV and WFR, a quicker and easier option is to use the ENS Compliance Check Tool available at ENS website for the same (GOI, 2017). The tool can be fed information pertaining to the project. The information to be entered does not require any simulation to be performed beforehand. Orientation of the tower, carpet area of the units, number of units on the floor, building envelope elements (windows, doors, ventilation units) and their individual orientations, area and U-value of walls are examples of the information required by the tool. In return, the tool checks if the requirements of the code (listed below) are met in the project and presents results for individual requirements accordingly. The result is subject to accuracy of the information entered.

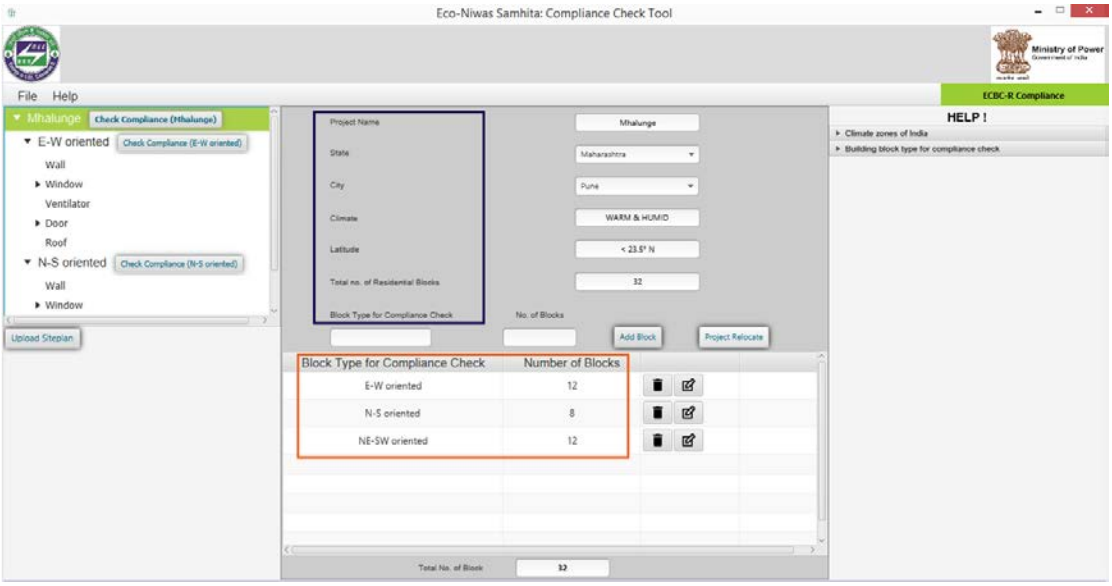
- WFR_{op}
- Uroof
- VLT
- RETV

Steps of the process

Location and climate: Firstly, the tool determines the climate zone and latitude of the project site by requesting geographical information such as state and city. Next, information related to site plan is gathered. This includes number of blocks designed within the site and their individual orientations. The evaluation for code compliance happens at the level of a building block and not a dwelling unit or the whole site due

Figure 115: Left- Site plan; Right- Dwelling unit layout of typical apartment in the tower oriented east-west.

Figure 116: Typical floor plate of a block with longer axis facing north and south directions



Project Name: Mhalunge
State: Maharashtra
City: Pune
Climate: WARM & HUMID
Latitude: < 23.5° N
Total no. of Residential Blocks: 32
Block Type for Compliance Check
No. of Blocks

Block Type for Compliance Check	Number of Blocks
E-W oriented	12
N-S oriented	8
NE-SW oriented	12

Total No. of Block: 32

Figure 117: Step 1- Site and block level information

to the high impact of orientation on building performance. Hence, each building block is required to be individually evaluated for code compliance.

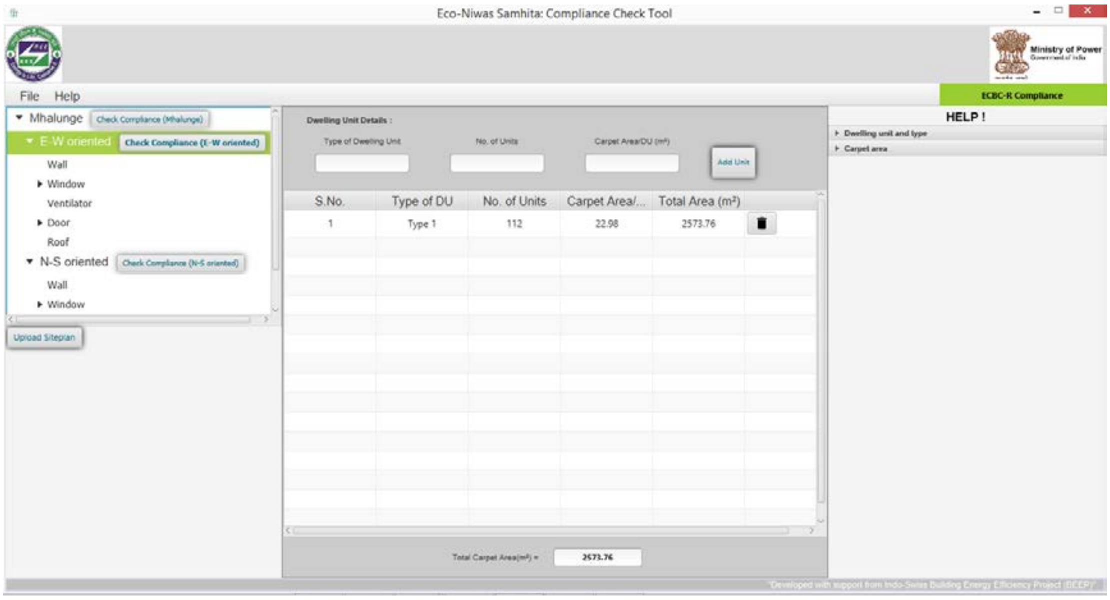
Carpet Areas: Next set of information required by the tool relates to dwelling unit details. Information such as types of dwelling units, their respective carpets area and the total area covered by these units is sought by the tool.

Walls: In the subsequent step, the tool moves towards information of the building envelope and its elements. It requests dimensional and construction details for the walls. It is important to note here that the details provided should be limited to external walls only. Internal walls, walls common with shared spaces should not be accounted for in the data. Additionally, external walls for shared spaces such as staircases also do not have any direct impact on the thermal environment of the dwelling unit and hence should be excluded. Figure 119 highlights the walls that must be included in the calculations and their individual orientations.

As seen in Figure 120, the tool seeks walling information such as orientation, dimensions (width, height, and area), and construction details i.e., material and thickness of each layer in the wall assembly of each wall. The tool auto-computes the total wall area in all four directions and the U-value of each assembly based on provided information. Alternatively, if the U-value of the assembly is known, the tool provides option to enter the same eliminating the need for entering material and thickness of each layer.

Once the walling details are submitted to the tool, the next set of information requested is regarding fenestrations- doors, windows, and ventilation units. In this project, each dwelling unit is identified to have two types of windows on the exterior walls. Moreover, a door opening into the balcony is also provided in design. Since these units contribute directly to the ventilation in the dwelling units, they should be included in the details provided to the tool.

Windows: For ventilation calculations, the tool seeks to understand the construction details of the windows. It requests the dimensions, shape and types of windows provided in the design. As the user selects whether it is a casement window or a sliding window



Dwelling Unit Details :

Type of Dwelling Unit

No. of Units

Carpet Area/DU (m²)

S.No.	Type of DU	No. of Units	Carpet Area/...	Total Area (m²)
1	Type 1	112	22.98	2573.76

Total Carpet Area(m²) = 2573.76

Figure 118: Dwelling unit details

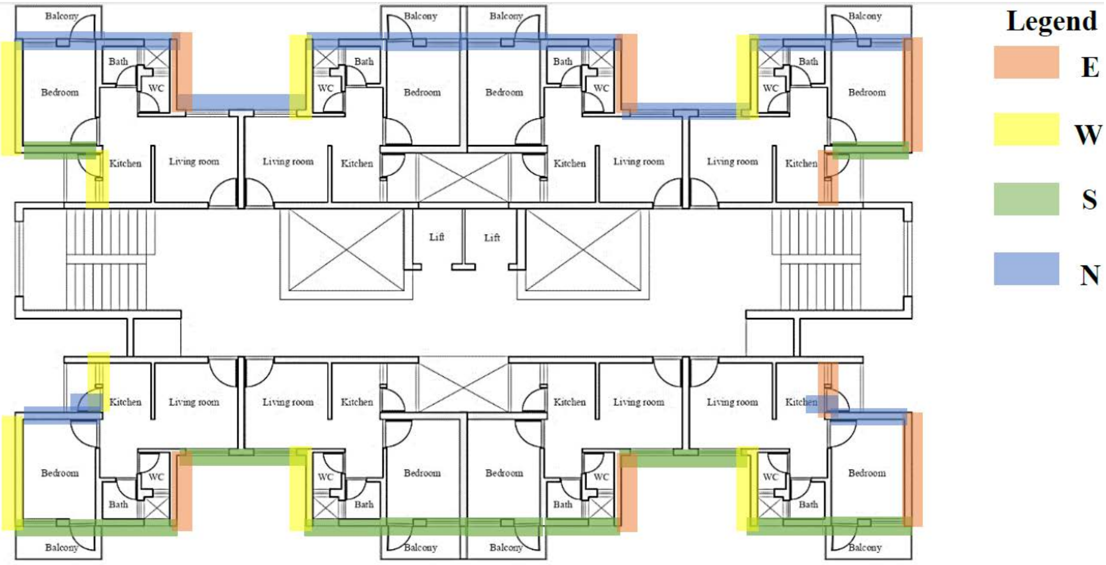
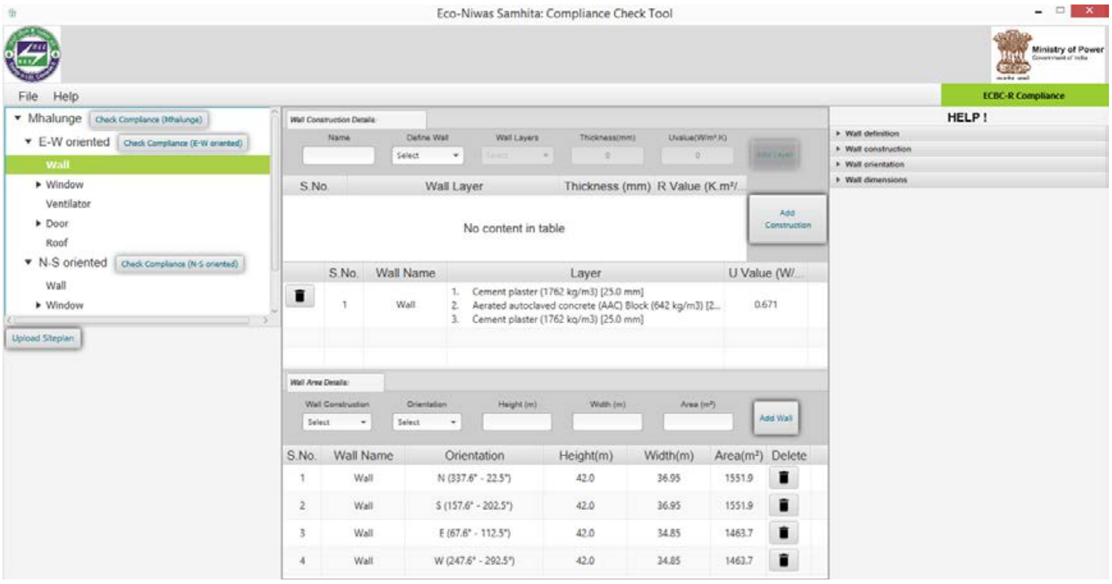


Figure 119: Wall related details should be restricted to external walls of the dwelling units



Wall Construction Details:

Name	Define Wall	Wall Layers	Thickness(mm)	Uvalue(W/m².K)
	Select	Select	0	0

S.No.	Wall Layer	Thickness (mm)	R Value (K.m²/...
No content in table			

S.No.	Wall Name	Layer	U Value (W/...
1	Wall	1. Cement plaster (1762 kg/m3) [25.0 mm] 2. Aerated autoclaved concrete (AAC) Block (642 kg/m3) [2... 3. Cement plaster (1762 kg/m3) [25.0 mm]	0.671

Wall Area Details:

Wall Construction	Orientation	Height (m)	Width (m)	Area (m²)
Select	Select			

S.No.	Wall Name	Orientation	Height(m)	Width(m)	Area(m²)	Delete
1	Wall	N (337.6° - 22.5°)	42.0	36.95	1551.9	🗑
2	Wall	S (157.6° - 202.5°)	42.0	36.95	1551.9	🗑
3	Wall	E (67.6° - 112.5°)	42.0	34.85	1463.7	🗑
4	Wall	W (247.6° - 292.5°)	42.0	34.85	1463.7	🗑

Figure 120: Wall details requested by the tool

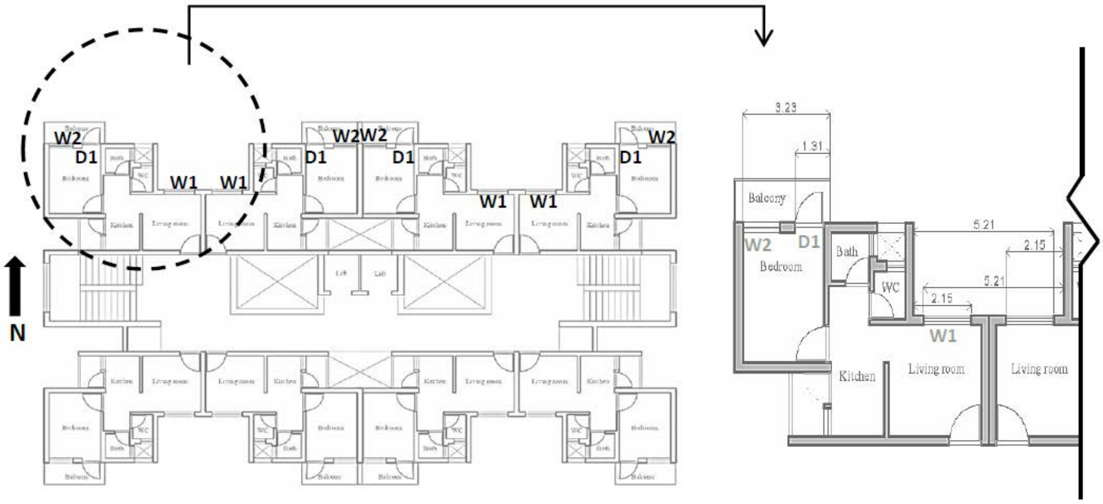
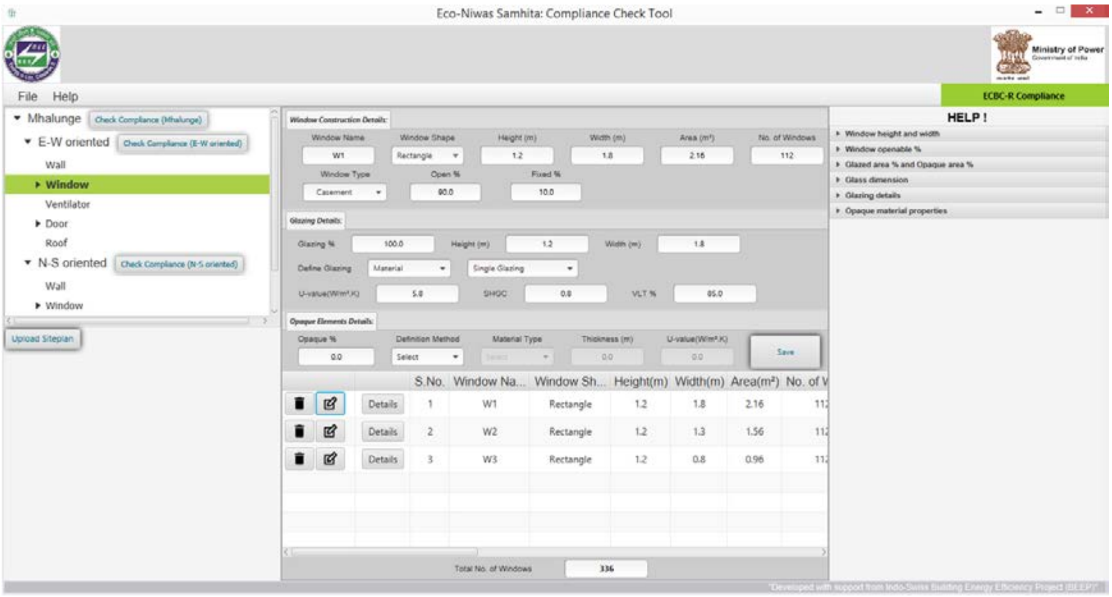


Figure 121: Window related information



Window Construction Details:

Window Name: W1
Window Shape: Rectangle
Height (m): 1.2
Width (m): 1.8
Area (m²): 2.16
No. of Windows: 112
Window Type: Casement
Open %: 90.0
Fixed %: 10.0

Glazing Details:

Glazing %: 100.0
Height (m): 1.2
Width (m): 1.8
Define Glazing: Material
Single Glazing
U-value(W/m².K): 5.8
SHGC: 0.8
VLT %: 85.0

Opaque Elements Details:

Opaque %: 0.0
Definition Method: Select
Material Type: Select
Thickness (m): 0.0
U-value(W/m².K): 0.0

S.No.	Window Na...	Window Sh...	Height(m)	Width(m)	Area(m²)	No. of W
1	W1	Rectangle	1.2	1.8	2.16	11
2	W2	Rectangle	1.2	1.3	1.56	11
3	W3	Rectangle	1.2	0.8	0.96	11

Total No. of Windows: 336

Figure 122: Window details requested by the tool

(with two panels or three panels) from a drop-down menu, the tool auto-computes the openable area of the window. Next is the glazing details containing dimensional information such as height, width and percentage of glazing in the window. It also includes glazing properties i.e., SHGC, VLT and U-value of the glazed part of window. Within the windows section, the tool also requests information of opaque elements in the window- most importantly its U-value, either directly or through material and thickness.

Since any form of shading provided to the window directly affects the solar heat gains in the dwelling unit, the tool also addresses this aspect. With regards to shading of the windows, the tool seeks to understand the dimensions od the shading and its nature (fins towards a certain direction, if any).

Ventilators: Similar level and categories of information as windows is requested for ventilators, including shading.

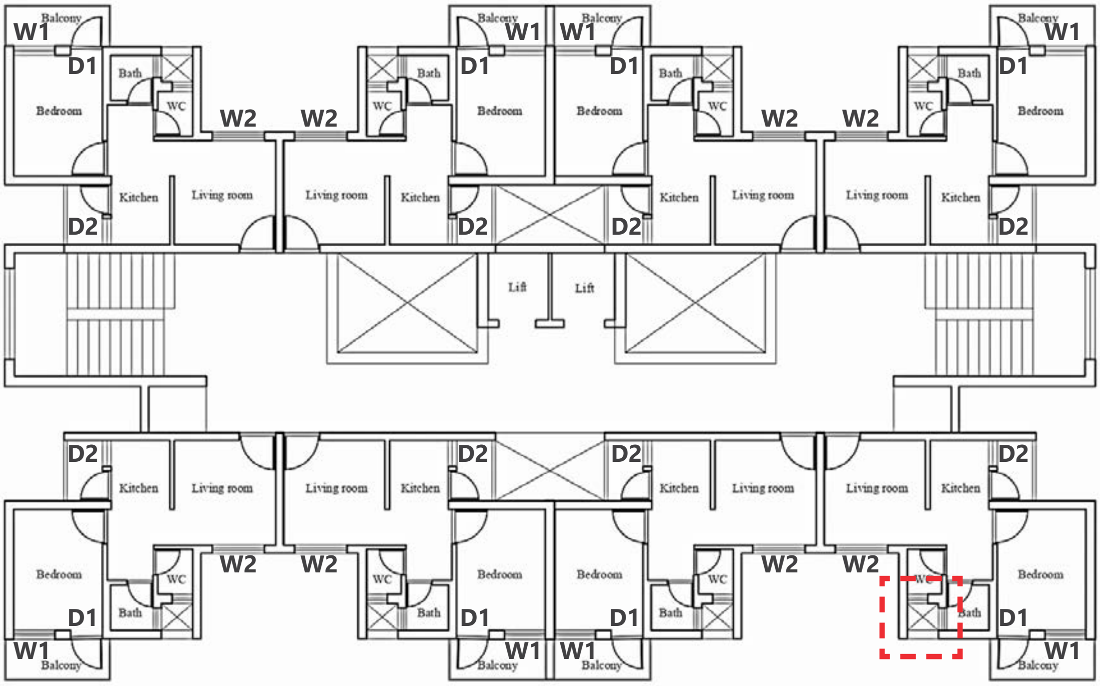
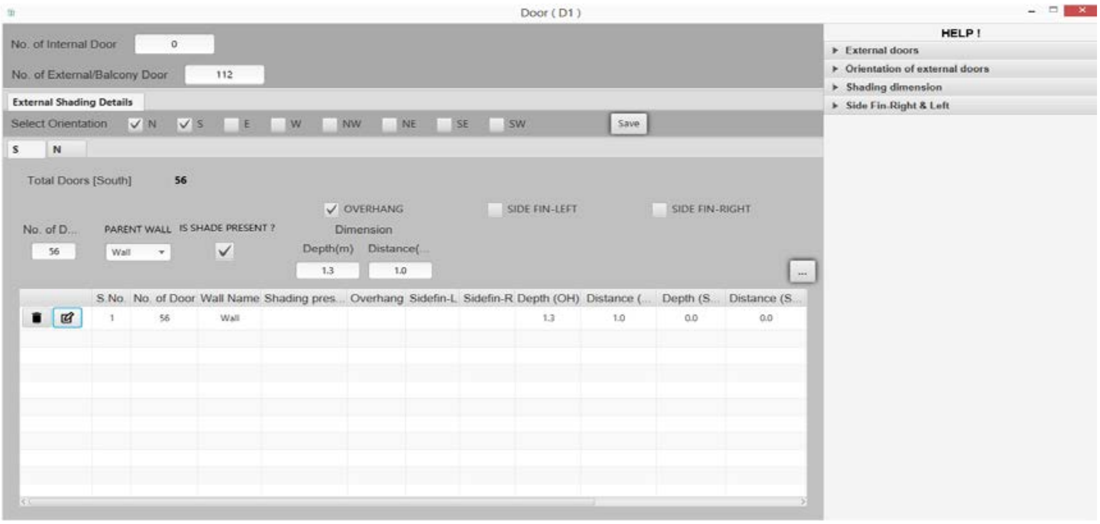


Figure 123: Ventilators identified in the design to be included in the tool



No. of Internal Door 0

No. of External/Balcony Door 112

Select Orientation ☑ N ☑ S ☐ E ☐ W ☐ NW ☐ NE ☐ SE ☐ SW

Total Doors [South] 56

☑ OVERHANG ☐ SIDE FIN-LEFT ☐ SIDE FIN-RIGHT

No. of D... 56

PARENT WALL Wall

IS SHADE PRESENT ? ☑

Dimension

Depth(m) 1.3

Distance(... 1.0

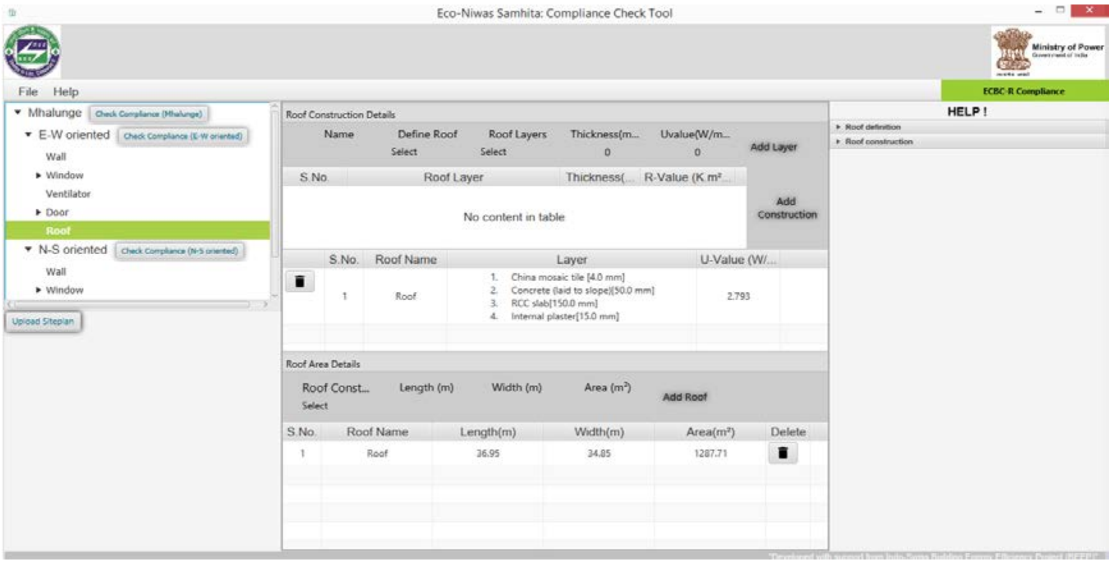
	S.No.	No. of Door	Wall Name	Shading pres...	Overhang	Sidefin-L	Sidefin-R	Depth (OH)	Distance (...	Depth (S...	Distance (S...
	1	56	Wall					1.3	1.0	0.0	0.0

Figure 124: Door details requested by the tool are similar to the window details.

Doors: Similar level and categories of information as windows is requested for doors, including shading.

Roofs: The last section in the tool relates to roof. Dimensional and construction details similar to walls are requested for the roof as well to determine the U-value and area exposed as shown in Figure 125.

It can be concluded that the tool requests simple information that is readily available in architectural drawings, construction material databases and products procured for the buildings. Based on the provided information, the tool presents results showcasing compliance check for individual requirements of the code as shown in Figure 126.



Roof Construction Details

Name	Define Roof	Roof Layers	Thickness(m...	Uvalue(W/m...
	Select	Select	0	0

S.No.	Roof Layer	Thickness(...	R-Value (K m²...
No content in table			

S.No.	Roof Name	Layer	U-Value (W/...
1	Roof	1. China mosaic tile [4.0 mm] 2. Concrete (laid to slope)[50.0 mm] 3. RCC slab[150.0 mm] 4. Internal plaster[15.0 mm]	2.793

Roof Area Details

Roof Const...	Length (m)	Width (m)	Area (m²)
Select			

S.No.	Roof Name	Length(m)	Width(m)	Area(m²)	Delete
1	Roof	36.95	34.85	1287.71	

Figure 125: Roof details requested by the tool

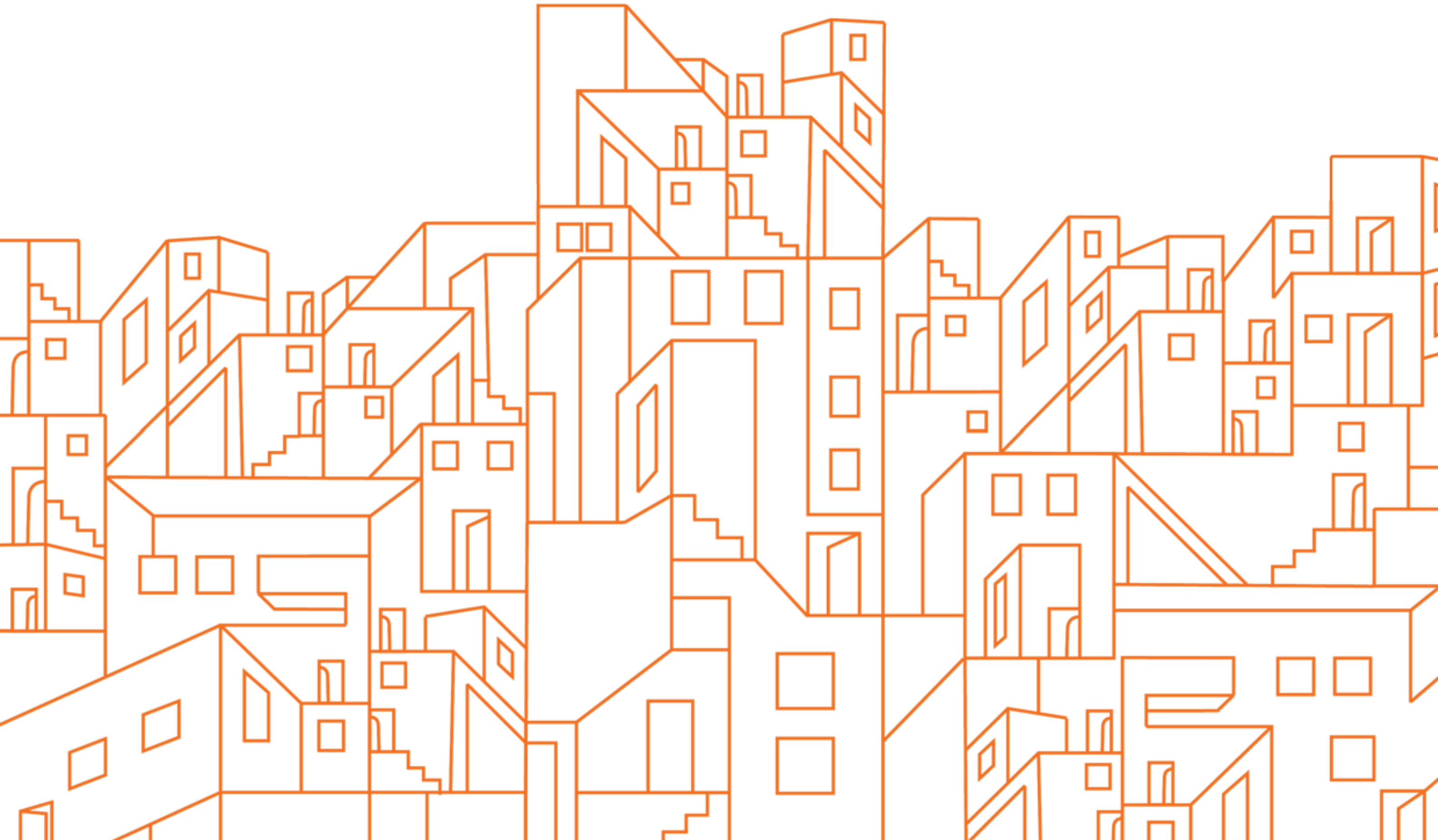
Eco-Niwas Samhita Compliance Result

	Calculated	Criteria	Status
WFRop (Window to Floor Area Ratio)	34.78	16.66	Compliant
VLT (%) (Visible Light Transmittance)	85.0	27.0	Compliant
Uroof ($W/m^2.K$) (Thermal Transmittance -Roof)	2.79	1.2	Non-Compliant
RETV (W/m^2) (Residential Envelope Transmittance Value)	6.4	15	Compliant

Figure 126: Results of the ENS tool

7

CASE STUDIES FOR APPLICATION OF THERMAL COMFORT IN AFFORDABLE HOUSING



7.1 Introduction

This chapter discusses four case studies in the spheres of thermal comfort in vernacular and contemporary affordable housing, and code compliance in affordable construction. Firstly, a case study shedding light on thermal comfort in vernacular architecture of warm-humid Northeast India is presented. It also addresses nuances of regional climatic variations in the houses studied. The next case study presents comparison of the thermal performance of vernacular and contemporary architecture of in a city with hot-dry climate. The third case study focusses on design decisions that can contribute to thermally comfortable and affordable houses through quantified metrics. Lastly, the fourth study is presented with the aim to bridge the gap between energy efficiency, affordability and code compliance.

7.2 Vernacular Buildings of North-East India

Various studies have been undertaken to understand the features of vernacular houses and their contributions towards thermal comfort in the North-East India. (Singh, Ooka, Rijal, & Mahapatra, 2016) (Singh, Mahapatra, & Atreya, 2009) (Singh, Mahapatra, & Atreya, 2010). The studies involved a mix of methods ranging from qualitative assessment and field measurements to quantitative analysis. Based on the ambient temperature, humidity, rainfall, wind speed, altitude, solar radiation and physical topography of the region, studies propose reclassification of the climate of North-East India as a mix of warm-humid, cool-humid, and cold-cloudy and highland climate (Singh, Mahapatra, & Atreya, 2007). Most of the residential construction is aimed to directly respond to the climatic constraints while maintaining provisions for social and cultural needs of the occupants (Singh, Mahapatra, & Atreya, 2010). It is noteworthy that nearly all

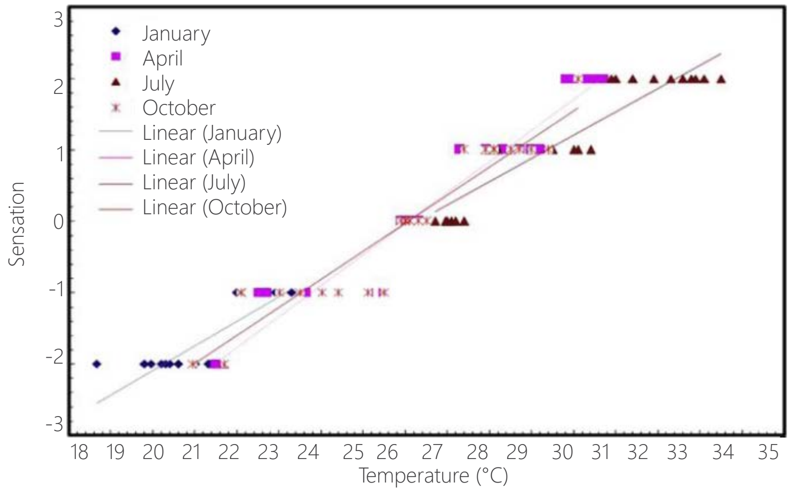
Table 29: Features of representative vernacular houses in North-East India selected for research

Features	Warm and Humid	Cool and Humid (Urban)	Cold and cloudy
Built up-area	94 sq. m.	77 sq. m.	44 sq. m.
Wall material and thickness	Brick, cement, and sand (0.127 m)	Processed mud and bamboo (0.076 m)	Rock slab, cement, and sand (0.20 m–0.25 m)
False ceiling and roof type	Asbestos sheet/wood. Galvanized tin sheet and tilted on two sides	Rare. Galvanized tin sheet and tilted on three sides	Asbestos sheet/ cane/bamboo mat/ wood. Galvanized tin sheet and tilted on four sides
Ventilation	High ventilation	Medium ventilation	Low ventilation
Layout and orientation	Open layout with courtyard; No specific orientation	Courtyard in rural housing only; East–west orientation and south facing	No courtyard; South sloping and east–west orientation
Prominent passive features	Air gap in ceiling, shading, extended roof used as overhang, chimney arrangement for effective ventilation	Houses are compact, proper care for ventilation	More compact, minimum surface to volume ratio, south sloping to receive maximum sun

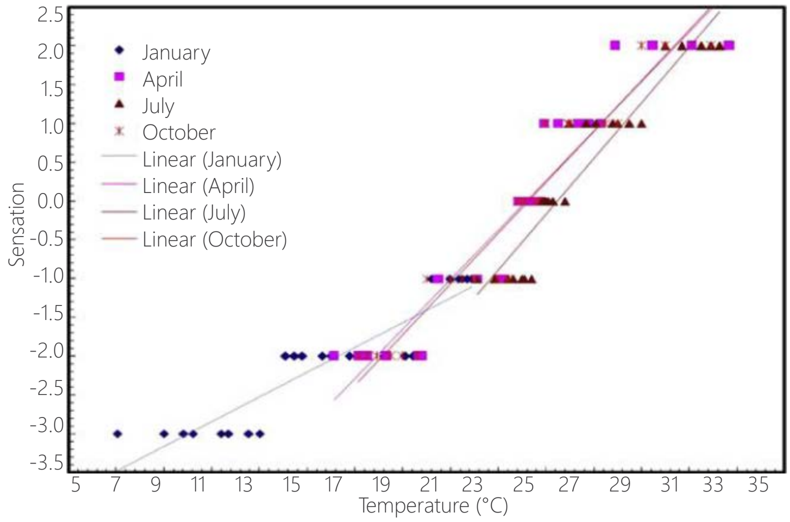
building materials observed in the houses are local to the region. The study states that popularity of the residence's layout, was a criterion for selecting buildings to monitor for long term along with functionality of the spaces. (Singh, Mahapatra, & Atreya, 2010). The features of the selected houses are tabulated in Table 29. Figure 127 shows few pictures of these houses.

Figure 127: Photographs of vernacular houses selected for long-term monitoring

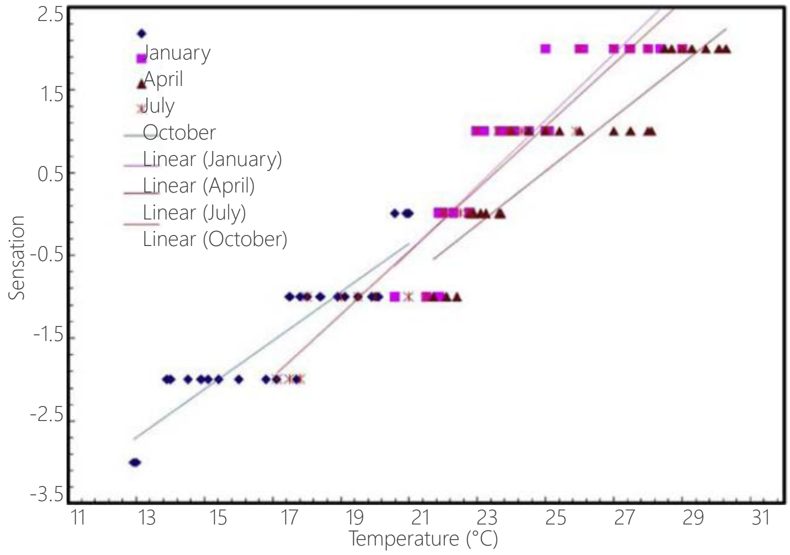
The study established a time duration of one year to observe thermal performance of the spaces in all seasons. The study also sought to understand the various behavioural adaptations of the occupants during different seasons and their impact on their thermal comfort perception in the given indoor environment. Objective and subjective measurements were recorded to account for occupant adaptations, thermal



Thermal sensation votes vs indoor temperature in Tezpur (Warm-Humid)



Thermal sensation votes vs indoor temperature in Imphal (Cool-Humid)



Thermal sensation votes vs indoor temperature in Cherrapunjee (Warm-Humid)

Figure 128: Assessing neutral and comfort temperatures in representative vernacular houses of North-East India

perceptions, and expectations in defining the range of comfort temperatures. The field tests included half-hourly measurements of both outdoor and indoor conditions for the metrics- air temperature, relative humidity, and illumination levels for 25 days in each season (January: winter, April: pre summer, July: summer/rainy and October: pre-winter). For additional details of the methodology, refer (Singh, Mahapatra, & Atreya, 2010).

Results

The study analysed the relationship between indoor operative temperatures and the corresponding thermal sensation votes of occupants of the selected houses in Tezpur (warm-humid) and Imphal (cool-humid). Figure 128 represents the same. Major conclusions of the research have been listed below.

- Indoor temperature swings are within 10ºC for all months in the case of representative houses located in warm-humid and cool-humid climates which is permissible limit for naturally ventilated buildings.
- For the representative house in the cold and cloudy climate, the temperature swings are higher. This can be attributed to lower insulation and thermal inertia of walls than required.
- Larger adaptability in Tezpur and Imphal as observed in Figure 128 (larger width of neutral temperatures) indicates higher adaptability of occupants in naturally ventilated buildings.
- None of the houses exhibit significantly thermally comfortable environments in the winter months
- Occupants have enhanced control over indoor environments in the vernacular houses because they have the flexibility to control their personal and environmental conditions in the form of different adaptations.
- For all the cases studied, range of comfort temperatures lies between 6°C and 7.3°C.

7.3 *Pol* Houses and Conventional Houses in Ahmedabad

A comparison of thermal performance of pol houses (PH) with contemporary houses (CH) in the city of Ahmedabad is discussed in this case study. The locations of five PH and five CH selected for the research are highlighted in Figure 129 (left). The climate of Ahmedabad is classified as hot-dry according to the National Building Code of India (BIS, 2016).

The study estimates the percentage of different operation modes for the building using the adaptive thermal comfort model described in ASHRAE Standard-55 (ASHRAE, 2013) as shown in Figure 129 (Right). Typical building in Ahmedabad can be operated in NV mode for around 20% of the operation hours annually. Out of the remaining 80%, it will need dehumidification for 37%, mild cooling for 20%, cooling for 11% and cooling with dehumidification for about 9% of time annually (Rawal, Kumar, & Manu, 2017).

Figure 130 shows a plan each of the PH and CH highlighting the position of data loggers that recorded air temperature and relative humidity of the spaces. Additionally, the outdoor conditions were measured using an outdoor weather station installed centrally in the city. It provided the readings for outdoor air temperature, relative humidity, solar radiation, wind speed, wind direction and precipitation.

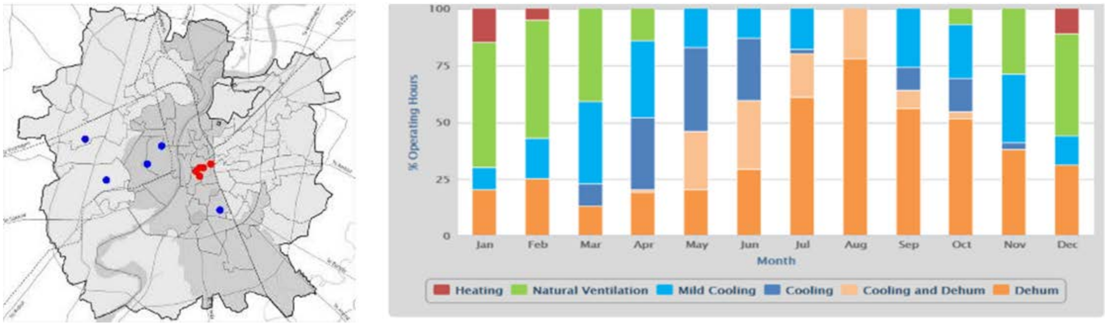


Figure 129: Left-City map of Ahmedabad showing location of PH (red) and CH (blue); Right- Estimated operation modes for a typical building in Ahmedabad

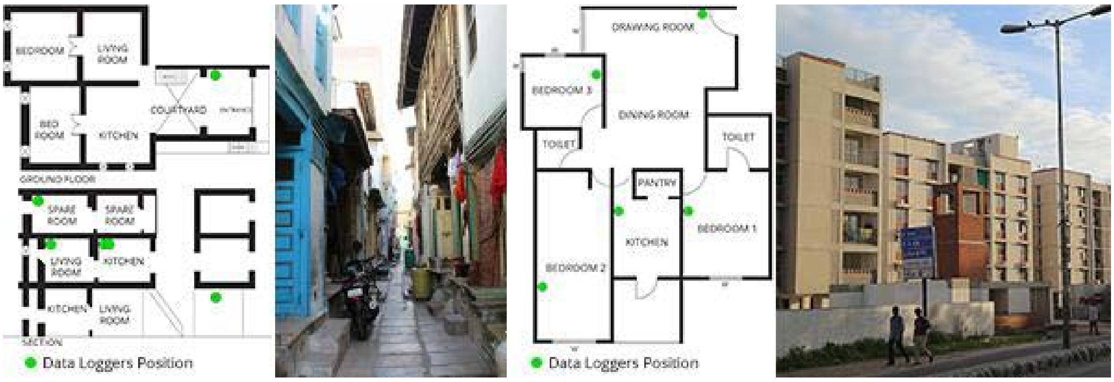


Figure 130: Plans of Pol House (PH) and Conventional House (CH) with data logger positions (green dots) and photographs

Figure 131 and Figure 132. are the heat maps of the 10 houses studied throughout the year. Based on IMAC-NV (Manu, Shukla, Rawal, Thomas, & de Dear, 2016) and ASHRAE-55 models, they indicate the comfort status (based on IMAC-NV and ASHRAE-55 models) for every hour of the monitoring period (shown on x-axis) for all spaces (shown on y-axis). The grey bands show the days or hours excluded from the analysis. They indicate that the 30-day outdoor running mean air temperature values fell outside the range of 12.5-31°C in the case of IMAC- NV and 10-33.5°C in the case of ASHRAE-55 adaptive models. The threshold for comfortable hours was set as 90% acceptability range of the indoor air temperatures. The comfort hours are indicated as green band while white cells indicate missing data.

Observations

The study presented interesting results surrounding the indoor thermal environment of both pol houses and conventional houses. It was observed that

- Both PH and CH perform almost similar with respect to comfort hours for both IMAC and ASHRAE-55 models
- The relationship between indoor air temperature and outdoor air temperature for pol houses (red regression line) and contemporary houses (blue regression line) is quite similar and moderately strong as can be seen in Figure 133.
- In terms of response time to the outdoor conditions, PH were found to be marginally faster than CH.

Conclusions

- Traditional knowledge and qualitative literature highlight thermal mass as one of the most important strategies to keep the heat out. However, the observations indicated that thermal mass alone may not be the best strategy in all situations.

- Mutual shading in case of pol houses ensures that the roof is the only surface exposed to direct solar irradiance. Additionally, vertical distribution of the total area further reduces the roof area. Hence closer look at the air temperature and relative humidity components may suggest the source of discomfort in pol houses as higher humidity levels.
- The contemporary houses are designed with lighter construction materials and have larger floor plates as compared to pol houses. However, their thermal performance does not differ significantly than the pol houses.

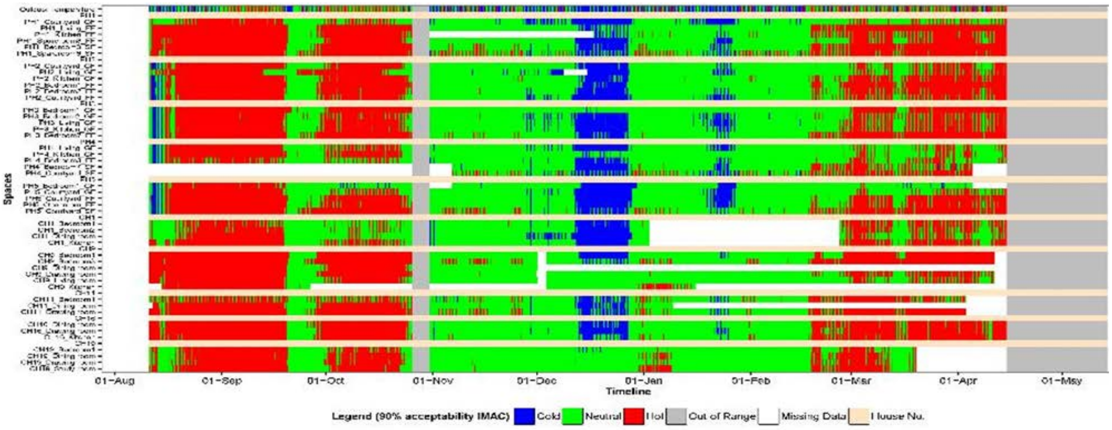


Figure 131: Heat map as per IMAC showing 90% acceptability range

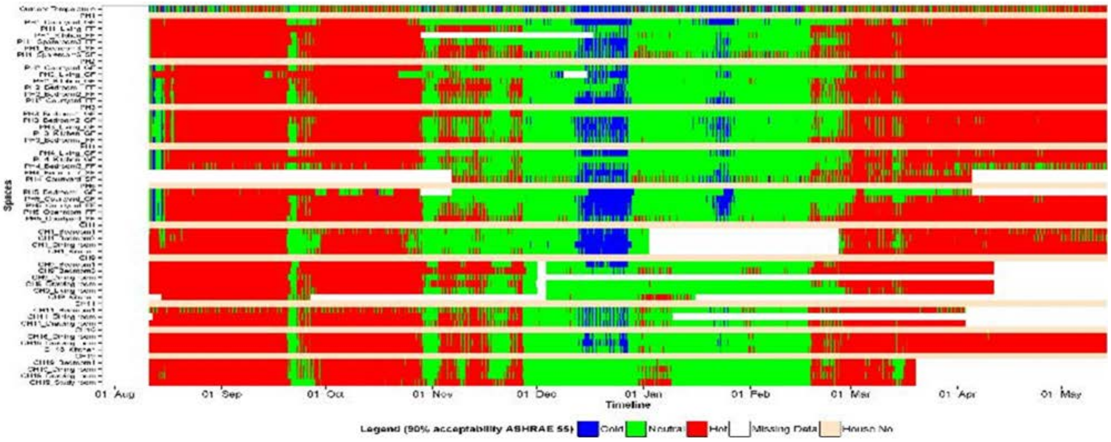


Figure 132: Heat map as per ASHRAE 55- 2013 showing 90% acceptability range

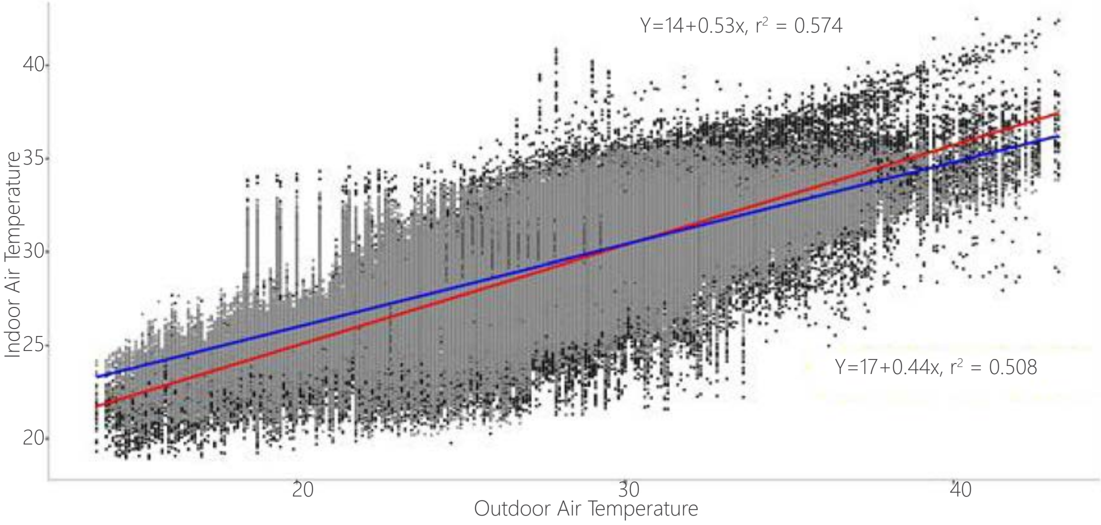


Figure 133: Correlation between Outdoor and Indoor Air Temperature in pol and contemporary houses

7.4 Rajkot Smart GHAR III

The Smart GHAR III in Rajkot is an affordable housing project under PMAY Untenable Slum Redevelopment. Some of the project details are listed below (Indo-Swiss Building Energy Efficiency Project (BEEP), 2021):

- Site Area: 17,593 m^2
- Built-up Area: 57,408 m^2
- No. of dwelling units (DU): 1176
- Type of dwelling units: 1bhk
- Built-up area per DU: 33.6 m^2
- Carpet area per DU: 29 m^2
- No. of residential towers: 11
- No. of floors: Stilt + 7

The climate of Rajkot is composite and the peak daytime temperatures during the summer reach 41°C-43°C. This can raise the peak room temperatures to 38°C in some cases. During the charrettes, reducing heat gains through building envelope variations was identified as most relevant approach to combat the peak temperatures and high diurnal temperature. Additionally, it was recognized that housing in Rajkot could benefit from the good wind speeds by utilizing them in natural ventilation for cooling. The energy efficiency measures proposed and implemented in Smart GHAR III are described below:

- **Reducing heat gains through walls and roof:** Walling material was changed to 230mm thick AAC blocks instead of 230 mm burnt clay bricks. In doing so, the U-value of walls dropped to 0.8 W/m^{2}K from 2 W/m^{2}K. As a result, lower heat gains through conduction were expected. 40mm PU foam insulation was added to the roof to bring the roof U-value to 0.56 W/m^{2}K from 2.7 W/m^{2}K. Moreover, the roof was finished with high-reflective china mosaic. Post charrettes, the cavity walls on southern side were decided to be constructed using 230 mm AAC blocks on both sides of the 50mm air cavity to ensure a U-value of 0.3 W/m^{2}K.

- **Improving Ventilation through shaft design:** Lack of cross ventilation in housing designs results in low or no wind flow. To maintain a desirable wind flow rate for cooling through ventilation (10 air changes per hour) at all times, the existing service shaft between two buildings was modified. A roof feature with exhaust fans on top of the shaft was added to create negative pressure in the shaft at all times as shown in Figure 135.

- **Reducing heat gains through window design and ventilation:** Before the charrettes, all window design included fully glazed sliding windows (Refer Figure 136). Hence, the openable window area for ventilation would lie between 50-75% with glazing contributing to maximum radiative heat gains possible. This design was changed to a taller partially glazed casement type for selected windows. The 90% openable casement windows allowed for better ventilation flow rates. The three-shutter design included two opaque and one glazed panel. The opaque panels cut the solar heat gains to 1/3rd of the original design while the 1/3rd glazed panel allowed daylight penetration into the spaces.

These measures were estimated to lower the peak summer room temperatures by more than 5°C and increase the comfortable hours by more than 3500 hours.

Figure 134: Site layout for Rajkot Smart GHAR-III (PMAY) project.
Source: (Rawal, Shukla, Patel , Desai, & Asrani, 2021)

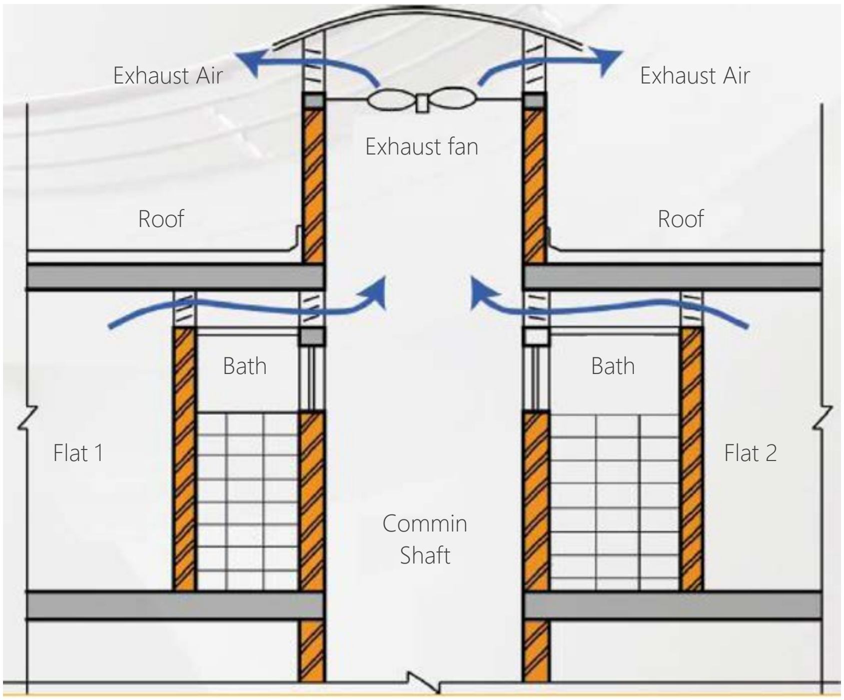


Figure 135: Improving ventilation through common service shaft.
Source: (Rawal, Shukla, Patel , Desai, & Asrani, 2021)

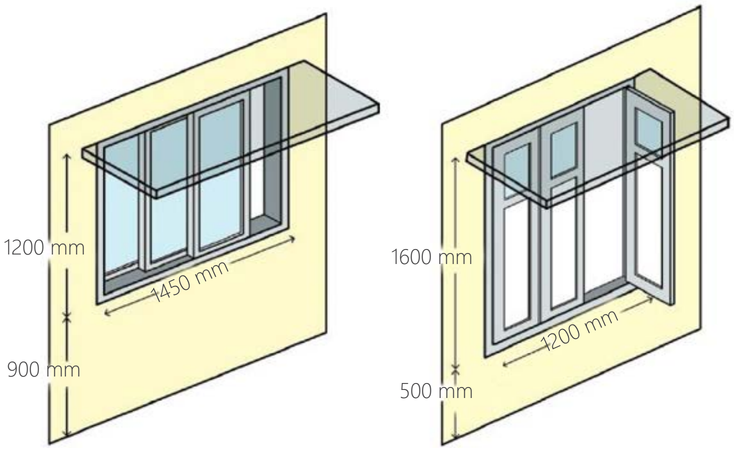


Figure 136: Fully glazed window design (left) was improved to taller, partially glazed casement windows (right)
Source: (Rawal, Shukla, Patel, Desai, & Asrani, 2021)

7.5 Code Compliant Housing

The study conducted on in-situ slum upgradation of Shree Ram Nagar Cooperative Housing Society, Ahmedabad (PMAY site) by CEPT University with GBPN aimed to bridge the gap between code compliance and implementation of Eco Niwas Samhita (Rawal, Shukla, Patel , Desai, & Asrani, 2021). The methodology adopted for this study involved identification of a PMAY (affordable housing) site and development of two intervention scenarios for building material, building orientation, and addition of shading/overhang. The two scenarios developed (Refer Figure 137 and Figure 138) were without any additional cost and with minimal additional cost to make the project ENS complaint.

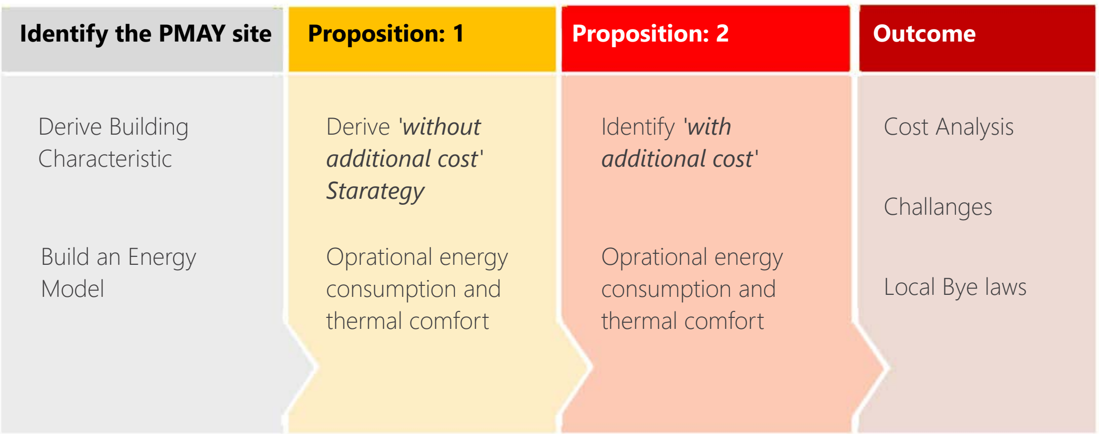


Figure 137: Approach for the study

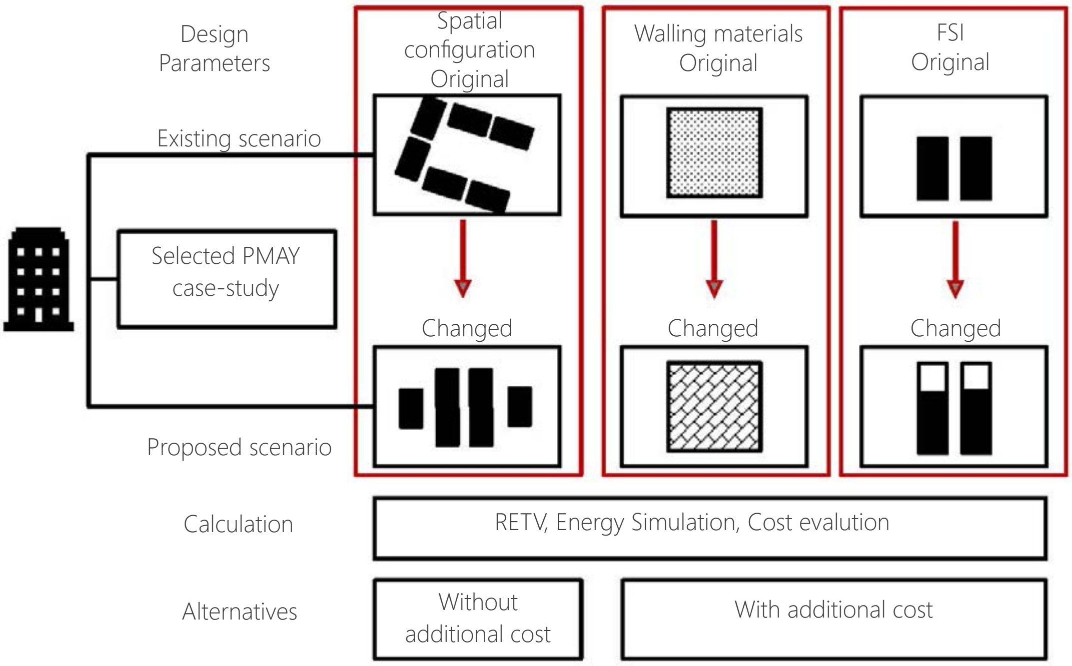


Figure 138: Design parameters and calculations involved in proposing scenarios with two cost alternatives to make the PMAY project code compliant.
Source: (Rawal, Shukla, Patel, Desai, & Asrani, 2021)

About the site

The Ahmedabad Municipal Corporation (AMC) has constructed 6623 PMAY sites and a total of 20715 housing units are under construction at 37 different locations in Ahmedabad. The affordable housing sites have similar characteristics and specifications due to identical construction technique, building materials, and design. All public and private organizations follow the state-issued guidelines surrounding design implementation technique. Shree Ram Nagar Co-operative Housing Society was selected as a representative in-situ rehabilitation site. Figure 139 indicates the site layout and Table 30 shows the site characteristics.

Table 30: Site Characteristics.
Source: (Rawal, Shukla, Patel , Desai, & Asrani, 2021)

No. of floors	4	
Carpet Area (m²)	26.76	
Building Material	Solid Concrete Block (100 mm thick)	
U-value of building material (W/m² K)	4.15	
RETV (W/m²)	29.46	

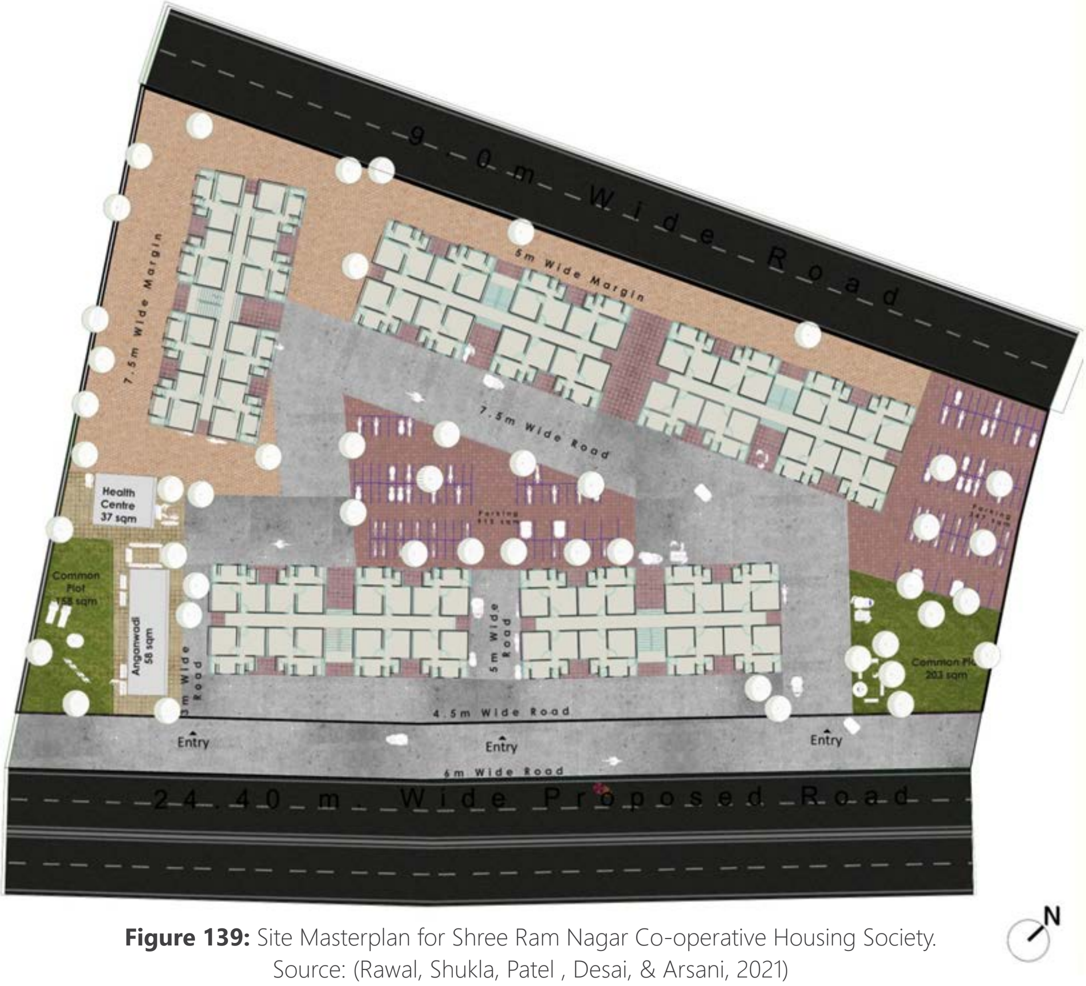


Figure 139: Site Masterplan for Shree Ram Nagar Co-operative Housing Society.
Source: (Rawal, Shukla, Patel , Desai, & Arsani, 2021)

Case Development

The cases were developed based on permutations and combinations of different building materials in combination with absence/addition of shading over the window (Refer Figure 140). All cases were various iterations of the same site plan and same unit plan. The variables that chosen for their impact on a building's thermal performance are presented below:

1. Orientation
- In the base case, the buildings were oriented in NE-SW and NW-SE direction,
- The proposed cases, i.e., Case 1 and 2, were oriented in E-W direction.

2. Shading/overhangs
- Absence of shading/overhangs covering the kitchen and drawing room windows was noted in base case. This was done to minimise the construction cost.
- For cases with nomenclature such as Case 1A.1, Case 2B.1, Case 3C,1, etc. the RETV was calculated without addition of shading; while RETV for Case1A.2, Case 2B.2, Case 3C.2, etc., was calculated with the provision of 600mm overhangs over kitchen and drawing room windows.

3. Building material
- Base case used monolithic RCC (A) as a walling material.
- RETV was calculated for different iterations of the original and proposed cases with varied walling materials. Given their availability and popularity in the city, following materials were considered:
  a. Burnt clay bricks (B)
  b. AAC blocks (C)
  c. Fly-ash bricks (D)
  d. Solid concrete blocks (E)

Figure 140: Case Development.
Source: (Rawal, Shukla, Patel , Desai, & Asrani, 2021)

4. Floor Space Index (F.S.I)

- Base case and Case 1 considered the original F.S.I. i.e., both were G+3 storey buildings with 32 units.
- For case 3, the full F.S.I was utilized by adding a floor, making it a G+4 storey building with 40 units.

Thus, the nomenclature of each iteration followed the pattern 'Case' 1/2/3 + walling material A/B/C/D/E + shading 1/2, as shown in Figure 140.

Occupant comfort and energy efficiency determine the 'live-ability' of the building/dwelling unit and 'actual cost of living' i.e., sum of house cost and recurring operational energy. The cases developed sought to understand the variation in building performance resulting from change in walling material, and other design parameters (provision of shading/overhangs over windows). These changes directly impact the cost of construction. Thus, the cost of construction for each iteration of each case was calculated. Moreover, the cost of operational energy consumption was also calculated.

Byelaws Terminology

The development of the interventions and cases was based on following terminologies mentioned in the byelaws.

1. **Floor Space Index:** Floor Space Index = Total Covered Area On All Floors/Gross Plot Area as shown in Figure 141 (a).

- **Permissible FSI Area:** FSI permitted by the Competent Authority as a matter of right.

- **Utilized FSI Area:** Amount of FSI used that is paid for and purchased by the applicant.

2. **Common Plot Area:** common open space exclusive of approaches and margin at ground level. Minimum required area of common plot is 10% of plot area as shown in Figure 141 (b).

3. **Parking Area:** A minimum of 11% of utilized FSI area must be provided as parking, and up to half of the common plot area may be used to meet this requirement as shown in Figure 141 (c).

4. **Distance between two buildings:** GDCR specifies the distance of 7.5 to 9.0m wide internal roads; however, 4.5 to 5.0 m width is considered sufficient as shown in Figure 141 (d).

Application of Byelaws and Site Characteristics

The site characteristics such as plot area, number of floors, FSI, Common plot area and parking area has been compared for base case, Case 2 (re-oriented site), and Case 3 (Re orineted site + Increased FSI) as shown in Figure 142 and Table 31.

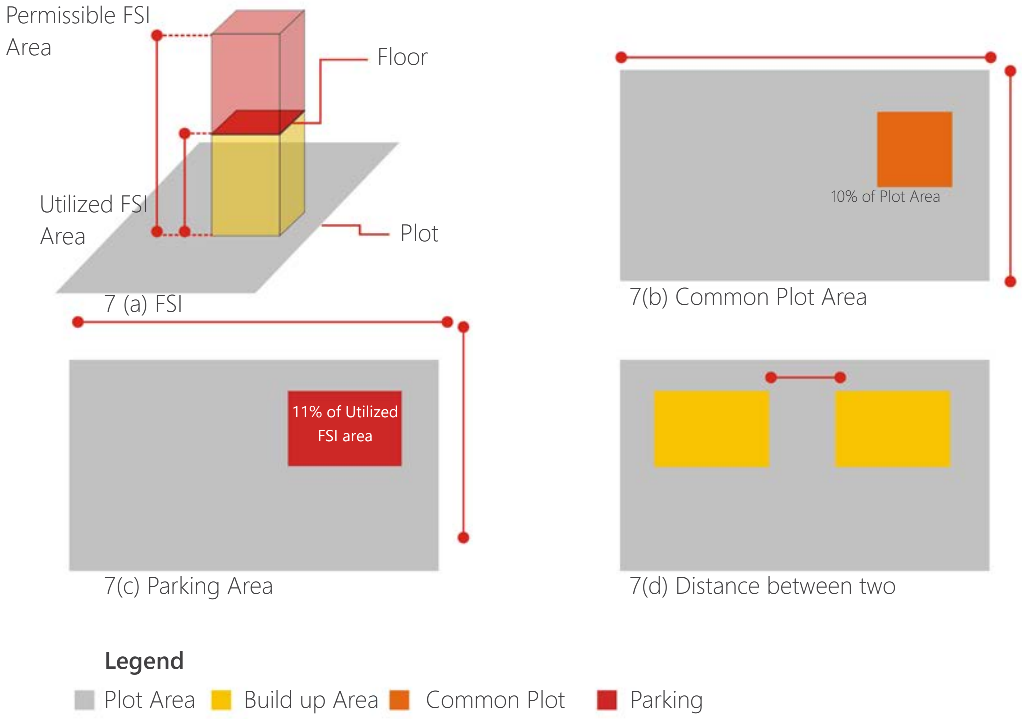


Figure 141: Byelaws Terminology followed in case development.
Source: (Rawal, Shukla, Patel, Desai, & Asrani, 2021)

Table 31: Application of Bylaws.
Source: (Rawal, Shukla, Patel , Desai, & Arsani, 2021)

Characteristics	Base Case – Existing layout	Case 1 – (Proposed) Re – oriented site	Case 3 – (Proposed) Re – oriented site + Increased FSI
No. of units	160	160	200
Utilized FSI area - % of permissible	64%	47%	58%
Common Plot Area - % of Plot Area	10%	13%	13%
Parking Area of % -utilized FSI area	21%	11%	12%
Parking Area of % -utilized FSI area	4.5 – 5.0 M	4.5 M	4.5 M

Observations

Table 33 presents the comparison of thermal comfort and affordability parameters for different walling material options with and without shading provisions for case 1 i.e., existing layout.

Table 34 presents the comparison of thermal comfort and affordability parameters for different walling material options with and without shading provisions for case 2 i.e., re-oriented site layout. Additionally it also presents comparison of the same parameters for case 3 i.e., re-oriented site layout with increased usage of available FSI.

Figure 142: (a)- Site plan for case 1; (b) Site plan for case 2 and 3

Table 32: Spatial site characteristics in cases 1, 2, and 3.

Case	Plot Area	No. of Floors	FSI			Common Plot Area		Parking Area	
			Available FSI	Permissible FSI Area (Sq.mt.)	Utilized FSI Area (Sq.mt.)	Required (Sq.mt.)	Provided (Sq.mt.)	Required (Sq.mt.)	Provided (Sq.mt.)
Case 1: Existing layout	5917 sq.mt.	G + 3	1.8	10561	6716.53	592	589.59	841.99	1235.56
Case 2 (Proposed): Re – oriented site		G + 3	1.8	10651	4900	592	750	539	547
Case 3 (Proposed): Re – oriented site + Increased FSI		G + 4	1.8	10651	6100	592	750	539	679

Table 33: Comparison of RETV, EPI, discomfort hours, and cost differences for various walling material options in case 1

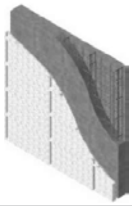
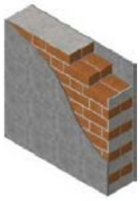
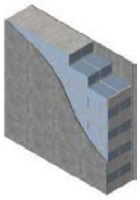
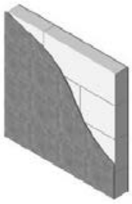
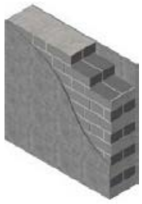
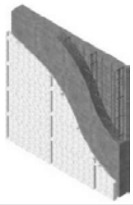
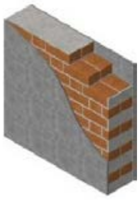
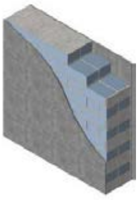
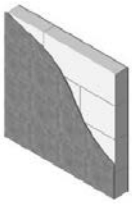
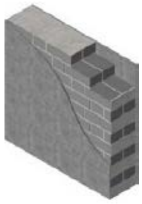
	Existing RCC (Mascon)	Burnt Clay Brick	Fly Ash Brick	AAC Block	Solid Concrete Block
					
Case	**Case 1**	**Case 1B 1**	**Case 1C 1**	**Case 1D 1**	**Case 1E 1**
Shading			Without		
RETV	26.00	16.62	16.34	12.35	25.48
EPI	75.92	48.53	47.71	36.06	74.40
Comfort hours	4760 - 7627	4887-8599	4716-8608	1874-8760	4618-8009
Difference in cost	₹ -	₹ -79,50,926	₹ -66,03,988	₹ -76,08,377	₹ +61,12,630
Case	**Case 1A2**	**Case 1B 2**	**Case 1C 2**	**Case 1D 2**	**Case 1E 2**
Shading			With 600mm overhangs		
RETV	24.95	15.56	15.28	11.29	25.47
EPI	72.85	45.44	44.62	32.97	71.74
Comfort hours	4815-7683	5230-8657	5147-8670	2943-8760	4671-8042
Difference in cost	₹ +46,072	₹-79,04,854	₹ -65,57,916	₹-75,62,305	₹ +61,58,702

Table 34: Comparison of RETV, EPI, discomfort hours, and cost differences for various walling material options in case 2

	Existing RCC (Mascon)	Burnt Clay Brick	Fly Ash Brick	AAC Block	Solid Concrete Block
					
Case	**Case2**	**Case 2B 1**	**Case 2C 1**	**Case 2D 1**	**Case 2E 1**
Shading			Without		
RETV	26.00	16.62	16.34	12.35	25.48
EPI	75.92	48.53	47.71	36.06	74.40
Comfort hours	4760 - 7627	4887-8599	4716-8608	1874-8760	4618-8009
Difference in cost	₹ -	₹ -79,50,926	₹ -66,03,988	₹ -76,08,377	₹ +61,12,630
Case	**Case 2A2**	**Case 2B 2**	**Case 2C 2**	**Case 2D 2**	**Case 2E 2**
Shading			With 600mm overhangs		
RETV	23.57	14.47	14.20	10.33	23.06
EPI	68.82	42.25	41.46	30.16	67.34
Comfort hours	4904-7785	5432-8691	3132-8760	5358-8699	4819-8059
Difference in cost	₹ +46,072	₹-79,04,854	₹ -65,57,916	₹-75,62,305	₹ +61,58,702
Case	**Case 3**	**Case 3B 1**	**Case 3C 1**	**Case 3D 1**	**Case 3E 1**
Shading			Without		
RETV	24.32	15.22	14.73	11.08	23.81
EPI	71.01	44.44	43.61	32.35	69.53
Comfort hours	4892-7730	5128-8657	4940-8664	1575-8760	4831-8112
Difference in cost	₹ -	₹-99,38,658	₹ -82,54,985	₹-95,10,471	₹ +76,40,788
Case	**Case 3A2**	**Case 3B 2**	**Case 3C 2**	**Case 3D 2**	**Case 3E 2**
Shading			With 600mm overhangs		
RETV	23.57	14.47	13.98	10.33	23.06
EPI	68.82	42.25	40.82	30.16	67.34
Comfort hours	4972-7785	5426-8690	5339-8700	2655-8760	4928-8172
Difference in cost	₹ +57,590	₹-98,81,067	₹ -81,97,395	₹-94,52,881	₹ +76,98,378

Compliance Analysis

Figure 143 depicts the RETV calculated for all cases, categorized as per the walling material.

- Notably, RETV of case 1 (all materials) was higher than cases 2 and 3 because of east-west orientation.
- It can be observed that RETV of cases 2 and 3 show little to no difference. Hence addition of a single floor does not impact the RETV value substantially.
- Amongst the varying walling materials considered, the performance of all iterations with AAC blocks as walling material, i.e., Case 1C.1, Case 1C.2, Case 2C.1, Case 2C.2, Case 3C.1, Case 3C.2, had RETV that complies with ENS requirement. Burnt clay bricks cases also present low RETV.

Figure 144 shows the correlation between the RETV of the building envelope with U-value of the corresponding walling material. It is interesting to note that the RETV for Cases 2 and 3 are almost equal. It can be speculated that additional of a single floor may not contribute to substantial increase in surface area

Figure 145 indicates the compliance check for all ENS requirements for all cases. The window to Floor area Ratio (WFR), and Visible Light Transmission (VLT) for all cases were compliant with ENS. However, the U-value of roof for Case 1 was higher than the prescribed ENS value due to lack of insulation. For all the proposed cases, the U value of roof was compliant with the ENS prescribed value due to the addition of insulating layers such as mortar, cement screed, XPS sheet and China-mosaic, on top of the roof slab.

Occupant comfort and Energy consumption

Figure 146 displays the monthly operational energy consumption for all cases. It was identified that more than 70% of energy consumption came from the baseload comprising of appliances like lights, television, and fridge. Seasonal load made of

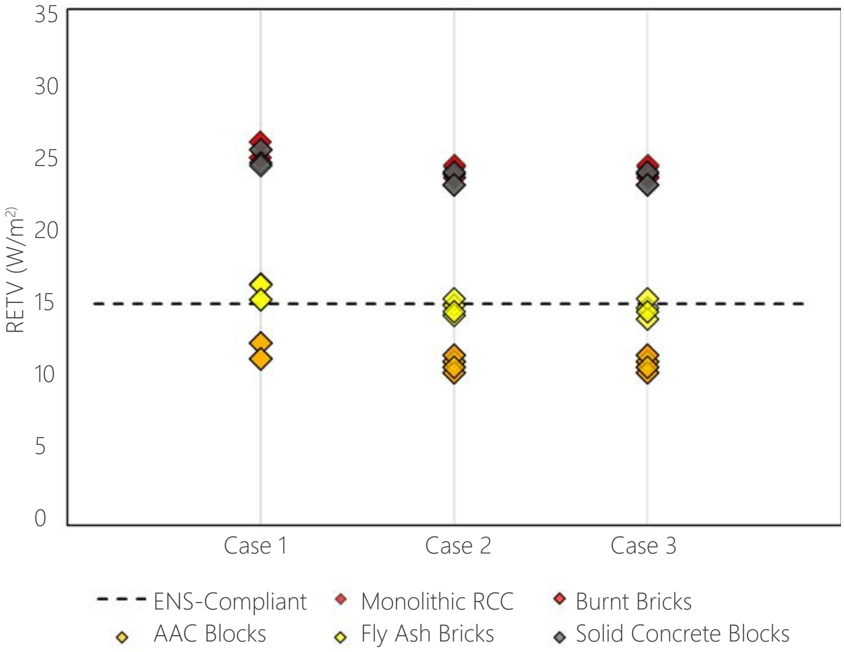


Figure 143: RETV as per walling materials

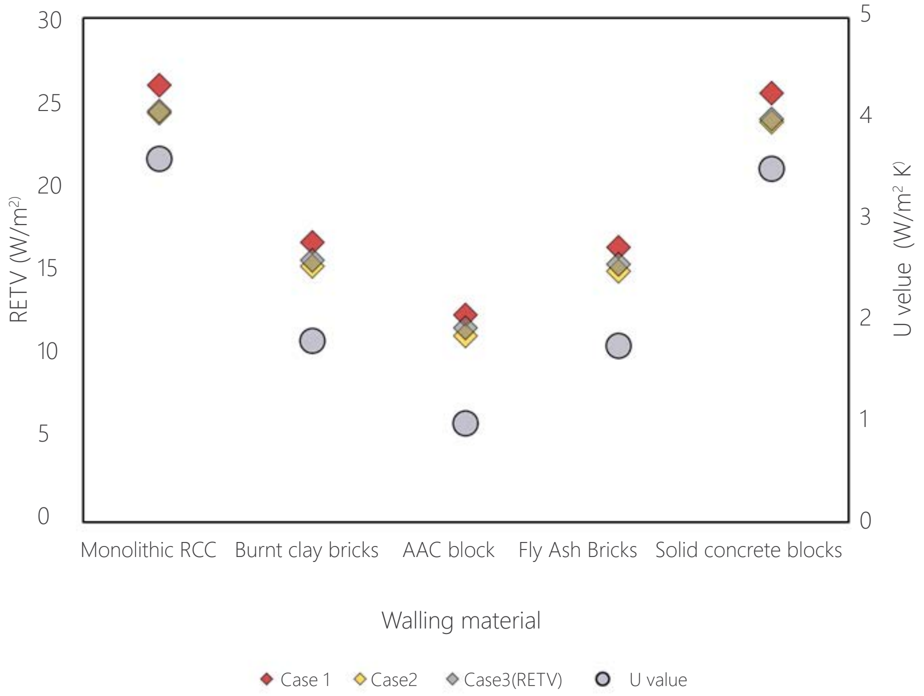


Figure 144: U-value and RETV for walling materials

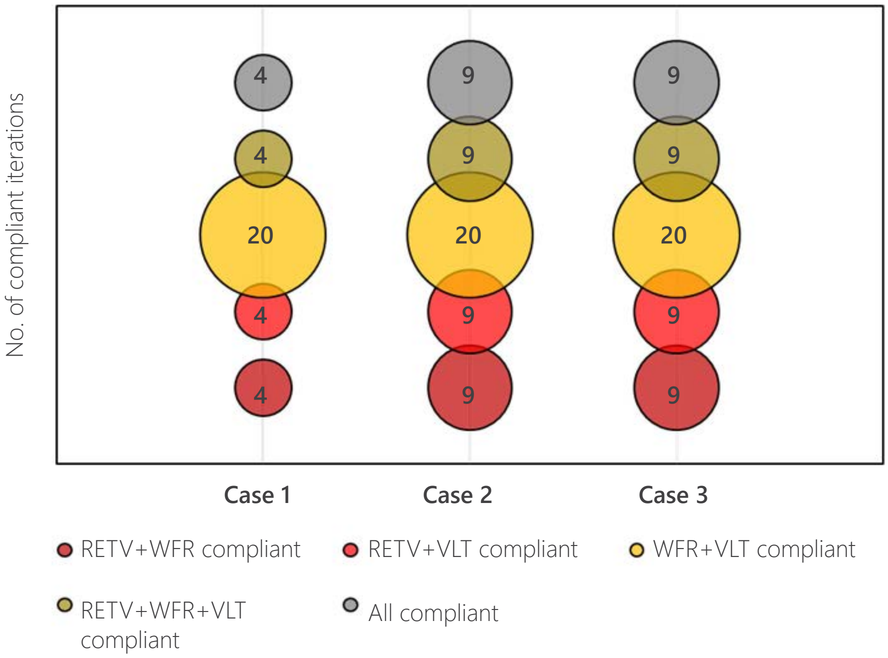


Figure 145: ENS compliant iterations for each case

appliances such as fans were seen to be lower in Cases 2 and 3 compared to Case 1. This can be attributed to re-orientation of site layout. Moreover, the seasonal load for Cases 2 and 3 was close due to same orientation and material.

Figure 147 explain the correlation between cooling load and RETV, and EPI and RETV, respectively. Increase in RETV will result in increased heat ingress though the building envelope. This subsequently increases the cooling load, thereby augmenting the EPI.

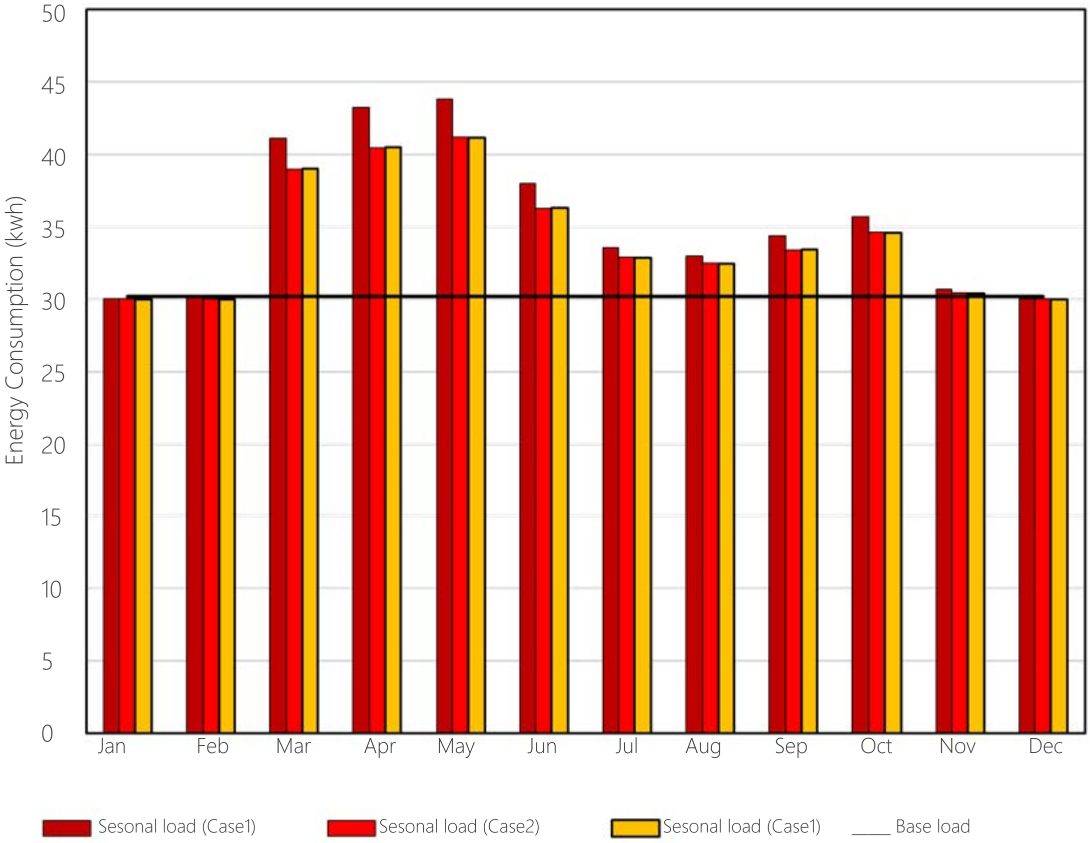


Figure 146: Operational energy consumption for each case

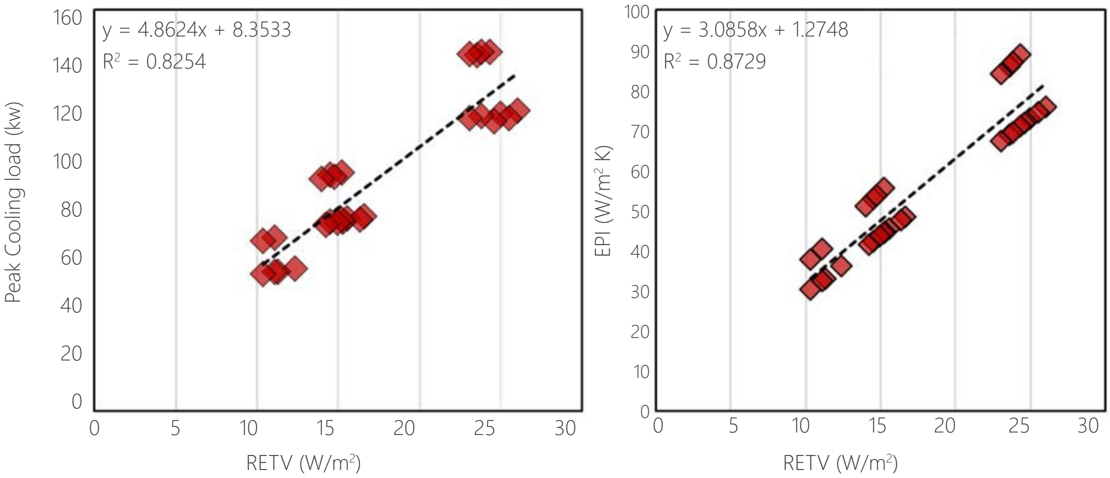


Figure 147: Correlation between: Peak cooling load and RETV (a), EPI and RETV

It was found that for materials with a relatively lower U-value, i.e., burnt clay bricks, and fly-ash bricks provided greater comfort hours and thus, were found to be thermally more comfortable. Similarly, AAC blocks provided the largest number of comfortable hours (refer Figure 148).

Cost

Figure 149 mentions the assumptions made for calculating the cost of various alternatives/iterations. The cost price (the price at which the unit is constructed) and the selling price, which is ₹ 7.5 Lakh for one PMAY-U unit, were assumed to be the same. This established a break-even scenario, where the contractor made no loss or profit.

1. No additional cost alternative

- **Change in orientation**: Re-orienting the site layout has no financial implications as

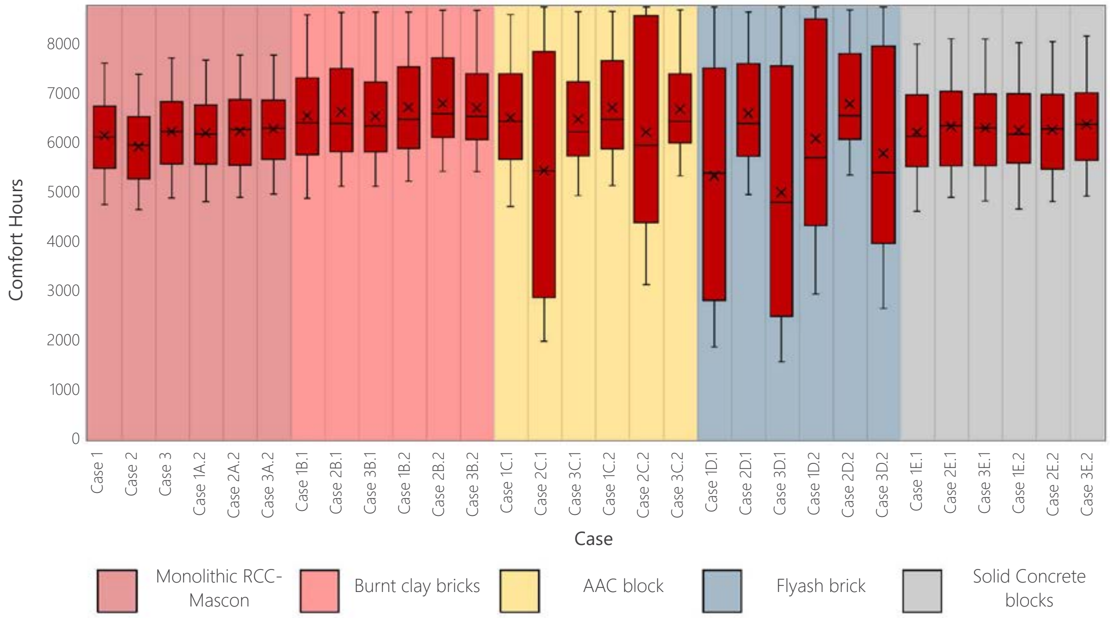


Figure 148: Comfort hours calculated for all cases

Figure 149: Assumptions for calculating cost of alternatives

seen in Figure 150. Lowering of the median for RETV from 16.48 W/m2 (Case 1) to 15.28m2 (Case 2) was observed. The cases differed only in orientation of building blocks on site. Hence, changing the orientation (or spatial arrangement) of the building blocks on site can lead to better thermal performance at no additional cost.

2. Incremental cost alternative

- **Addition of shading/overhangs**
  Cases 2 and 3 included subsets where 600mm of shading was provided over kitchen and living room windows. This led to decrease of the RETV median from 16.34 W/m2 to 15.28 W/m2, as shown in Figure 151. The associated additional cost for a G+3 storeyed building, with 8 units per floor, was estimated to be less than ₹ 50 thousand i.e., 0.2% of the total building cost.
- **Varying the walling material**
  Case 1 used Mascon construction technology (monolithic RCC) for faster construction that involved less labour and provides a monolithic structure. However as visible in Figure 153 the U-value, and RETV were found to be highest for RCC. Solid concrete blocks also presented similar U-values and RETV, while costing close to ₹ 3000/m3 more than the former. Additionally Figure 152 indicates the difference in cost/m3 by varying the walling material with their corresponding U-value; while Figure 153 denotes the compounded impact of varying the walling material on a building level (G+3 storey, 32 units) along with the range of RETV. Noticeably, use of burnt clay or fly-ash bricks instead of concrete (MASCON) in the building cost would decrease the cost by 33% and 32% respectively. However corresponding change in U-value and RETV was not significant. AAC blocks, decreased the overall building cost by 27% and presented best thermal performance out of the considered materials.

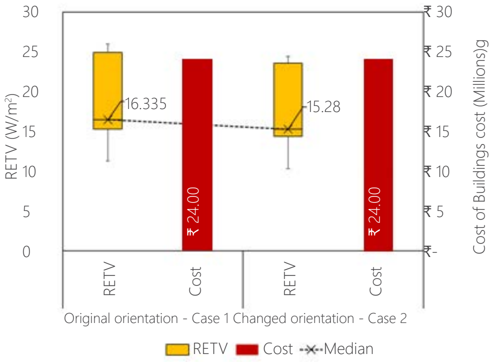


Figure 150: Implication of change in building orientation on RETV and building cost

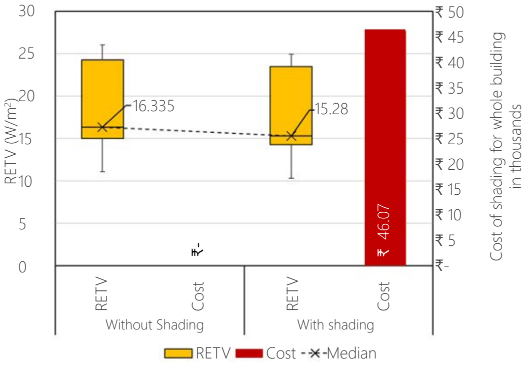


Figure 151: Implication of adding shading (chhajja) on RETV and building cost

Figure 152: Impact of varying walling material on cost/m3 compared with RETV

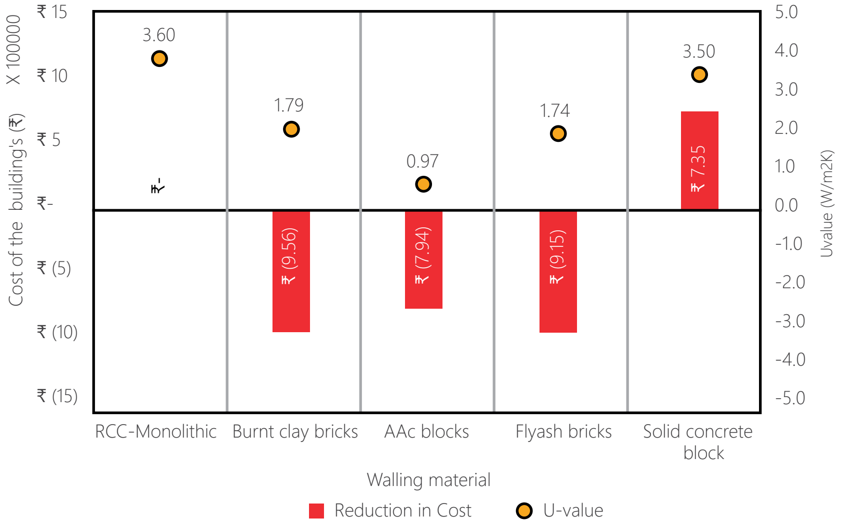
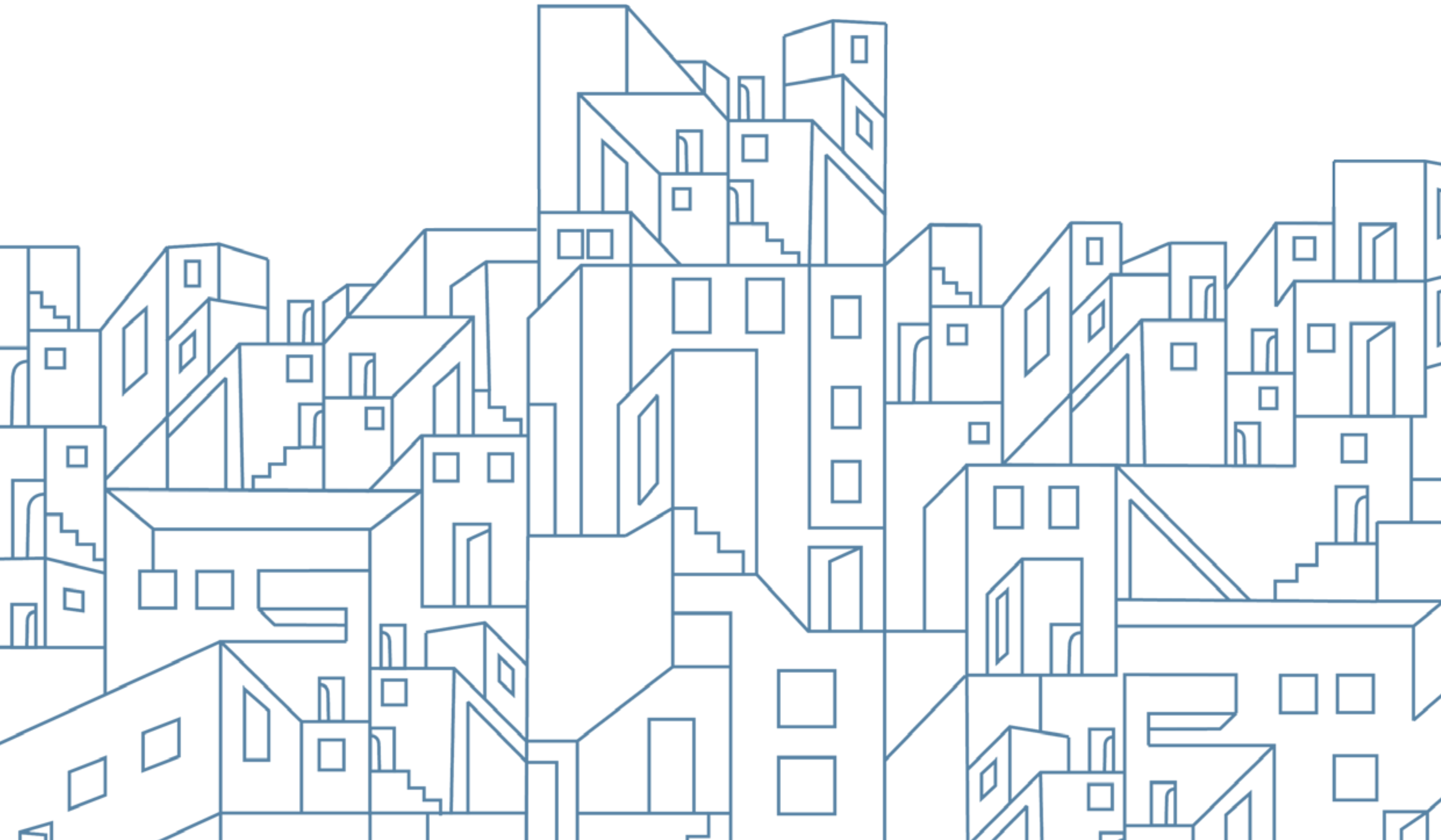


Figure 153: Impact of varying walling material on total project cost for G+3 building having 8 units per floor.

8

THERMAL COMFORT STUDY METHODS



8.1 Introduction

This chapter presents ways of undertaking thermal comfort studies. It begins with explanation of various types of study environments. These are described in detail relating to their applicability and advantages. Research protocols in each category are also mentioned. Further, the chapter establishes relevance of handling the datasets with methods that can avoid impartial results. It identifies various sources of errors in database generation and the general role of statistical analysis in thermal comfort studies.

8.1.1 Indoor environment and human body

As previously mentioned, ASHRAE defines thermal comfort as a state of mind that expresses satisfaction with the thermal environment. This definition establishes that thermal comfort should be viewed as an occupant-centric concept and hence it differs subjectively across individuals. At the same time, it is concerned with the thermal environment of the occupant which is an objective element that can be easily quantified. Hence, measurement of thermal comfort must include both- subjective scales and objective metrics. ASHRAE RP-884 states that thermal comfort involves three categories of adaptation:

Behavioural Adjustment: This includes all adjustments that can result in modification of heat and mass fluxes governing the body's thermal balance. The three subcategories under behavioural adaptation are- personal adjustments (clothing, metabolic rate, etc), technological or environmental adjustment (switching on fans, etc), and cultural adjustments (scheduling siestas, etc).

Physiological Adaptation: This includes all changes in the physiological responses which aim to reduce the strain arising from exposure to thermal environmental factors (e.g.- acclimatization)

Psychological Adaptation: This refers to either modified perception of sensory information or altered reaction to sensory information stemming from personal experiences or expectations.

To understand the impacts of these three types of adaptation on human thermal comfort, various metrics and indices have been developed. In terms of measurable quantities, thermal comfort studies involve measurements of

- Physical (environment)
  Quantified metrics- Air Temperature, Relative Humidity, Air Velocity, MRT (derived from globe temperature)
- Physical (human body)
  Quantifiable metrics- MET rate, CLO value, skin temperature, core body temperature, Heat flux of body part
- Psychological
  Quantified through- votes on comfort, air quality, overall acceptance

8.2 Study Environments

Depending on the research aim, thermal comfort studies can be undertaken in one or combination of following ways:

- **Field Studies:** Field studies are conducted in operational built environments that are regularly inhabited by occupants. This methodology allows researchers to measure and evaluate occupant comfort and their behaviour in spaces of daily occupancy. This approach accounts for real-life scenarios through consideration of factors such as degree of control over immediate environment, psychological factors influencing thermal comfort perception and more. Additionally, field studies also provide opportunity to understand the influence of provision or lack of thermal comfort on the productivity and concentration levels of occupants in varied work profiles.
- **Laboratory Studies:** Laboratory studies offer possibility of understanding thermal comfort in specialized environments. Additionally, the impact of individual variables (such as relative humidity or air speed) or specific combinations can be measured and evaluated only in laboratory studies conducted in thermal comfort chambers as it is possible to keep the other influencing factors constant. Lab environments also offer chances of studying radiant thermal asymmetry studies or local discomfort over different body parts. Combinations of control systems and cooling systems can be calibrated and assessed for thermal comfort provisions with low energy implications.
- **Digital Simulations:** Digital simulations are useful tools to perform thermal comfort studies that overlap with cooling systems, control systems, local discomfort, radiant thermal asymmetry, and majority of studies around thermal comfort. Contemporary advances in digital simulation softwares provide resource-efficient solutions for integrating most aspects of the studies but suffer in accounting for the impact of occupant psychology. Moreover, studying the thermal comfort provisions and associated energy consumption in building is also possible in simulations.

Field Studies	Laboratory Studies	Digital Simulations
• Occupant Behaviour	• Thermal Comfort	• Thermal Comfort
• User Behaviour	• Body Parts	• Body Parts
• Productivity	• Cooling Systems	• Cooling Systems
	• Control Systems	• Control Systems
	• Productivity	

Figure 154: Methods of studying thermal comfort

8.2.1 Field studies

Planning

Figure 155 illustrates the typical initial planning involved in field studies pertaining to thermal comfort. The strategy presented below was adopted for the development of IMAC-R (Rawal, et al., 2022).

- The first step for planning field studies is identifying the scope of climate zones and geography to be addressed in the research. For IMAC-R, cities were selected such that they included all climate zones of India and represented the typical residential typologies. Additionally, attempt to mimic the population distribution ratios within these climate zones determined the number of cities selected in each climate zone.
- Next, building selection within cities is done, informed by parameters that establish comparability across the dataset. For example, various typologies of residential

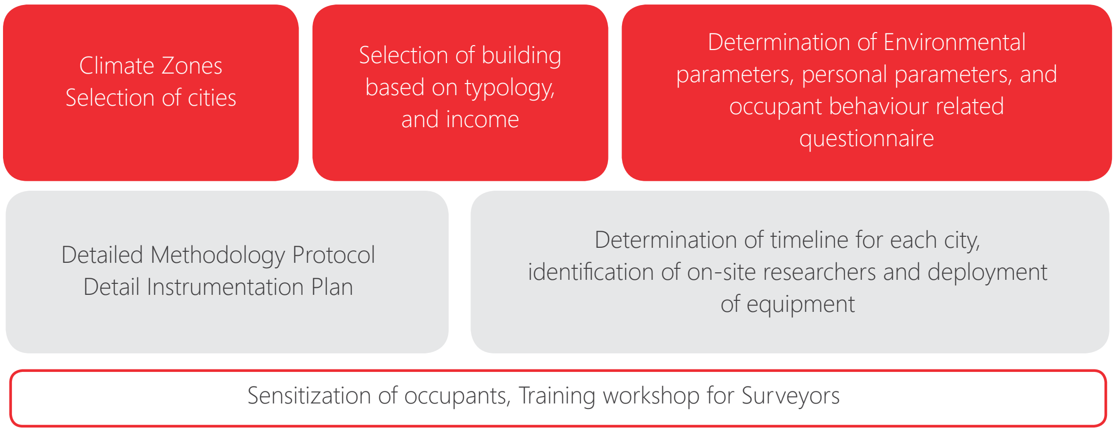


Figure 155: Forethought for thermal comfort studies

buildings ranging from traditional houses and bungalows to affordable housing apartments, penthouses and more were included in IMAC-R. Building operation modes such as NV, AC and MM can also be reflected to ensure that data is inclusive and representative.

- Following step involves the identification of metrics for measurements of the representative dataset. Additionally, protocols to be followed during measurements and data quality checks are also enlisted. This part of the process can be referenced from protocols specified in international standards that regularize the testing.
- Based on the selections made so far, a detailed plan for instrumentation and methodology protocol is developed. Subsequently testing timelines, personnel and equipment required and other logistics of execution are worked out.
- Lastly, the surveyors are trained for equipment operation and conducting surveys. Additionally, the occupants are sensitized to the research and their consent is obtained.

Execution

Indoor environment measurements and recordings

As previously mentioned, the surveyors are trained in workshops to effectively conduct field surveys of two types:

- A set of background surveys that collect one-time data specific to site which usually remains relevant throughout the study. They include information pertaining to buildings (envelope details, appliance usage etc), and socio-economic context (occupation of residents, etc)
- Information that requires repeated recording over regular time intervals is noted in Instantaneous Right Now Right Here (RNRH) surveys.
- The RNRH surveys involve two categories:
    - Environmental parameters: This set is used to record the air temperatures, relative humidity, air velocity and globe temperature indoors (to derive MRT).
    - Personal parameters: The surveyors record their observations of occupant activity before and during the surveys as well as clothing value (including the material of chair where occupant was seated). The corresponding MET and CLO values are determined after referencing international standards such as ASHRAE-55 (2020) during post-processing. This set also records information such as thermal sensations, acceptance, and preference of the occupants.

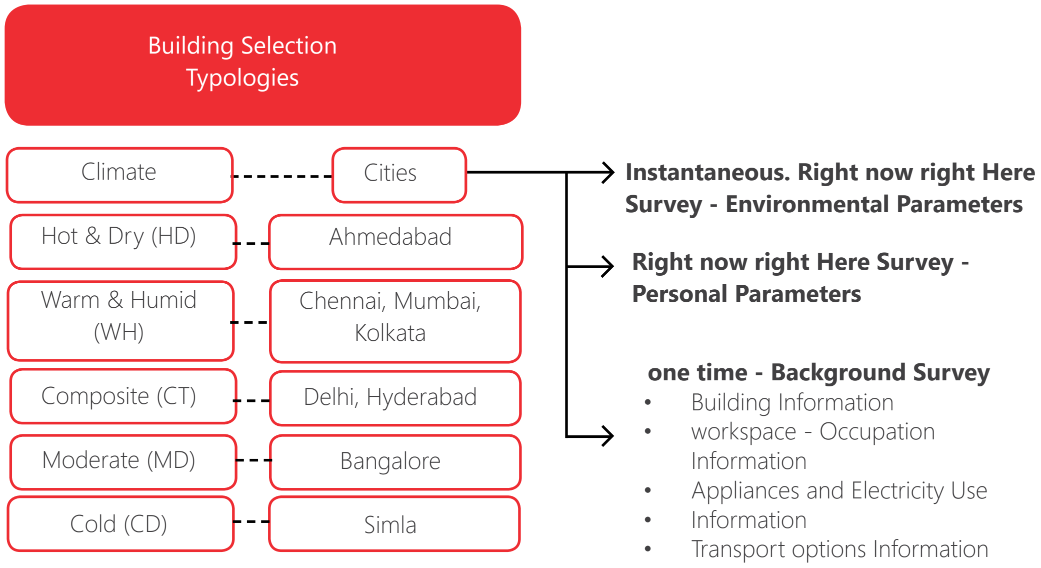


Figure 156: Thermal comfort survey execution aspects

Figure 157 shows the data collection method and preparedness of the surveyors for field studies. The measurement of environmental parameters involves use of hand-held instruments to measure air temperature, air velocity, globe temperature, and relative humidity respectively. Since it is not possible to measure the mean radiant temperature of a space, globe temperature is recorded to derive the MRT from it subsequently during post-processing. Further, the range, resolution and accuracy of instruments must be calibrated to capture the variations in the parameters over time effectively (Refer Table 35).

For recording thermal sensation, acceptability, and preference, digital forms that allow easy record-keeping are preferred. Most importantly, the measurements of environmental parameters must be taken simultaneously as the occupants respond with their thermal comfort indices and observations of clothing and activity are also recorded. Table 36 represents the scales for thermal sensations, preferences, and acceptability that can be used in the RNRH surveys.

Recording humidity sensations of occupants help to identify possibilities of thermal discomfort arising due to relative humidity levels of the space even if the temperatures remain in comfortable ranges for the occupants. Moreover, while the occupants feel thermally neutral in an environment, they may have preferences that are not necessarily met, especially in relation to air movement or velocity. Ultimately, the surveys provide opportunity to document the occupants' acceptance of their thermal environment.

Surveyor's responsibilities

The surveys are repeatedly conducted throughout the designated duration at decided intervals. To account for responses in all seasons, the full duration is often preferred to be one year. Moreover, depending on the desired data granularity, monthly or weekly schedules are preferred. Since often unreliable data can be provided in surveys (explained in post-processing), weekly measurement of data is preferable. Typically, the RNRH surveys take place between 09h00-10h30 and/or 18h00-20h00 to respect the occupants work schedule and maintain consistency in survey time across the projects.

This allows for each surveyor to record measurements and responses for at least 2-3 houses daily. The weekly/ monthly schedule of visits is decided after consultation with the occupants to ensure their availability. Additionally, the on-site surveyors are required to conduct the survey for occupants who are willing to provide responses, despite suspicion of receiving unreliable data. Moreover, surveyors are not authorized to discard or label any recordings as inaccurate or incorrect. However, they are required to note their observations about the survey which may be useful in determining data reliability as they conduct the survey.

Outdoor environment measurements

Outdoor measurements are recorded at the city level simultaneously while the surveys are conducted to allow comparable analysis. These measurements are recorded for the whole day with hourly granularity of the data either at one of the sites or

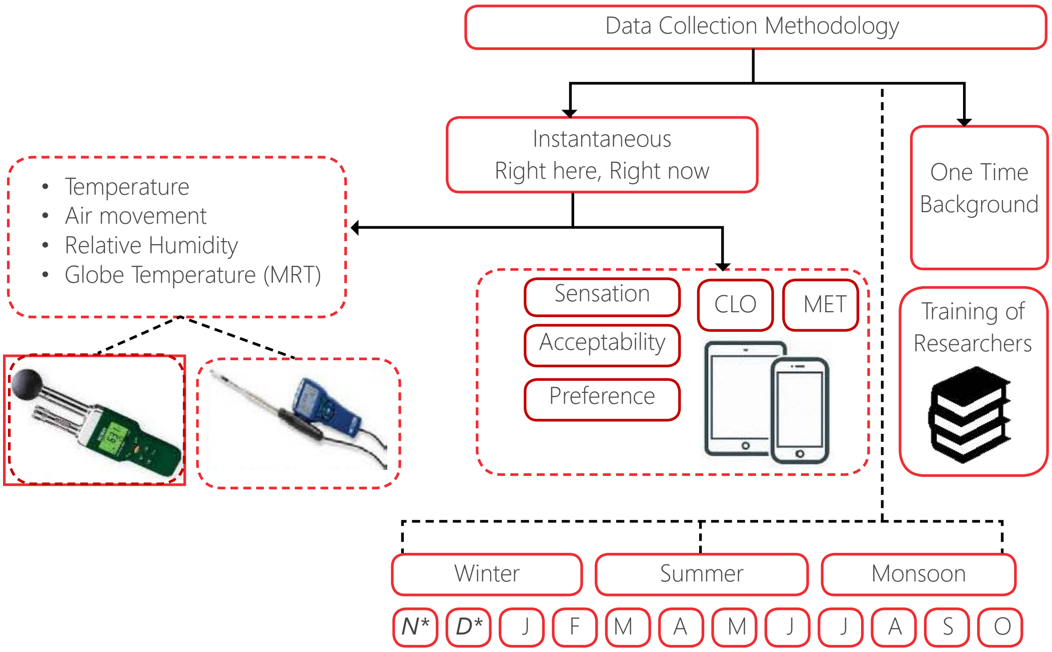


Figure 157: Data collection method for field studies

Table 35: Instrument details such as range, resolution, and accuracy

Instrument	Parameter	Range	Resolution	Accuracy
Instrument A	Indoor air temperature	-10 to 60°C	0.1°C	±0.3°C
	Indoor air velocity	0 to 30 m/s	0.01 m/s	±3% of reading or (±0.015 m/s), whichever is greater
	RH	5 to 95% RH	0.1% RH	±3% RH
Instrument B	Wet Bulb Globe Temperature (WBGT) – (without sunlight)	0 to 59°C	0.1°C	WBGT = (0.7×WET)+ (0.3×TG)
	Wet Bulb Globe Temperature (WBGT) – (with sunlight)	0 to 56°C	0.1°C	WBGT= (0.7×WET)+ (0.2×TG)+ (0.1×TA)

a central location that can be representative of the environmental conditions in the whole city. Additionally, centralised data sources such as newspaper, websites, Indian Meteorological Department (IMD) are also referred for recording environment data at the daily scale. At the annual scale, IMD and weather data service providers are preferred. This is used for data quality checking during post-processing.

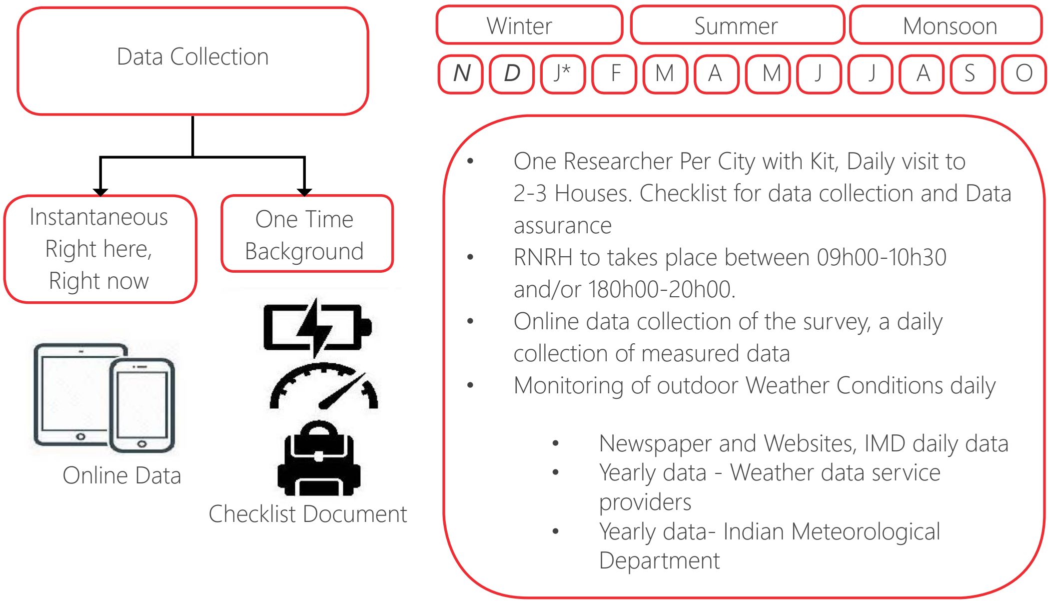
Post-processing: Quality Assurance/ Quality Check (QA/AC)

Post-processing of data refers to clearing of the raw data to ensure that accurate or reliable data is used during the analysis. Sources of error in data include but are not limited to the following:

- Survey fatigue: Occasionally, the occupants may not be interested to participate in the surveys. The repetitive nature of the task, exhaustion from responding to long questionnaires and bias towards survey outcomes are some of the reasons often cited for survey fatigue.

Table 36: Scales of thermal sensations, preferences, and acceptability.

Vote scale	Thermal Sensation	Thermal Acceptability	Thermal Preference	Humidity Sensation	Air movement preference
-3	Very cold			Very humid	
-2	Cold	Completely unacceptable		Humid	
-1	Slightly cold	Just unacceptable	Cooler	Slightly humid	Want less
0	Neutral	Acceptable	No change	Neutral	No change
1	Slightly warm	Just acceptable	Warmer	Slightly dry	Want more
2	Warm	Completely acceptable		Dry	
3	Hot			Very dry	



- One Researcher Per City with Kit, Daily visit to 2-3 Houses. Checklist for data collection and Data assurance
- RNRH to takes place between 09h00-10h30 and/or 180h00-20h00.
- Online data collection of the survey, a daily collection of measured data
- Monitoring of outdoor Weather Conditions daily
    - Newspaper and Websites, IMD daily data
    - Yearly data - Weather data service providers
    - Yearly data- Indian Meteorological Department

Figure 158: Indoor and outdoor data collection sources during thermal comfort survey

- Instrument failure: Various reasons such as improper maintenance or handling of the instrument, low battery level in case of batter-operated devices and more can lead to incorrect readings from the instrument.
- Change in occupant behaviour: Occupant behaviour is subject to change in situations of poor physical health such as temporary illness, exceptional exhaustion at the end of a day and other circumstances.
- Unprecedented scenarios: Global issues such as the SARS-CoV-2 pandemic can also temporarily affect the occupant responses when they are not acclimatized to the situation

An example of the quality assurance process is presented in Figure 160 (Rawal, et al., 2022). The confidence level and margin of error for the dataset determine the robustness of the study and help to validate the analysis.

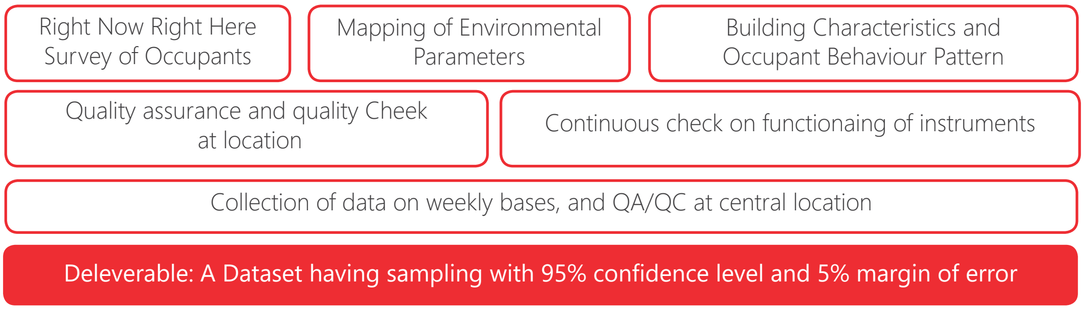


Figure 159: Post processing (QA/QC) of raw data

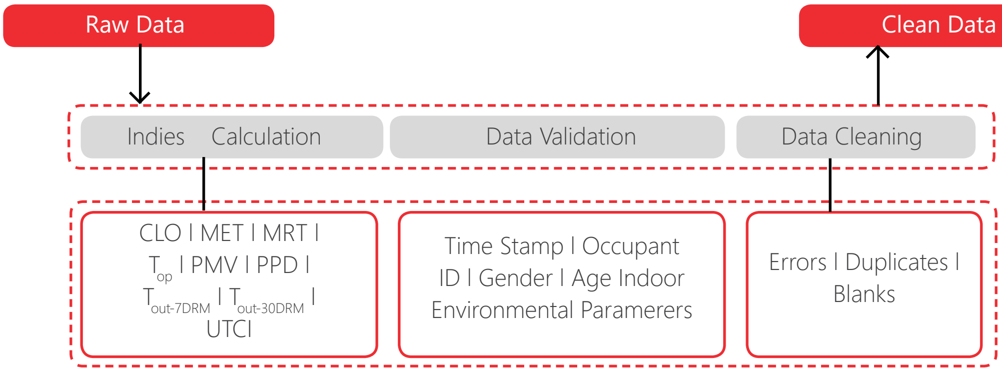


Figure 160: Quality assurance framework for IMAC-R

Results

When thermal comfort studies are undertaken with the objective of developing adaptive thermal comfort models, the result of the data analysis is presented in the form of an equation. This equation is intended to guide the design and operation of thermally comfortable buildings. Its format can be referred in Equation 9.

$$\text{Indoor Operative Temperature} = x \times \text{outdoor temperature} + y$$

Equation 9: Typical format for adaptive comfort model.

Here indoor operative temperature (°C) refers to the neutral temperature at which specified percentage of occupants will feel comfortable. Typically the equation is given for 90% or 80% acceptability. The outdoor temperature (°C) that should be used in the equation is the 30-day outdoor running mean temperature. X represents a numerical coefficient and y is a numerical constant in the equation derived for specific building operation modes in the thermal comfort study. Adaptive thermal comfort model suggests that neutral temperatures are a range as opposed to a specific value. Hence, the range of neutral temperature for given acceptability in given building operation mode is also established. Different equations for adaptive thermal comfort model have been prescribed in the NBC based on building operation modes.

The more recent study IMAC-R (Rawal, et al., 2022) suggests two adaptive thermal comfort model applicable for Indian residential buildings considering 7-day outdoor running mean (between 5.5°C and 33°C) and 30-day outdoor running mean temperatures (between 5.5°C and 33°C). The equations apply to two modes of operation- NV and MM.

$$T_{neut} = (0.39 \times T_{out\text{-}7DRM}) + 18.42$$

$$T_{neut} = (0.42 \times T_{out\text{-}30DRM}) + 17.60$$

Figure 161 shows the relation between the indoor operative temperature or neutral temperature with the 7-day and 30-day running outdoor mean temperatures.

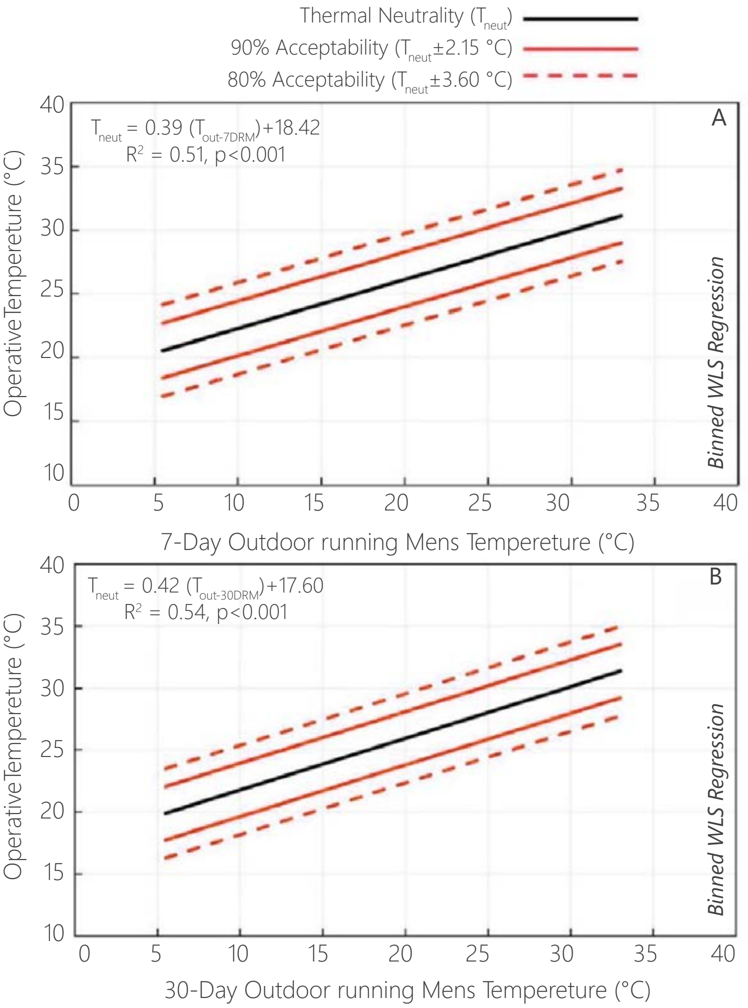


Figure 161: Proposed adaptive thermal comfort model for Indian Residences with absicca of (A)7-day outdoor running mean temperature and (B)30-day outdoor running mean temperature

8.2.2 Laboratory studies

Laboratory studies are conducted in climate chambers or thermal comfort chambers which can create required environmental conditions in terms of air temperature, relative humidity, and air velocity. They can also be equipped to provide opportunity to control surface temperatures. Hence, they offer completely controlled environments which are necessary in understanding impact of one specific parameter. Depending on the objective of the study, these parameters can be either maintained at static levels or modulated individually throughout the study. Laboratory environments are specially used to in studies that require recording both Predicted Mean Vote (PMV) and Actual Mean Vote (AMV) for later comparison.

Certain studies involve researching heating and cooling systems based on different principles and their impacts on occupant's thermal comfort sensations. They require consistency in focus groups and the spatial and material configurations of the room. Alternatively, interaction of occupants with systems and their control over the systems is also a widely researched topic that requires nuanced control over indoor thermal environment.

Another category of experimentation that has been identified to require high control over the indoor environment along with provisions of sophisticated monitoring systems is thermal sensations of individual body parts or development of digital thermal models of humans. Likewise lab environments also facilitate studies focussing on clothing value and metabolic rate of occupants.

Often, climate chambers are required to imitate spaces that feel familiar to individuals whose responses of thermal sensations are recorded. As adaptive thermal comfort model notes, an individual's thermal perceptions are influenced by experiences and expectations of indoor climate. However, they have sophisticated systems in the vicinity to maintain controlled environments.

Laboratory- based research offers possibility of working with subject other than humans. There are four ways to conduct experiments in controlled laboratory environments:

Measurements: In this category, the component of human is removed from experiments allowing measurements of environmental parameters and their inter-dependencies at desirable granularity.

Occupants: This category refers to involvement of humans in studies that require monitoring of thermal preferences and acceptability or productivity related response

Figure 162: Testing room for Laboratory studies

to indoor environment. It is different than field studies as a greater degree of control is available over the environment. Additionally, the intervals of measurement are smaller i.e., in minutes as compared to weekly intervals in field studies.

Thermal mannequins: Thermal mannequins are manufactured to house thermal sensors in a composition and intensity that mimics human thermal sensations. Essentially, they represent the physiology of a human body, but without the involvement of psychological influence on thermal perception. They were developed to perform thermal comfort studies on specific body parts and overcome challenges associated with human component in thermal comfort studies such as survey fatigue. Thermal mannequins are also regularly used in researching the clothing insulation levels.

Digital Simulations: Often digital simulations are used to understand the environmental parameters of a space. However, using physiological models with building physics models is an avenue offered by digital simulations.

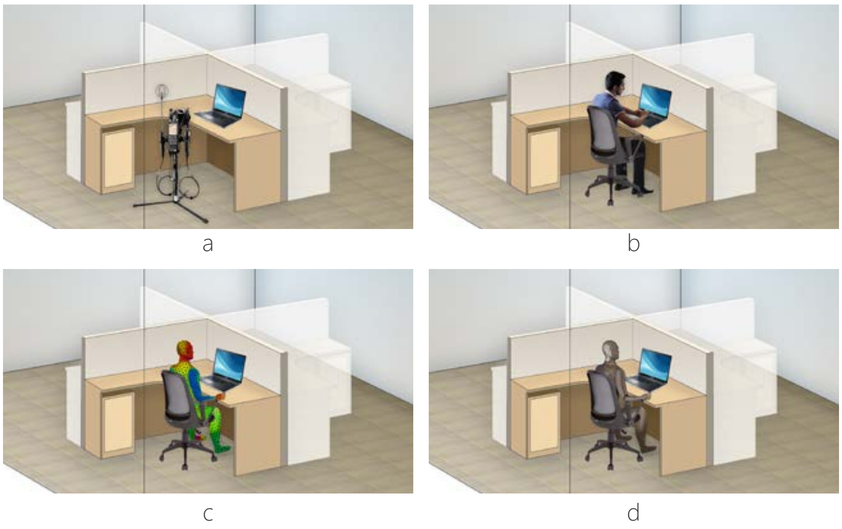


Figure 163: Thermal comfort studies in controlled environments with (a) measurements, (b) Occupants, (c) thermal mannequins, and (d) digital simulations

Working with Human Subjects

Before commencing experimentation with volunteers, ethical clearances such as consent and readiness for various aspects of the experiment must be obtained from the volunteers. Protocols established in standards are required to be followed to obtain accurate and representative data for analysis.

Comparability of cases in occupant-based lab tests

Protocols followed in occupant- based lab tests that study influence of environmental parameters on thermal comfort perception of occupants include but are not limited to:

Selections of 30-40 volunteers for a test group should ensure that BMI of the occupants lies within ±5% of the mean BMI.

- The clothing of volunteers should be regularized to eliminate the role of clothing insulation in the measurements and observations.
- Composition of the test group should be representative of the population for which the research is undertaken in terms of gender, race, age.

- It should also be ensured that volunteers being tested are not in the influence of short or long term acclimatization processes unless the study particularly requires it. For example, occupant-based thermal comfort studies in Ahmedabad (hot-dry climate) to understand physiological responses to cold environment may accept volunteers who have lived in the hot-dry climate for the past 6-12 months. This is done to ensure that their physiology is not familiar to cold environments from recent previous habitation. For the same reason, volunteers are often required to occupy an acclimatization room for some duration (usually 30 minutes) before they proceed to thermal comfort chambers for testing and observation. Protocols such as consent of individuals before testing should be followed.

Achieving and maintaining indoor environments

- The thermal comfort chambers are prepared for the desirable indoor environment conditions and stabilised to maintain these conditions over the duration of the study.
- During the experimentation time, the volunteers are allowed to perform activities of their choice from a pre-determined list of acceptable activities. The required measurements and observation for both environmental and behaviour aspects are recorded at premeditated time intervals (usually 10 or 15 minutes) during the experimentation time. Human behaviours (such as pacing, switching on the fan, etc) and system responses to these behaviours (time taken by fan to create comfortable conditions, etc) are also recorded until the experiment time ends.
- Lastly, in the cooldown time, the indoor environment conditions are brought to comfortable levels with respect to outdoor conditions and occupants are allowed to empty the space. Typical total duration of one isolated experiment is 60 minutes with 2 hours as the maximum possibility.

Working with Thermal Mannequins

Thermal mannequins, as previously mentioned facilitate research on thermal responses of individual body parts. The mannequin is divided into twenty-two body parts can be individually measured for thermal sensitivity and sensation shown in Figure 164 (right). The recorded measurements of thermal sensations in the individual body parts also contribute to developing digital physiological models. These can be used in combination with building physics based models for simulation-based studies pertaining to thermal comfort.

Working with human subjects to understand clothing insulation levels has historically presented ethical, socio-cultural, and methodological challenges. Hence, the use of thermal mannequins in measuring insulation levels of various types of clothing became a commonly adopted approach. Figure 164 (left) shows a thermal mannequin in PPE kit, wearing a mask. The study aimed to understand the thermal sensations and comfort requirements of doctors wearing PPE kit during the SARS-CoV-2 pandemic.

New generation of thermal mannequins are capable of simulating complex physiological responses like the human body. These include vasomotion, sweating, shivering and more to adapt to the indoor thermal environment changes. Hence, the use of these mannequins extends to research relating to sweating. Moreover, research relating to indoor air quality and airflow for breathing can also be performed with the help of thermal mannequins.

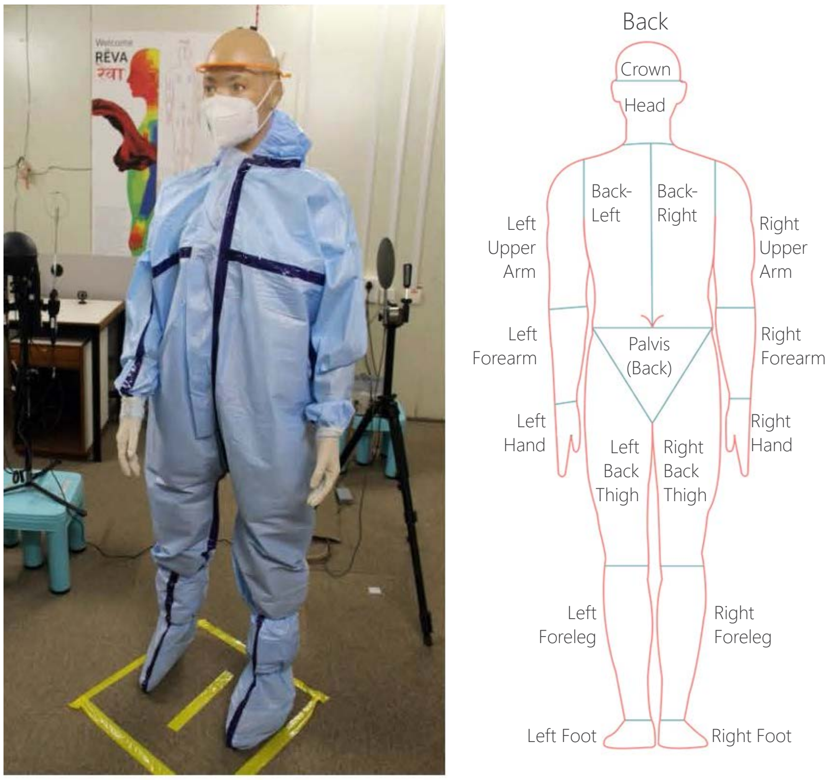


Figure 164: Left- thermal mannequin with PPE kit being tested for clo value. Right- parts of thermal mannequin capacble of recording individual thermal sensations.

8.2.3 Digital Simulations

Digital simulations using thermal physiological models of human body and building physics based models of indoor spaces can be used to address research questions in the domain of thermal comfort in indoor environments. These models can also be extended to include details such as HVAC, CFD (Computational Fluid Dynamics) and thermal modelling of buildings.

Digital simulations offer a cost-effective and scalable methods to generate knowledge regarding thermal comfort in built environment for application in real world. However, it is important to note that the results of a simulation depend heavily on the accuracy of the inputs. This means that for incorrect or unrealistic inputs, the simulations may still produce results which are not reliable. Hence, using digital simulations as tools requires high level of accuracy of input data. Moreover, since the simulations are essentially based in mathematical algorithms, it is also critical to consider the use of correct algorithm for the given research.

Figure 165 (left) shows the behaviour of various body parts in terms of skin surface temperature with respect to difference in room air temperature. It can be observed that the skin temperature of the head remains around 33 with a narrow range of variation. However, the rest of the body exhibits wider range of change in surface temperatures; the highest being in legs. Figure 165 (right) shows the layers of the human across which heat transfer occurs allowing the room temperatures to influence the core body temperature.

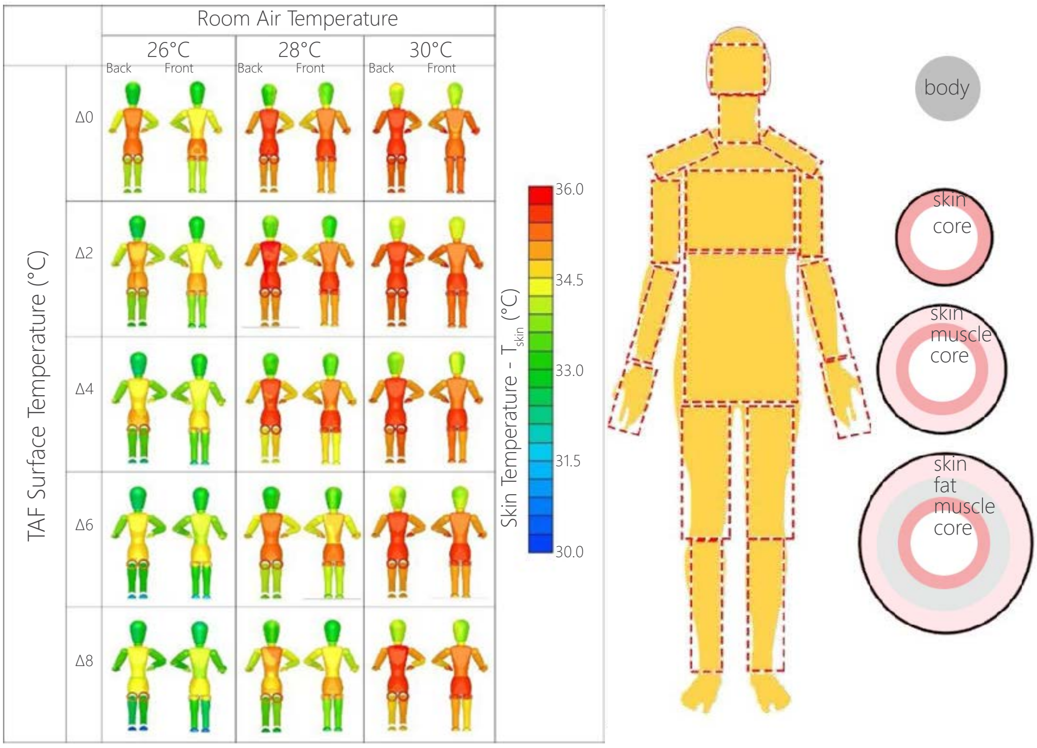


Figure 165: Left- surface temperature of various body parts in different room air temperatures; Right- layers of body through which heat transfer occurs.
Source: (Takahashi, et al., 2021)

8.3 Statistical Analysis

Thermal comfort studies involve analysis of large databases containing multiple data points attributed to various indices and metrics. Incorrect handling of data can lead to wrong inferences. Performing statistical analysis before cleaning the data may result in null hypothesis (H0) or alternate hypothesis (H1). Hence, the method of data analysis should be appropriate to the objective and robust to result in reliable observations and relevant conclusions. Figure 167 shows the difference in fitting models obtained when different approaches were applied to the same dataset.

The databases involved in research should be checked and filtered for bogus and/or contradictory data points. This can be achieved in multiple ways. Comparison with corresponding databases (if available) for consistency is one approach. For example- Measurements of outdoor air temperature recorded at a site can be validated by comparison against temperature recorded by IMD or reported in newspapers for the given day and city. Another method to filter inaccurate data is corelating it with subjective data or physical reasoning. Moreover, databases should also be scanned for duplication of data to avoid undesirable bias in analysis.

After filtering and cleaning the data, possible models of correlation should be identified and weighed for suitability. Linear regression, Kendall correlation, and spearhead correlation are common statistical methods used to establish the direction and strength of correlation between the variables.

Various tools such as Shapiro – Wilk test, ANOVA (Analysis of Variance), Kruskal-Wallist Test, T test and Wilcoxon Rank test are available to determine the nature of data distribution.

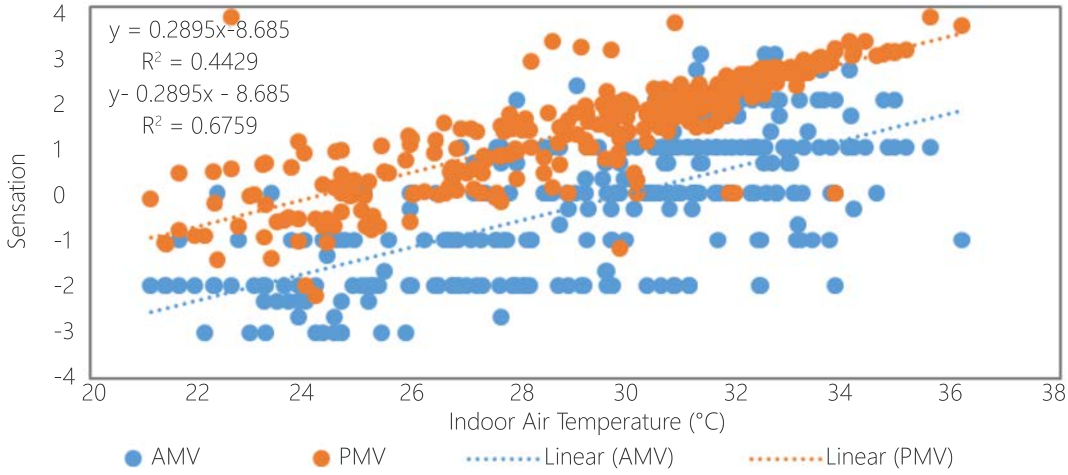


Figure 166: Linear fit for Actual Mean Votes and Predictive Mean Votes

8.4 Reference Documents

- Water based surface embedded heating and cooling systems – Part 5: Heating and cooling surfaces embedded in floors, ceilings, and walls – Determination of the thermal output **TS EN 1264-5:2010**
- Free hanging heating and cooling surfaces for water with a temperature below 120°C. Pre-fabricated ceiling-mounted radiant panels for space heating. Test method for thermal output **BS EN 14037-2 : 2016**
- Radiators and convectors. Test methods and rating **BS EN 442-2:2015**
- Moderate thermal environments-Determination of the PMV and PPD indices and specification of the conditions for thermal comfort **TS EN ISO 7730:2016**
- Method of Testing for Rating Ceiling Panels for Sensible Heating and Cooling **ANSI/ASHRAE 138-2013 (R2016)**
- Ventilation for buildings. Chilled ceilings. Testing and rating **BS EN 14240:2004**
- Thermal Environmental Conditions for Human Occupancy **ANSI/ASHRAE 55-2020**

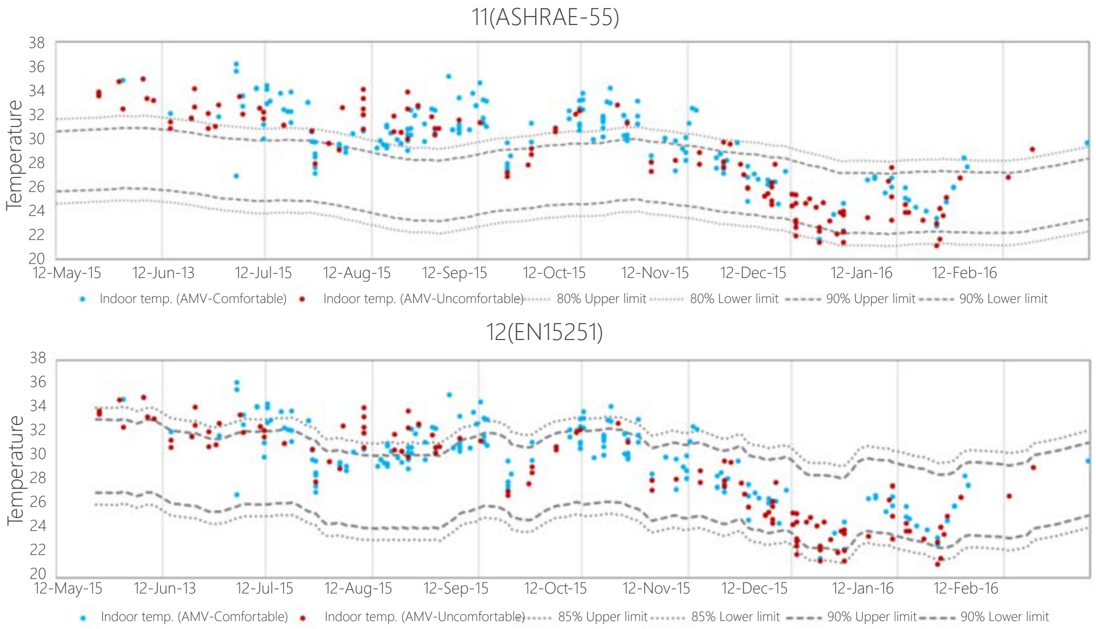
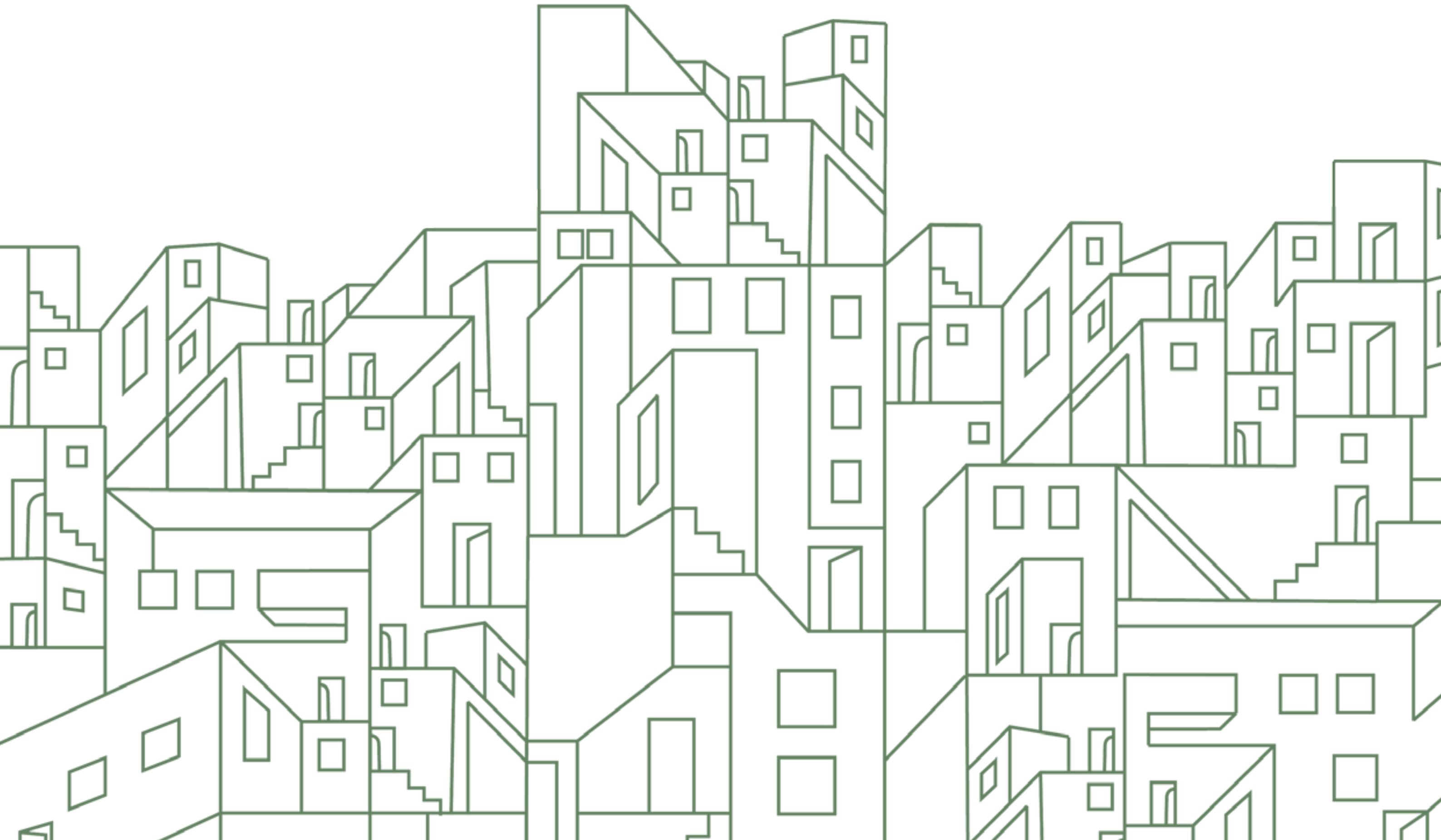


Figure 167: Different results of the fitting model for the same dataset due to different approaches

9

LOW ENERGY COOLING TECHNOLOGIES AND COMFORT



9.1 Introduction

This chapter discusses various low energy cooling systems. It begins by establishing their relevance and definition. It proceeds to explain functioning mechanism, underlying principles, system advantages and disadvantages as well as applicability of these systems in great detail. Further, it describes the calculation for establishing energy efficiency of the systems and presents list of reference standards that govern the design, implementation, and operation of these systems. It concludes with a case study for one of the systems.

9.1.1 Importance of Low-energy Cooling Systems

Low energy cooling technologies is a relatively new term with no commonly accepted scientific definition. However, it can be loosely defined to include technologies that do not use vapor compression cycles which is traditionally the most used refrigeration cycle in current mechanical devices for cooling. These include split air conditioner, chillers, variant refrigerant flows systems and many more.

As the name suggests, a characteristic of majority of low energy cooling technologies is reduced energy consumption for operation when compared to conventional vapor compression-based systems. The involvement of chemicals deemed to have high global warming potential is limited or completely absent from these technologies. Some of these technologies are designed to eliminate refrigerate heating or cooling. Few low energy technologies that use the concept of refrigerant-based cooling replace coolant fluids with water. It is one of the measures implemented in these technologies to reduce the undesirable environmental impacts.

These technologies are often used as alternative mechanisms of cooling such as nighttime cooling with mechanical ventilation. Some of these technologies also explore the involvement of renewable systems such as ground or aquifer coupled cooling. Low energy cooling technologies can be done categorized in multiple formats such as systems that provide ventilation by interaction of indoor and outdoor air through glazing or systems that reduce the dry bulb or wet bulb temperatures of the air inside the building spaces.

Low energy cooling technologies adopting ventilation- based cooling strategies can be classified into night cooling by natural ventilation and night cooling by mechanical ventilation.

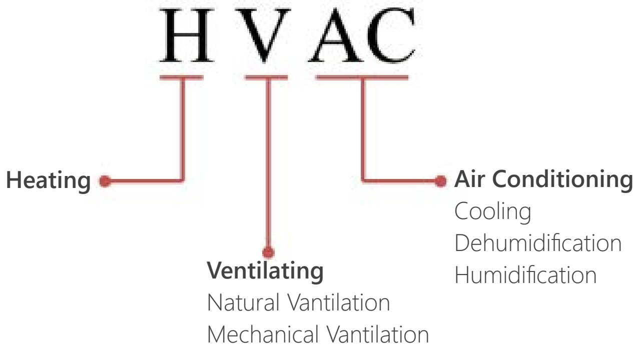


Figure 168: Scope of HVAC systems

One of the most used cooling systems in the affordable housing sector is evaporative cooling and its variations. It is highly applicable in the hot and dry climate where the dry air has high potential to facilitate evaporation. An example of this system is a desert cooler. Direct evaporative cooling systems use wet beds to provide cooling. Indirect evaporative cooling strategies employ a secondary air stream to provide cooling inside the building .

Another category of low energy cooling technologies uses desiccant materials to extract moisture from the indoor environment. This technique is highly effective in reducing the latent cooling loads of the building arising due to high moisture levels. It works well in warm and humid climate where controlling the indoor relative humidity offers opportunities to increase effectiveness of other forms of cooling that may be employed .

Displacement ventilation refers to strategies of air distribution that induce cooling through stack effect of air. In traditional systems, the air enters and exits a space from grilles or openings embedded in the ceiling. Displacement ventilation strategy alters this situation by proposing entry points for air near the floor level while exit points remain in the ceiling. This gives rise to a draft or stack ventilation like scenario which is responsible for cooling the space through modulation of air velocity.

Ground Cooling systems use the stable temperatures of the ground to regulate the temperature of the air by moving it in pipes embedded at suitable depths in the ground. This regulated air is further distributed in the building to provide cooling effect. In case of aquifers, the high specific heat capacity and thermal mass of water ensure stable temperature conditions beyond certain depth of the water body. The mechanism for air temperature regulation in aquifer cooling system is same as the ground cooling system.

Radiative cooling is a relatively new concept that utilizes the thermal emittance capacity of surfaces to ensure minimum transmittance or absorption of radiation in building materials. This strategy uses material properties to maintain cool surfaces around the building that effectively reduce sensible loads inside the buildings.

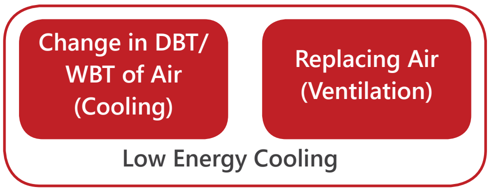


Figure 169: Cooling principles of low energy cooling technologies

Radiative cooling is different from radiant cooling systems that use refrigerant cycle to regulate the temperature of water flowing inside pipes enclosed either structurally or non-structurally in a space. This technology uses the concept of radiative heat transfer between different surfaces- occupants and chilled water pipes (in this case) to ensure thermal comfort.

Chilled ceiling and beams use radiant panels that allow exchange of heat between indoor air and cooled water pipes embedded in the panels through radiation to remove heat from the space. This is bolstered by convective heat exchange to maximize the cooling effect. Radiant panels also use refrigerant cycle.

Figure 170 presents a comparison of traditional, conventional, and low energy cooling systems on the parameters of energy consumption and comfort level provisions when implemented in a building located in Ahmedabad (hot-dry climate). In the graph, the conventional systems have been highlighted in black boxes and low energy cooling system in red boxes. While Direct expansion (DX) refrigerant coil-based conventional technology can provide maximum comfortable hours , it is always accompanied with a high EPI of over 90 kWh/m2 indicating high energy penalty. Combination of direct evaporative cooler with DX coil system has similar performance levels . Hence these are high comfort- high energy systems. On the other hand, traditional low energy cooling systems like direct evaporative cooler or desiccant cooling are low comfort-low energy systems when used as standalone cooling mechanisms. Indirect evaporative coolers and certain technologies deploying two-stage direct and indirect evaporative cooling offer higher comfort hours at around 40-50% in an EPI range not more than 10-15 kWh/m2. Most interestingly, recent radiant cooling technologies emerge as high comfort- medium energy systems. They offer nearly 100% comfortable hours at a lower EPI than traditional systems.

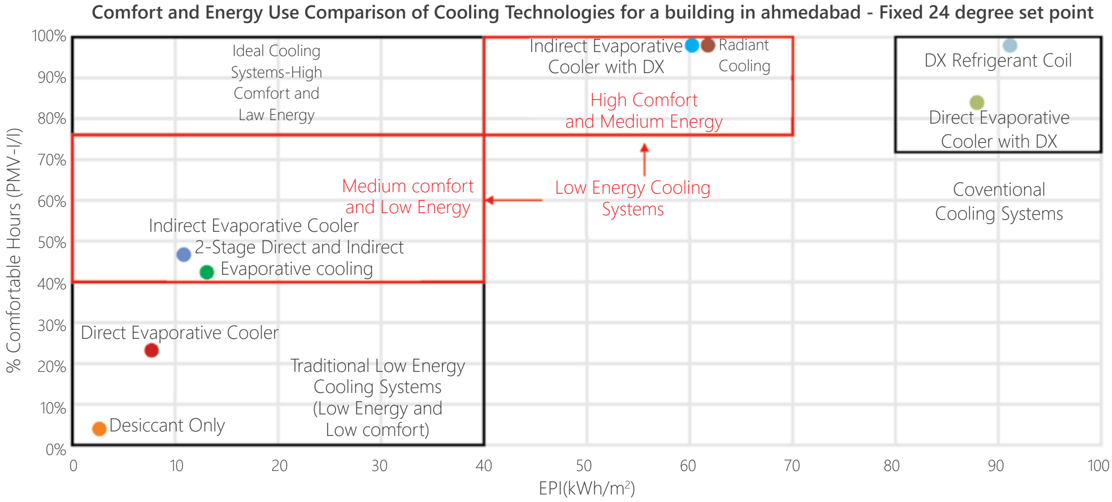


Figure 170: Comfort and energy use comparison of cooling technologies for a building in Ahmedabad- Fixed 24 set point

9.2 Categories of Low energy cooling systems

9.2.1 Evaporative Cooling (and its variations)

The categorization for the variations of evaporative cooling systems is presented in figure below. Primarily they can be bifurcated into direct, indirect and combination of the two. Details regarding further categorizations can be viewed in Figure 171. Active and passive direct evaporative cooling condition the air by bringing it in contact with wet media or surfaces to lower its heat energy. Direct contact between air and water also raises the relative humidity of the air slightly.

Indirect evaporative cooling system also lowers the air temperature but without increasing its relative humidity. This is done by using a buffer layer of air. Since two layers of air are involved, effectivity of cooling the supply air in this system may be lower than direct evaporative cooling (it is dependent on WBT of primary air layer i.e., supply air). However, the trade-off is minimal or no increase in relative humidity. A combination of direct and indirect evaporative cooling systems works in more than one stages. The first stage is usually IEC, followed by DEC. Additional iterations of these can be generated in a multistage combined system. Alternatively, a three-stage combined system also exists where IEC followed by DEC are supported by active cooling through DX systems in third stage.

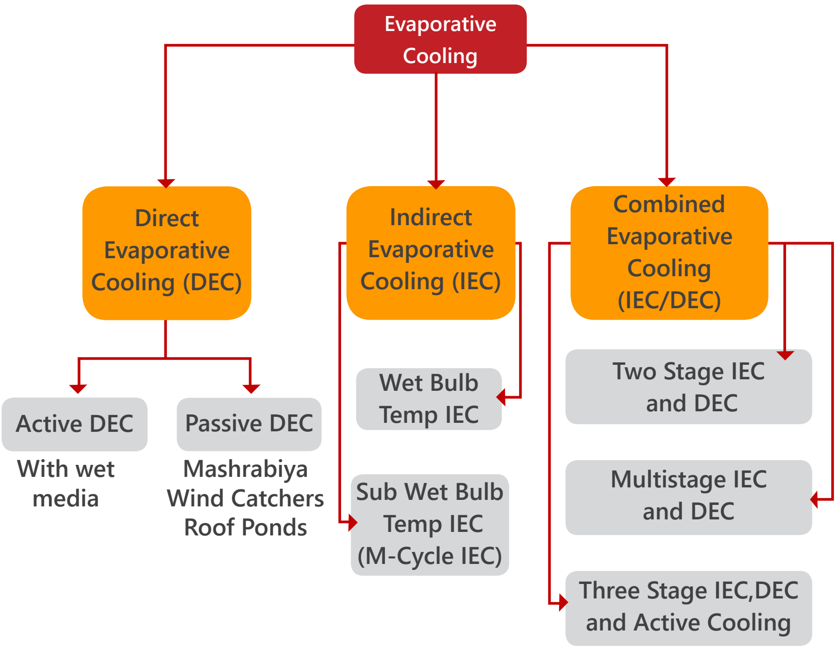


Figure 171: Evaporative cooling

Direct Evaporative Cooling (DEC) Systems

System Description:

The system is called "Direct" because the outside airstream comes in direct contact with the circulating water which cools and humidifies the airstream by evaporation as shown in Figure 172 (a). DEC systems achieve latent cooling of air and are very low energy systems. The moist air should be effectively removed by keeping sufficient number of windows and door open. This will ensure that DEC works effectively.

System Components:

- Evaporative media (Wetted pad)
- Supply Fan
- Pump
- Water Reservoir

System Advantages:

- Low Energy consuming system
- Environmentally friendly as it does not use any refrigerants
- the evaporation pads also act as effective filters ensuring effective air filteration
- Less number of moving parts resulting in low maintenance requirements
- Does not require duct work for residential systems

System Disadvantages:

- Keeping the evaporative pads moist at all times requires monitoring
- Moisture accumulation inside the building due to insufficient removal rate of

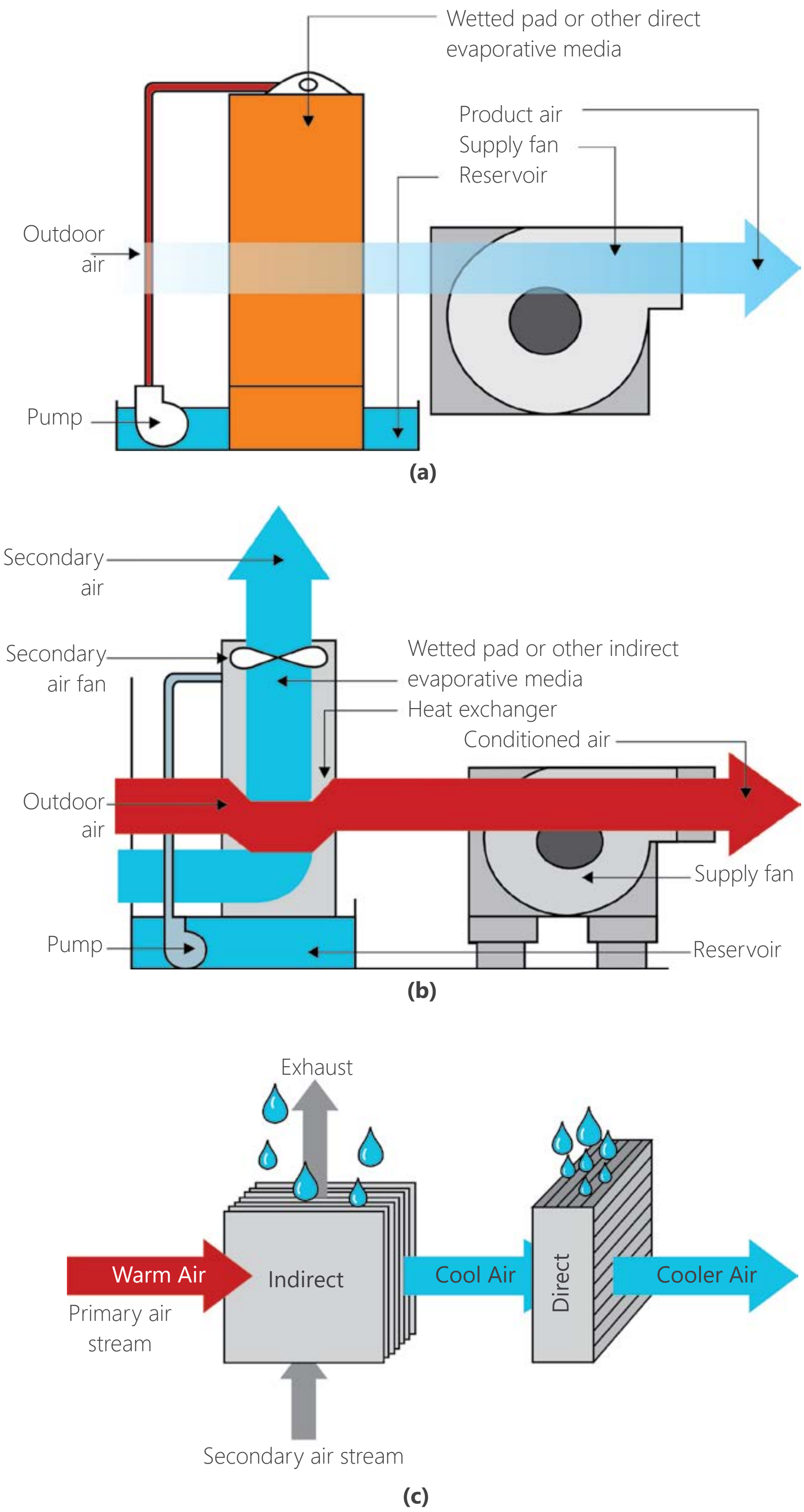


Figure 172: (a) Schematic showing typical Direct Evaporative Cooling System; (b) Schematic showing typical Indirect Evaporative Cooling System; (c) Schematic showing typical two-stage Indirect/Direct Evaporative Cooling System

moist air, will help in mould build up, which can cause serious health issues for the occupants
- The water sump needs continuous monitoring to algae and mineral built up

System Applicable in India:
- DEC systems are most applicable in hot dry climate in the western part of India.

System Implementation Constraints:
- DEC uses water for cooling. Hence, water availability in the hot dry climate can be a potential issue.
- The user needs to be properly informed about exhausting the moist air.

Indirect Evaporative Cooling (DEC) Systems
System Description:
In IDEC systems the incoming outside air is cooled without raising the humidity. It is split into 2 streams: Primary Air Stream and Secondary Air Stream. The secondary air stream will pass over the heat exchanger that is sprayed with cold water. The primary air stream passes inside the heat exchanger tube. The primary air passage is called dry passage and the secondary air passage is called wet passage. IDEC systems achieve sensible cooling of the primary air stream.

System Components:
- Supply Fan
- Pump
- Water Reservoir
- Heat Exchanger
- Exhaust Fan

System Advantages:
- IDEC is Low Energy consuming system. Only additional power consuming component here is the exhaust fan
- Environmentally friendly. Does not use any refrigerants
- IDEC can be used as pre coolers for Air Handling/Air Conditioning units. This will reduce the refrigeration load on the compressors, thus saving energy.
- IDEC helps to satisfy base cooling load under partial loading conditions. This will be free cooling, eliminating the need for refrigeration.

System Disadvantages:
- If stand-alone indirect evaporative cooler is installed, a whole air distribution system may need to be modified because the required airflow is increased
- The moist air must be exhausted properly. Moisture accumulation inside the building will help in mould build up, which can cause serious health issues for the occupants
- The water sump needs continuous monitoring to algae and mineral built up

System Applicable in India:
Hot dry climate in the western part of India provides an ideal climate for IDEC systems.

System Implementation Constraints:
IDEC uses water for cooling. The water availability in the hot dry climate may become an issue. The user needs to be properly informed about exhausting the moist air and maintaining the water sump.

9.2.2 Night Cooling through Natural Ventilation

Night cooling through natural ventilation is an effective no-cost strategy for ventilative cooling. In terms of building components, it only requires intentional positioning of operable windows or openings in the building design to facilitate movement of outdoor air inside the building.

However, effective cooling though natural ventilation at night requires low nighttime Dry Bulb Temperature to ensure that outdoor air replacing the indoor air during ventilation is cooler. This strategy is also effective in lowering internal loads and maintain them in a periodic cycle. Since natural ventilation will regulate the indoor air at nighttime, use of air-conditioners can get restricted to few hours during the middle of the day.

Certain factors that may hamper the effectiveness of night-time cooling by natural ventilation are listed below:

- Humid conditions during the day or night restrict the cooling effect of ventilation
- External pollution/ noise may cause displeasure upon opening windows. The discomfort from these elements may not compensate for the ventilative cooling effect. Additionally, pollution essentially prevents lowering of nighttime DBT as the particles may contribute in trapping the radiative heat emitted by earth’s surface.
- Deep plan floor plates affect the movement of air flow within the deeper spaces of the building and hence, evaporative cooling may not contribute in even cooling of all spaces.

Good air contact with thermal mass and unobstructed air flow paths significantly increase the efficiency of night cooling through natural ventilation.

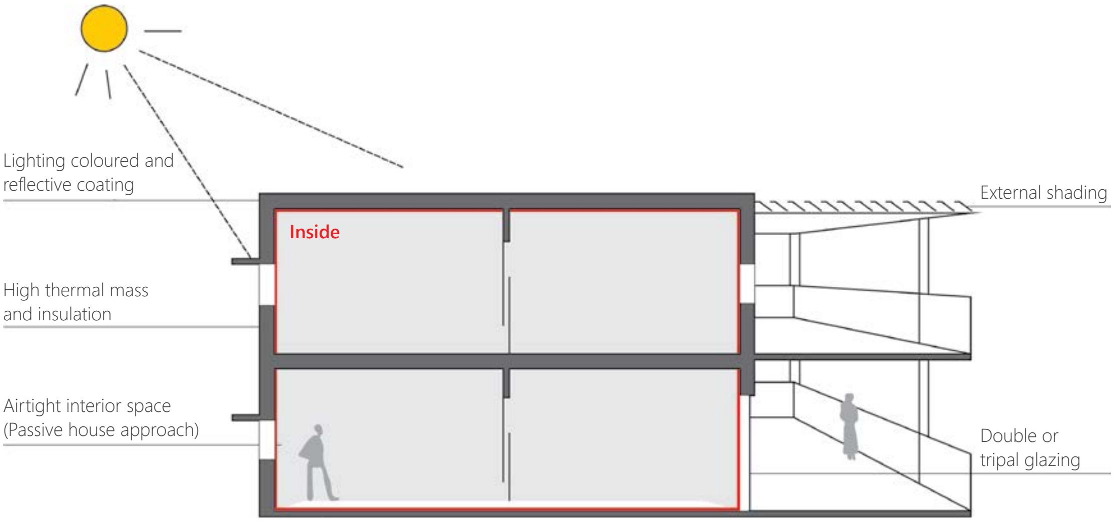


Figure 173: Night cooling through natural ventilation

9.2.3 Night Cooling through Mechanical Ventilation

Mechanical ventilation-based cooling at night refers to use of air motion devices such as fan to force outside air to enter indoors and generate cooling effect within the building or space.

In addition to the favourable factor of low night-time DBT, also required in night cooling through natural ventilation, mechanical ventilation also requires uninterrupted electricity supply for continuous ventilation induced cooling effect. It exhibits the same advantage of less and periodic internal loads, however, the use of fans, etc also adds to the operative loads of the building. When compared to the savings it incurs in operative load during the daytime, it emerges as a beneficial trade-off.

Certain factors that may hamper the effectiveness of night-time cooling by mechanical ventilation are listed below:

- No possibility of fresh air intake
- The forced motion of air through mechanical ventilation requires a certain volume of the space to be effective. If the building has low floor to ceiling height, adequate air movements or drafts, pressure differences may not be created, thereby reducing the cooling effect.
- Additionally, the poor insulation or low thermal mass of walling materials can also reduce the effectiveness of cooling effect of mechanical ventilation at night.

Studies indicate that under favorable conditions, this system can offset ~20-30 W/m^2 heat gains using fans having low energy consumption.

System Description:

In night cooling by mechanical ventilation, the temperature of the building thermal mass is reduced by ventilating the building during night-time. For the night-time ventilation the cooling equipment can be operated low capacity. But the fans will operate at normal speed to increase the air flow.

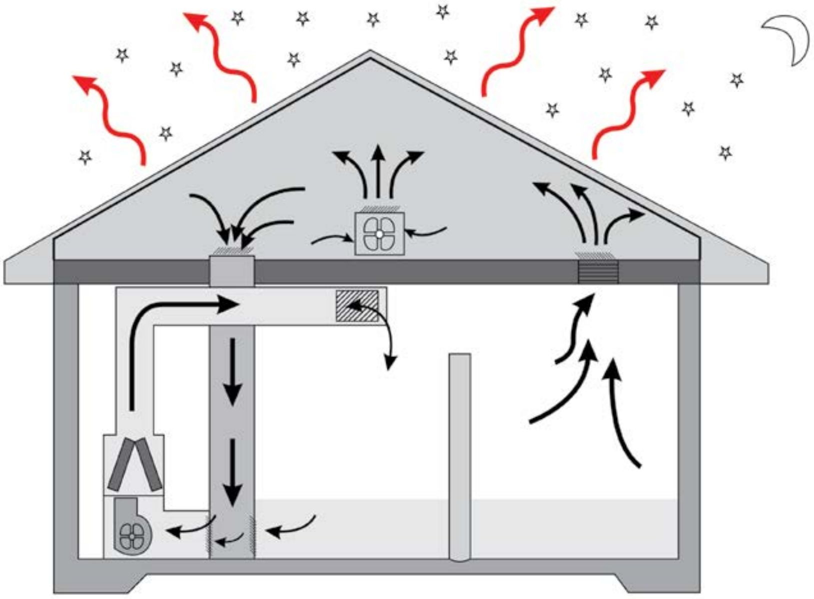


Figure 174: Night cooling through mechanical ventilation

System Components:
Existing building cooling equipment.

System Advantages:
The advantages of this strategy are:

- The thermal mass of the building envelope will be cooled
- This will be achieved by running the cooling equipment at low capacity and relatively higher temperature
- The Air flow through the zones will increase
- By night cooling the building the cooling load on the cooling equipment will reduced thus saving peak energy demand.

System Disadvantages:

- There will increase in fan energy consumption.
- With the increase fan speed there will be a risk of draught.

System Applicable in India:
Since this is a strategy or a method which can be used with the existing system, the applicability will be settled with the selection of the system.

System Implementation Constraints:
The installed mechanical cooling system needs to reprogram to operate according to the logic specified above. The installed equipment should have programmable controllers. If they, don't it will very difficult to implement this strategy.

9.2.4 Desiccant Cooling Systems

Desiccant cooling system rely on materials capable of absorbing moisture from the air. It is noteworthy that all materials have a limit to their moisture absorption capacity. Once saturated, the desiccant materials must be refreshed i.e., they require periodic charging to ensure maximum efficiency in moisture absorption. They are highly useful in warm and humid climate where relative humidity of indoor air needs to be regulated for effective cooling.

Availability of waste heat or affordable thermal source is helpful in regenerating the desiccant material by releasing the collected moisture. Hence, they also function in hot and dry climate. Additionally, this technology requires minimal electrical energy.

Certain factors that may hamper the effectiveness of desiccant cooling technology are listed below:

- In dry climate, the system works well in provide cooling. However, maintaining precision in temperature and humidity conditions may be difficult due to the limitations in moisture absorption capacity.

Combining desiccant cooling systems with night cooling and/or displacement ventilation is more effective strategy for cooling than operating desiccant cooling system as standalone cooling system.

Occasionally, it is possible that mechanisms for regeneration of desiccant material i.e., use of waste heat may act as additional heat gains in the space. Therefore, they must be

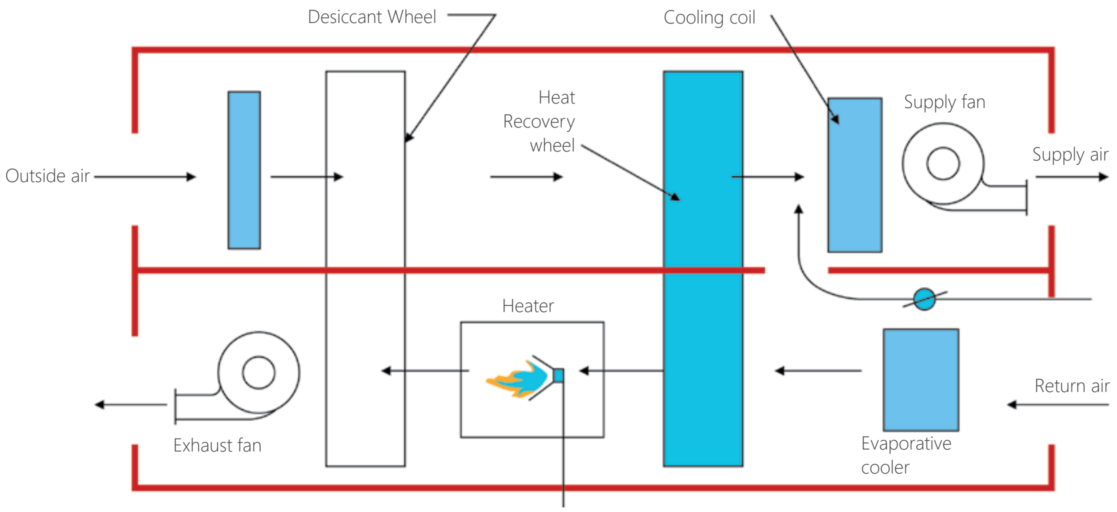


Figure 175: Desiccant cooling systems

accounted for in the initial design of the desiccant cooling system to avoid inefficiency in operation.

System Description:

Desiccant cooling system is a low energy and potentially clean cooling system. Desiccant cooling is a heat driven cycle unlike conventional AC units which use electrical energy for cooling. The above schematic shows a desiccant cooling system which combine dehumidification (desiccant wheel), heat recovery, cooling coil, evaporative cooler, and heating to create a cooling process which can offer energy savings compared to conventional air conditioning systems. Since it is driven cycle clean energy sources like natural gas, solar energy and waste heat from other equipment can be used for regeneration of the desiccant wheel. Desiccant wheel is used to reduce the outdoor air humidity. The hot dry air passes through a heat recovery wheel which absorbs heat and reduce the dry air temperature to provide cooling. Desiccant wheel can also be used with conventional cooling coil in which desiccant wheel will provide dehumidification and cooling coil will provide cooling required.

System Components:

- Desiccant Wheel
- Heat Recovery Wheel / Cooling Coil
- Heat Source for regenerating the Desiccant Wheel
- Supply Fan
- Exhaust Fan

System Advantages:

- Desiccant Cooling System uses heat cycle for cooling. Heat source can be clean energy source as natural gas, solar energy and waste heat
- Desiccant wheel and heat recovery wheel can be used in tandem. Incoming warm-humid air can be dehumidified and cooled.

System disadvantages:

- Desiccant wheel needs to be recharged regularly
- The system needs continuous monitoring for the desiccant wheel effectiveness
- Effective only at large sites like pharmaceutical industries, supermarkets, cold storage

System Applicable in India:
Desiccant cooling system is applicable only in warm-humid conditions. The entire coastline of the country has this climate. So, this system can be applied in India. Combined with solar energy they form a very good system for large facilities.

System Implementation Constraints:

- Applicable only for large scale facilities which require very tight tolerance.

9.2.5 Displacement Ventilation

Displacement ventilation strategy uses natural gravitational movement of air having variable heat energy levels. In this system, the cool air is supplied from vents in the floor or from areas of wall closer to the floor. As this cool air absorbs heat from the space, its density reduces, allowing it to naturally rises and reach the ceiling in convective air flow. This exhaust air is later removed from vents in the ceiling.

One advantage of this system is that fresh air is made available closer to the occupants than in the case of conventional systems. Secondly, the amount cooling delivered in the supply air is usually lower than in the case of supply air vents located in the ceiling. Thus, operation costs of this technology are lower. In cases where indoor temperature is high, slightly warmer air may work more effectively than cold air to remove further heat from the space as it dependent on the time available for heat absorption. Displacement ventilation technology requires surface temperature at heat source to be around or greater than 35 °C.

Certain factors that may hamper the effectiveness of displacement ventilation are listed below:

- Since the air moves from floor to ceiling it requires slightly higher airflow than the conventional systems which may also result in some noise generation.
- Typically, displacement ventilation requires high ceiling for the air to obtain enough time for creating cooling effect. Additionally, carefully calibrated wind speeds must be generated to avoid discomfort in occupants from air velocity or draft. Similarly, it also needs low-velocity terminals at a supply end.

The technology must be designed to achieve an ideal supply air temperature of 18 ° C and the vertical temperature gradient should be maintained below 1.5K.

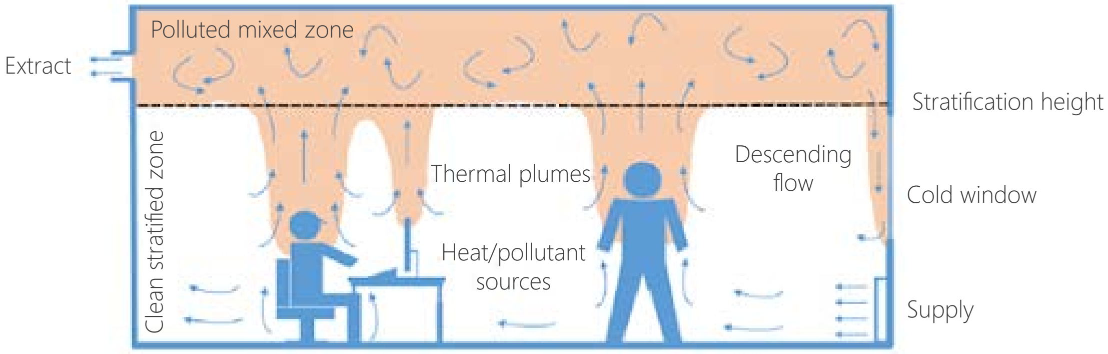


Figure 176: Displacement Ventilation
Source: (Javed, Ornes, Dokka, Myrup, & Holos, 2021

System Description:
Displacement Ventilation (DV) uses a low velocity moderately cold air supplied to the zones using diffusers. These diffusers are located on the walls at the floor level of the zone. The diffusers can be located on the raised floor of the zone also. The cold air which will be heavier will spread slowly across the zone. As the cold air spreads, it displaces warm air to the ceiling where it will be exhausted to the air handler.

As the cold air in the zone gains heat it gets lighter and start raising towards the ceiling. As the air moves up, it will take the pollutants in the zone along with it. DV systems can handle moderate cooling loads. Like a small office building, conference rooms, etc.

System Components:
- Roof Top Air Handling Unit
- Supply Air Diffuser Column
- Exhaust Grill

System Advantages:
- Energy Efficient
- Cold Supply Air (SA) is supplied at relatively higher temperature compared to a conventional system.
- Use low horse power fans
- Quite Operation
- Using higher SA temperature increases Air Handling Unit economizer potential
- Improved air quality in the occupied area

System Disadvantages:
- It can handle only moderate cooling loads
- Wall-mounted diffusers occupy large part of the wall
- Risk of draft if the diffusers are not placed properly
- Cannot be used for heating, needs a separate heating system.

System Applicable in India:
The system is suitable for low to moderate cooling loads. It suits well for temperate and composite climate zones.

System Implementation Constraints:
Applicable only for moderate loads. For large facilities it has to be supplemented with other systems.

9.2.6 Ground and Aquifer cooling

The temperature of earth beyond a certain depth (3 m in most cases) remains constant in comparison to the air just above or near ground. This is because of the high thermal mass of the soil or earth which heavily inhibits heat transfer. This constant temperature can be used to regulate indoor air all throughout the year to maintain thermal comfort inside the buildings. With the use of fans, untreated air is blown in the earth tunnels for conditioning. Once regulated, it is distributed indoors to achieve thermally comfortable indoor temperatures.

If ground temp is below 12°C, it allows earth to be used as heat sink. The presence of flowing water in the ground may add to the cooling capacity of the system in terms of air volume.

Certain factors that may hamper the effectiveness of ground and aquifer cooling are listed below:

- Rock / Solid ground: The thermal conductivities of different types of soil affect the cooling capacity and optimization of depth of earth tunnel required. If the earth is rocky, constructing air tunnels in the ground can be a challenge.
- This technology offers little precision and limited opportunity to regulate the relative humidity of the conditioned air. The capacity of cooling
- Additionally, moving the air through a large distance and allowing it to condition before distribution translates into slow response time

This technology is most useful as a pre-cooling strategy to reduce the internal loads of the building and avoid reliance on less precise conditioning of air for thermal comfort.

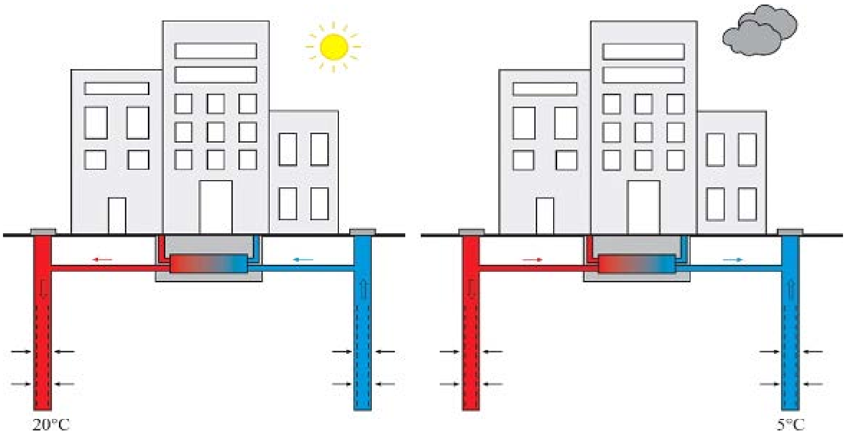


Figure 177: Geothermal ground coupling

System Description:

The geothermal aquifer system is considered as an open-loop system. In this system 2 wells are drilled below the water table of the site. First is the production well from where the water for cooling/heating is sourced. The water is pumped through the heat exchanger located inside the building. The hot/cold water depending on the system state i.e., cooling or heating mode, is rejected into second wall called injection wall. Since the source water is used only once, the system is considered open loop.

System Components:

- Production and Injection Wells
- Ground Loop Pipes
- Heat Exchanger
- Circulation Pump
- Air Handling Unit

System Advantages:

- Renewable. Aquifers are naturally replenished.
- Custom man-made wells can be constructed for the purpose. This can be replenished using rainwater.
- Environment Friendly. No harmful chemicals used. Water is used as cooling/ heating medium.

System Disadvantages:

- High water usage. The water will be discarded after just one run. Additionally, using this for heat pump is not considered wise use of the ground water
- The risk of contamination is an increasing concern. Improperly installed wells or plumbing can be a path to carry pesticides, fertilizers, organic materials, and other contaminants into underlying aquifers.
- Open-loop systems that discharge warmed water may have an impact on surface-water quality, plants, fish, and winter oxygen levels.

System Applicable in India:

Most of the urban and semi urban areas in India source drinking water from underground aquifers. The aquifers supplement the water coming from rivers and lakes. Here, using the aquifers for cooling/heating is not considered a good idea. However harvesting rainwater facilitates implementation.

System Implementation Constraints:

Initial cost of the system is still very high. The ground source water is used majorly for drinking in India. Using this for cooling and discarding only after one used will be considered waste and is a wise use of the precious resource. The technology is pretty new and there may be very few installations in India as of now. So there is lack of skilled manpower available.

9.2.7 Chilled Ceiling and Beams

This technology utilizes radiative and convective heat transfer mechanisms to effectively manage sensible loads of an indoor space. Active and Passive chilled beams are two categories that differ in terms of presence of nozzle blowers to aid the convective motion of air for greater efficiency in cooling.

Chilled ceilings differ from chilled beams in that they rely more on radiant heat exchange as opposed to convective heating and cooling. A chilled ceiling is a metal sheet with water pipes running above it. The pipes heat or cool the metal panel, which then radiates that energy toward the building occupants.

The chilled ceiling and beam technology is a highly efficient system that manage sensible loads well with low electrical energy consumption.
Certain factors that may hamper the effectiveness of cooling by chilled ceiling and beams are listed below:

- The surface temperature of chilled beams and ceilings must be controlled to avoid risk of condensation and water leakage situations must be avoided.
- Chilled ceiling and beams technology does not include an air exchange system with is essential for maintain indoor air quality
- The system does not cater to latent loads and hence must be used in combination with another system in spaces where latent loads are high.

System Description:

Chilled beams are building heating/cooling system. Chilled beams are heat exchangers attached to the ceiling. Chilled beams are classified into 2 types:

- Active Chilled Beams
- Passive Chilled Beams

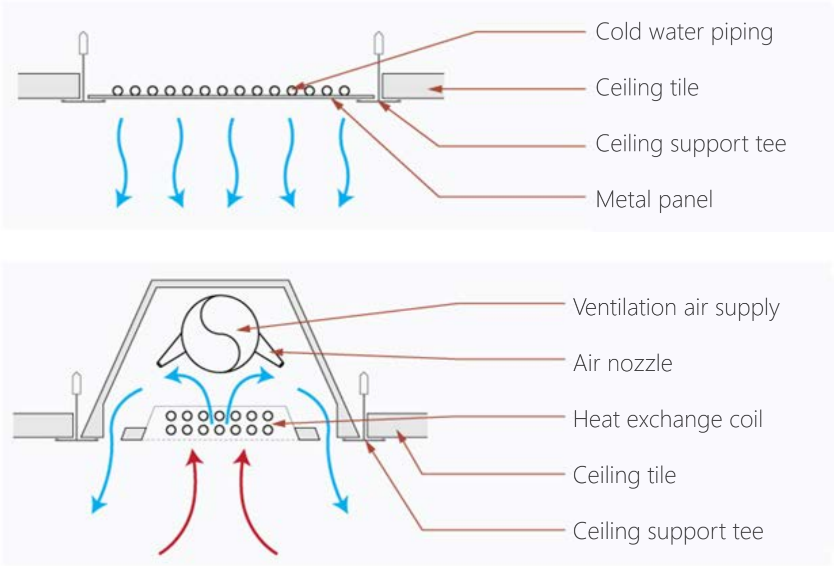


Figure 178: Chilled ceiling and beams.
Source: Ehrlich, B. (2010, March 31). Active Chilled Beams: Saving Energy and Space. Retrieved from https://www.buildinggreen.com/product-review/active-chilled-beams-saving-energy-and-space

The name active chilled beam is used in the context of using the chilled beam for both cooling and heating. In active chilled beams the return air from the zones are forced through the cooling/heating coils into a primary air duct. The primary air duct will have a ventilation fan, which distribute the air uniformly across the zone. The ventilation fan is more useful when the chilled beam is in heating mode. The ventilation fan will push the light hot air across the zone.

Passive chilled beam will be used only for cooling. In passive chilled beam the warm and light return air is passed through the cooling coil. The cold and heavy supply air will enter the zone through diffusers. The entire process of air movement takes place through natural draft.

System Components:
The Passive chilled beam will have the following components:

- Ceiling installed chilled water coil
- Pump for circulation chilled water through the coil
- Air Handling Unit
- Chiller
- Boiler

The Active chilled beam will the following components:

- Ceiling installed chilled and hot water coil
- Pump for circulation chilled and hot water through the coil
- Ventilation fan for effective air distribution

System Advantages:

- Active Chilled Beams:
- The term active indicate that the coil is linked with the ventilation fan
- System can be used for both cooling and heating
- Uses water as the cooling medium, no harmful refrigerants

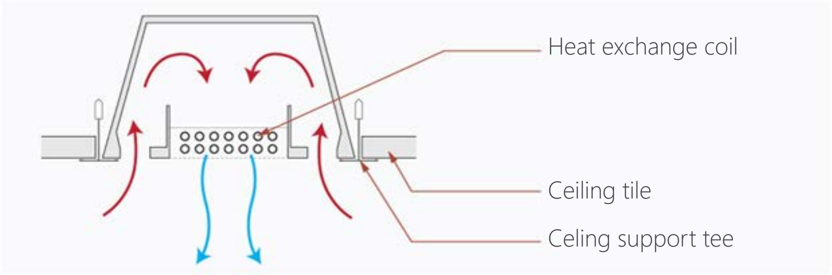


Figure 179: Chilled beam

- Uses high velocity ventilation fan to force hot air across the zone in heating mode
- The ventilation air is blown through high velocity nozzles back into the zone
- Does not require duct work for air distribution
- Since the cooling is only sensible no condensate drain is required

Passive Chilled Beams:

- The passive chilled beams will not have ventilation fan
- System can be used only for both cooling
- Uses water as the cooling medium, no harmful refrigerants
- System will have very quiet operation as it has no fans
- Does not require duct work for air distribution
- Since the cooling is only sensible no condensate drain is required

System disadvantages:

- Chilled water beams requires accurate control of chilled water temperature and flow through the coils.
- For active chilled beams the static pressure requirement is quite high to achieve uniform distribution
- Requires careful planning to get the system right
- Still a predominantly and European technology, not enough expertise available for accurate installation.
- For active chilled beams some kind of sound masking is essential to isolate the fan sound
- Passive chilled beams are used for cooling only. A separate heating system will be required

System Applicable in India:

The chilled beam systems are installed along with an Outside unit. The outside units can be a chilled water plant and cooling tower to cool the warm water returning from the beams. The chilled beam can be used in hot-dry and cold weather conditions.

9.2.8 Radiative Cooling

Radiative cooling is a relatively new technology that uses material property of emissivity. The building envelope component receiving the highest amount of direct solar radiation is roof. Hence, cutting down radiative heat transfer in the indoors through roof is a highly effective strategy to lower cooling loads. Termed as radiative cooling, this concept includes covering or coating roof surfaces with tiles, paints or materials having SRI values to increase the amount of radiation reflected by the surfaces. Since this radiation is directly reflected in the same wavelength as incident radiation, deep sky becomes the heat sink in this system. Radiative heat transfer to surrounding environment is therefore minimized. Hence, radiative cooling is highly effective in managing sensible loads.

Certain factors that may hamper the effectiveness of radiative cooling are listed below:

- The effectiveness of this system is dependence on sky conditions. Higher the sky view factor, greater is the radiative heat reflected in deep sky.
- Presence of pollution and particulate matter in air may diffuse the reflected radiation and trap them in the surroundings of the coated roof surface and building.
- On occasions with low sky view factor or high pollution particles in air, heat gain and losses should be calculated to ensure that the system is functioning in a net heat loss scenario.

The technology can be used in combination with other effective strategies to ensure sufficient cooling for thermal comfort on days of low performance.

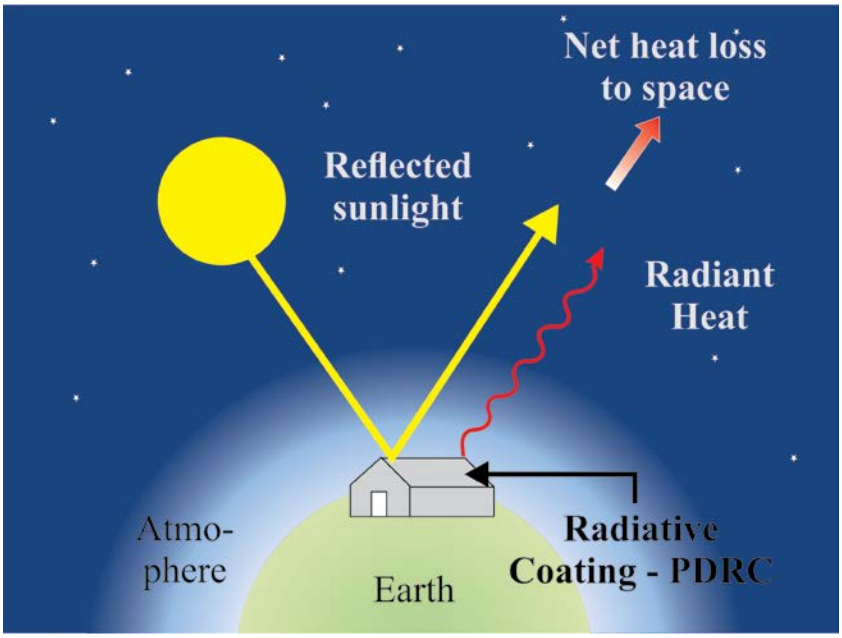


Figure 180: Radiative Cooling

9.2.9 Radiant Structural Cooling

In this technology, chilled water pipes are embedded in the structural system of the building i.e., either roof or walls. Cooling tower or vapor compression cycle is used to maintain the supply temperature of water at 17°C with a return temperature of 20°C which is higher than conventional systems having 7°C supply temperature and 12°C return temperature. Heat transfer predominately occurs through surfaces like floors, ceiling, or wall which in turn are heated or cooled by embedded coils. Radiant systems are installed in combination of large thermal mass to facilitate absorption and radiation. For optimizing performance of the systems, coils should be installed in floors for heating purposes, and in ceiling for all cooling purposes. However, improperly installed systems can lead to condensation on the building structural elements.

This technology is effective in maintain low nighttime DBT of the space by ensuring cooling of the structural system and providing additional resistance to the conductive heat transfer through the thermal mass of the envelope or structural system. This in turn results in less and periodic internal loads similar to nighttime cooling with ventilation strategies. It however requires uninterrupted electricity supply to ensure that desirable water temperatures are maintained.

Certain factors that may hamper the effectiveness of radiant structural cooling are listed below

- No possibility of fresh air intake in this system renders it ineffective in providing air changes required for good indoor air quality.
- Low ceiling to floor height may increase inefficiency of the system and lead to local thermal discomfort in occupants
- Lastly, poor insulation or low thermal mass of the envelope may allow the coolth to escape.

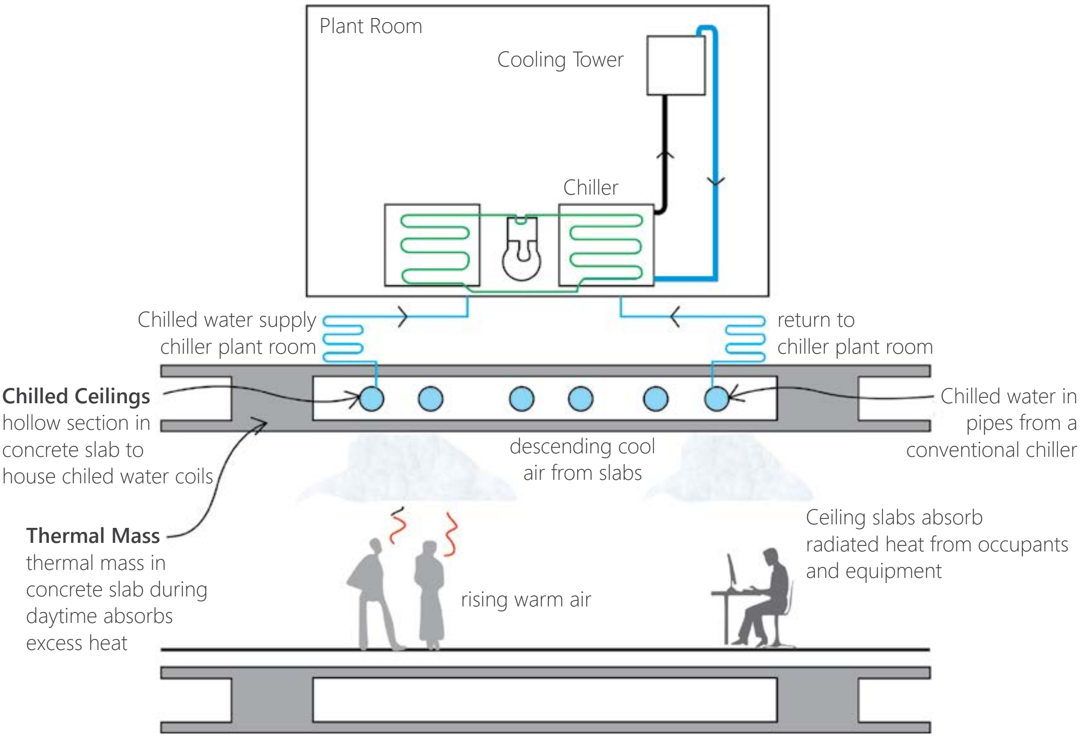


Figure 181: Radiant structural cooling

9.3. Rating Steps and Standards

9.3.1 Energy Efficiency Ratio calculation steps

This section explains the procedure to determine the energy efficiency of the cooling technology. The DBT, WBT and pressure conditions at the inlet and outlet of the low energy cooling technologies should be measured to derive the enthalpy, specific volume and relative humidity values of the indoor air using a psychrometry chart or table. Measuring the flow rate of air determines the total cooling capacity of the technology. This amount of total cooling load delivered is bifurcated into sensible and latent cooling capacity by either measuring the latent cooling capacity directly or removing calculated sensible cooling capacity from the calculated total cooling capacity. This feeds into the calculation for dehumidification capacity, and subsequently the power consumption is measured to obtain Energy Efficiency Ratio (EER) of the test unit.

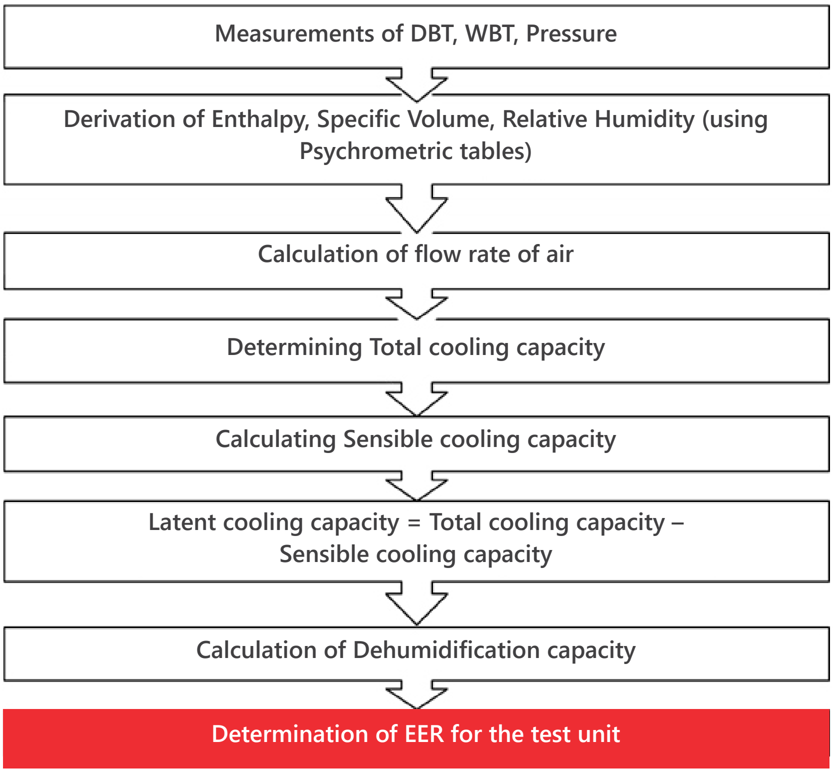


Figure 182: Steps for rating as per standards

9.3.2. Reference Standards

Country specific standards for evaporative cooling systems (not included in the table) are available in various parts of the world

Table 37: Reference standards for testing HVAC systems

Standard	Scope
AHRI 340/360	Performance testing of commercial and industrial unitary air conditioning and heat pump equipment (up to 65,000 Btu/h)
ASHRAE 37	Performance testing of electrically driven unitary air conditioning equipment (less than 65,000 Btu/h)
ASHRAE 116	Determining seasonal efficiency of unitary air conditioning equipment
ASHRAE 16	Performance testing of room air conditioners and packaged terminal units
IS 1391 – 1	Performance testing of room air conditioners – unitary air conditioners (from 6000 Btu/h to 35,000 Btu/h)
IS 1391 – 2	Performance testing of room air conditioners- split air conditioners (12,000 Btu/h to 65,000 Btu/h)
AHRI 1230	Performance testing of variable refrigerant systems (VRF) and heat pump equipment (12,000 Btu/h to 65,000 Btu/h)
AHRI 210/240	Performance testing of unitary air conditioning and heating pump equipment (capacities less than 65,000 Btu/h)

9.4. Case Studies

Food manufacturing facility in Nadiad, Gujarat; Total system capacity- 30,000 CFM

Figure 183 and Figure 181 show that the supply air temperature variation is nearly 5-6 °C and the RH level fluctuates within 30-35% range from 12h00 to 18h00 hours. Considering wet bulb effectiveness (Figure 183), the variation is quite high (25%-100%) and the system takes nearly one hour to stabilize. On the other hand, the energy consumption (Figure 184) throughout the day is constant.

Figure 187 and Figure 188 show that at 35°C, base case system consumes high amount of energy to provide maximum comfort indicated by 0.2 on the PMV scale. Standalone DEC systems indicate the opposite scenario of low energy consumption and less comfort. However, hybrid systems comprising of base case and DEC combination are capable of providing slightly higher thermal comfort with relatively lower energy consumption. As the humidity levels change, energy consumption of compared cases increase significantly to maintain thermal comfort of same level.

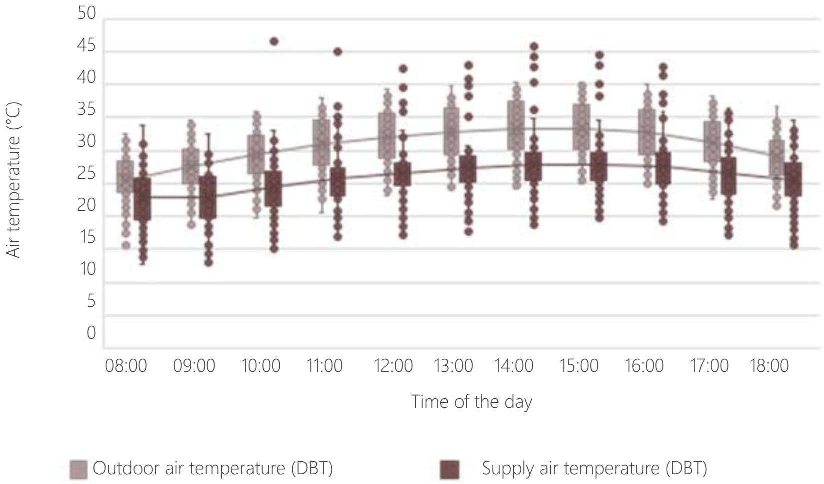


Figure 183: Graph showing outside and inside DBT range from July to Dec for operating hours

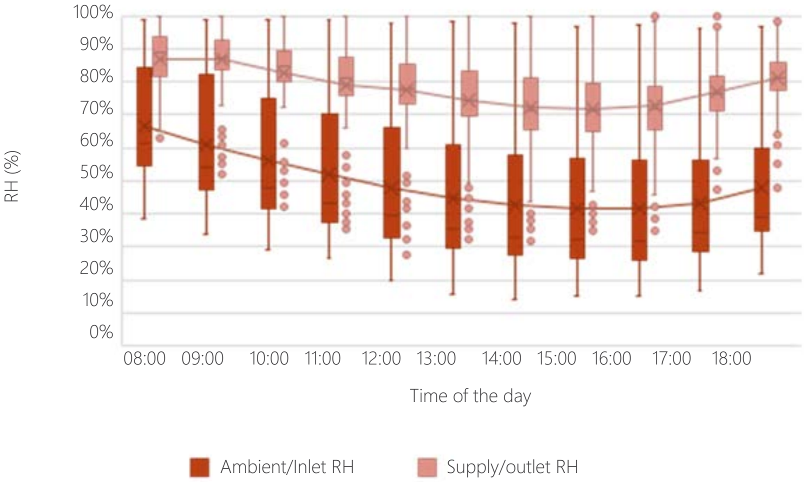


Figure 184: Graph showing outside and inside RH range from July to Dec for operating hours

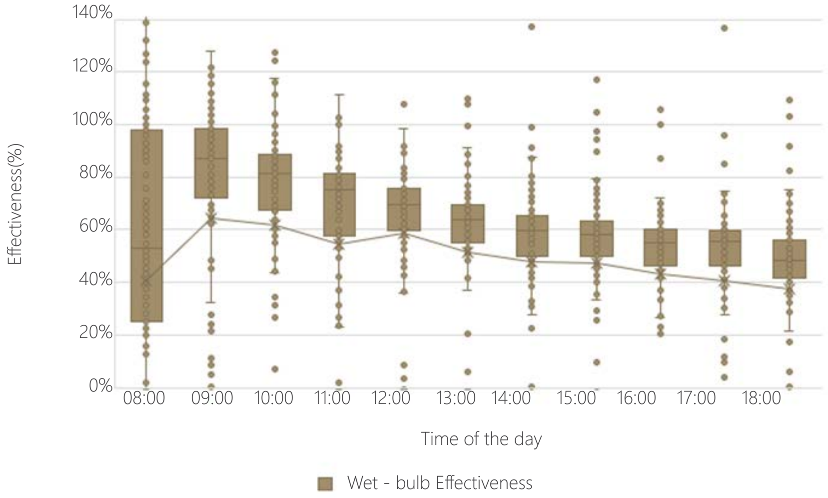


Figure 185: Graph showing Wet Bulb Effectiveness range from July to Dec for operating hours

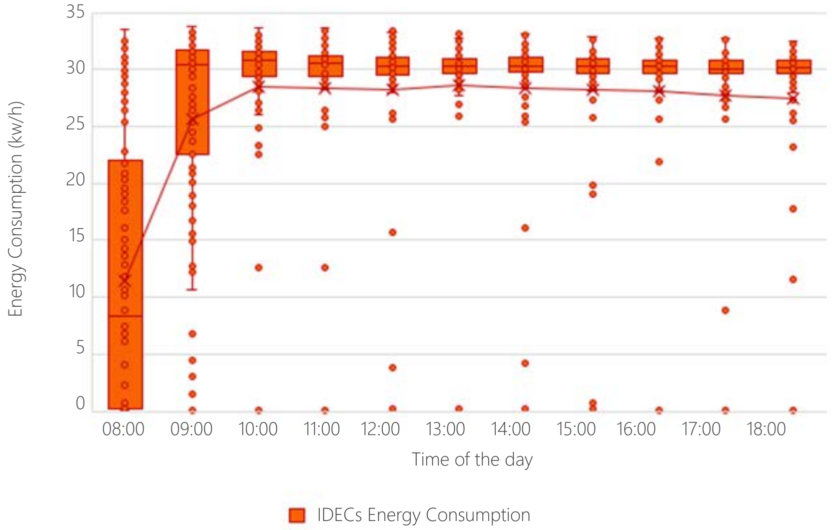


Figure 186: Graph showing energy consumption range from July to Dec for operating hours

Following observation and conclusions can be made from Figure 189:

- Smart control algorithms reduce energy use by 10-25% compared to current operational practices
  - Comparison is performed with on/off low energy cooling systems
  - Fan speed modulation significantly reduces power consumption especially when cooling needs in the space are low
- Smart control increases comfort by 0.5 to 1.0 PMV
  - Increased air velocity in the space further improves heat loss
  - Maintains sensible heat dissipation of Manikin but needs to avoid the draft
  - Humidity control of low energy cooling system is effective

Hybrid systems reduce energy consumption by 30-40% due to capacity reduction of the baseline system and maintain comfort throughout the year

- Smart control algorithms vary suitable for control of hybrid systems

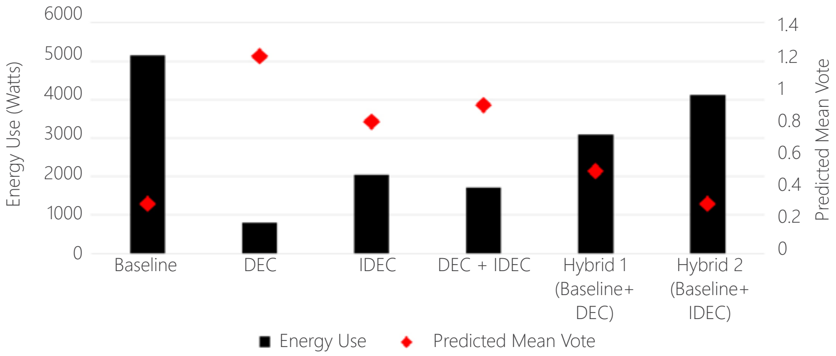


Figure 187: Energy use and comfort for five ton cooling system at 35°C and 50% RH

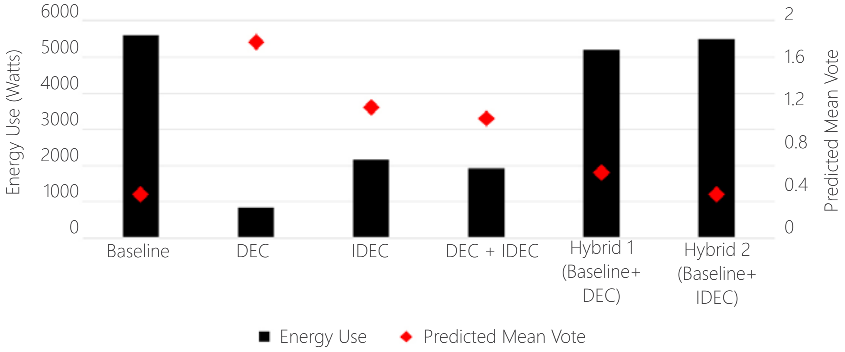


Figure 188: Energy use and comfort for five ton cooling system at 35°C and 75% RH

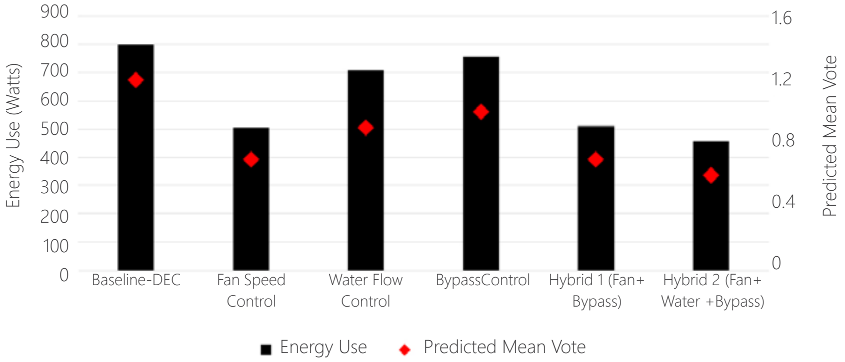


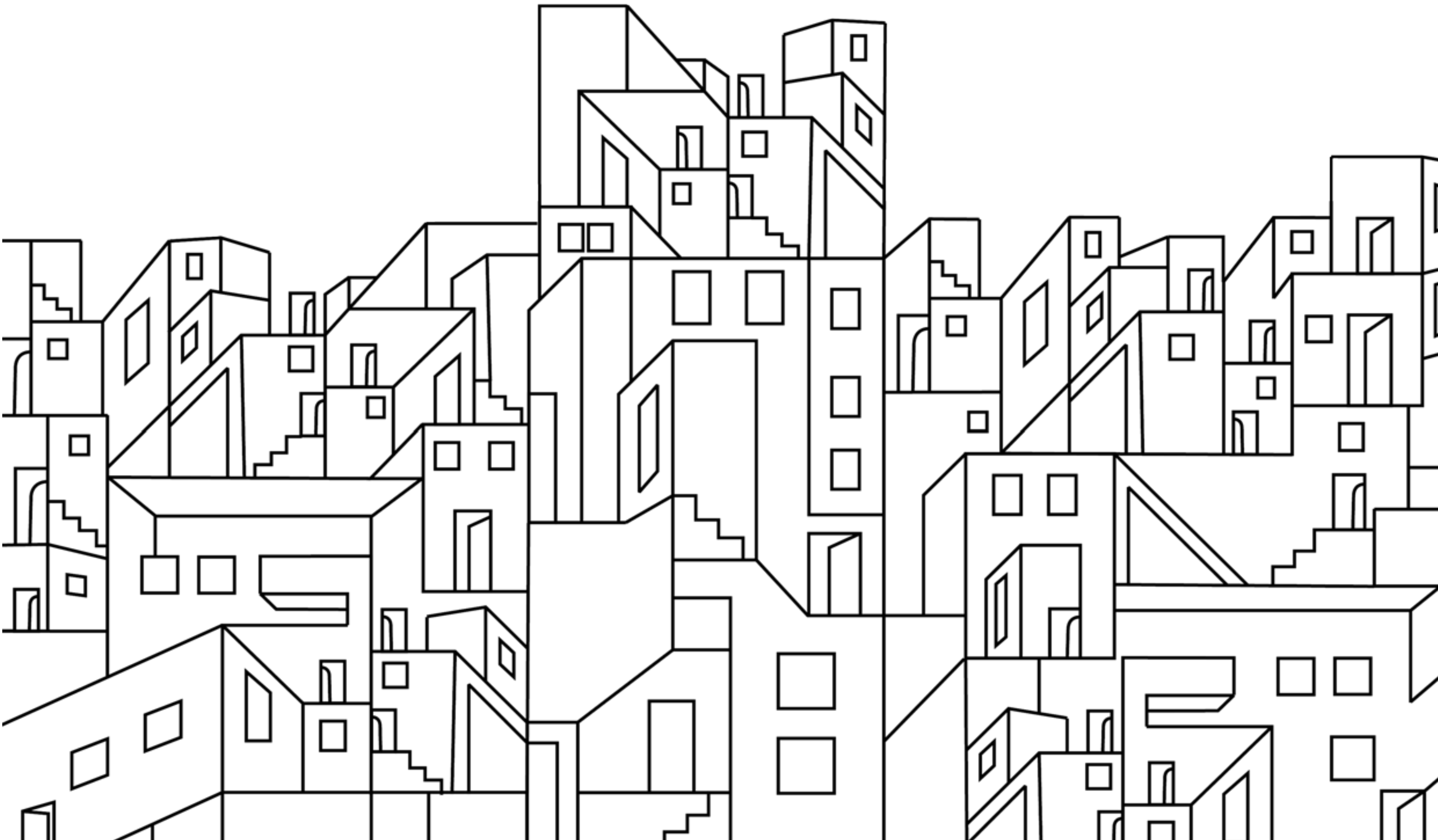
Figure 189: Energy use and comfort for control algorithms

Disclaimer

The content of this chapter is based on the work originally supported by Shakti Sustainable Energy Foundation Grant No. 1503 – 50681, during 2014 – 2015 and its deliverable report (Rawal & Shukla, 2015)

10

QUIZ



1. **Thermal Comfort depends on environmental parameters such as:**
    a. Air temperature
    b. Relative Humidity
    c. Air Velocity
    d. Globe Temperature/MRI
    e. All the above
    f. A and b

2. **Mean Radiant Temperature can be:**
    a. Measured
    b. Guessed
    c. Evaluated
    d. Fixed

3. **In rooms with different surface temperatures, MRT**
    a. Remains same
    b. Increases at centre of the room
    c. Decreases at centre of the room
    d. Changes with spatial location in the room

4. **The core body temperature of humans**
    a. Oscillates with ambient temperature differences
    b. Is maintained in close limits to the operative temperature
    c. Typically, around 37°C
    d. Typically, around 40°C

5. **Lack of thermal comfort may cause**
    a. Elevated heart rate
    b. Unconsciousness
    c. Loss of concentration
    d. Fatigue
    e. All the above

6. **If relative humidity is 100%,**
    a. DBT> WBT
    b. DBT<WBT
    c. DBT=WBT
    d. Relative humidity is never 100%

7. **Expression for steady state heat transfer between outdoor air to indoor air is**
    a. $hA\ (T_{outdoor} - T_{indoor})$
    b. $kA\ (T_{outdoor} - T_{indoor})$
    c. $UA\ (T_{outdoor} - T_{indoor})$
    d. $RA\ (T_{outdoor} - T_{indoor})$

8. **In the northern hemisphere, solar radiation is the highest for a surface oriented**
    a. East

   b. West
   c. North
   d. South

9. **In sensible cooling process, the humidity ratio**
   a. Decreases
   b. Increases
   c. Remains constant
   d. Reaches its maximum value

10. **For retaining heat, the U- value should be**
   a. High
   b. Low
   c. Does not matter
   d. Moderate

11. **Double glazed units (DGUs) mainly reduce heat transfer due to**
   a. Conduction
   b. Convection
   c. Radiation

12. **For a surface with higher emissivity, heat loss by radiation will be**
   a. Lower
   b. Moderate
   c. Higher
   d. Independent of emissivity

13. **Thermal environment of a building (post occupancy) is more commonly evaluated by the metric-**
   a. Thermal acceptability
   b. Thermal satisfaction
   c. Thermal comfort

14. **Existing guidelines of thermal comfort in India are based on**
   a. Heat balance model
   b. Adaptive thermal Comfort Method
   c. Combination of both
   d. None of the above

15. **For comfort ranges to comply with standards, all occupied spaces should have PPD less than**
   a. 10%
   b. 20%
   c. 30%

16. **Thermal comfort at higher temperatures can be achieved with (You can choose more than one option!)**
   a. Lower air velocity
   b. Higher air velocity
   c. Higher relative humidity

d. Lower relative humidity

17. **What causes more discomfort?**
    a. warm wall
    b. warm ceiling
    c. cold wall
    d. cold ceiling

18. **Air temperature difference between the head and ankle should not be more than**
    a. 1 °C
    b. 3 °C
    c. 5 °C
    d. 7 °C

19. **Heat balance equation accounts for**
    a. Heat loss through respiration
    b. Evaporative heat loss from skin
    c. Heat storage in skin and core compartments
    d. All of the above

20. **External Surface to building volume ratio affects heat transfer through conduction (You can choose more than one option!)**
    a. True for all climates
    b. False for all climates
    c. High impact in hot and dry climate
    d. Low impact in warm and humid climate

21. **A building with square form (footprint) performs better in terms of heat ingress than a rectangular building with longer axis oriented east-west**
    a. True
    b. False
    c. Depends on climate of the location

22. **Vertical shading devices are best suited for which façade?**
    a. East
    b. West
    c. North
    d. South

23. **Arrange the passive design strategies in order of increasing cost-effectiveness**
    a. Glazing
    b. Orientation
    c. External Shading
    d. Natural Ventilation

24. **Horizontal Shading devices are more suitable on**
    a. East
    b. West
    c. North

   d. South

25. For reducing solar heat gains, the building's
   a. Longer axis is oriented East-West
   b. Longer axis is oriented North-South
   c. Longer axis orientation doesn't matter
   d. None of the above is true

26. In naturally ventilated spaces, comfort temperature is
   a. Lower than those in air-conditioned buildings,
   b. Same as that in air-conditioned buildings
   c. Higher than those in air-conditioned buildings

27. Glass is (You can choose more than one option!)
   a. Opaque to visible solar radiation
   b. Opaque to thermal (infrared) radiation
   c. Transparent to visible solar radiation
   d. Transparent to thermal (infrared) radiation

28. A thermal bridge__________ the overall U-value of the wall/ window assembly
   a. Reduced
   b. Increases
   c. Does not affect

29. Thermal mass works best when
   a. Diurnal temperature range is high
   b. Diurnal temperature range is low
   c. Ambient temperatures are high
   d. Ambient temperatures area low

30. Roof coating materials with high SRI values are good as they have (You can choose more than one option!)
   a. High thermal emittance
   b. Low solar absorptance
   c. High solar reflectance

31. The resistance of a multilayered wall is given by the
   a. Product of resistances of individual layers
   b. Addition of resistances of individual layers
   c. Addition of resistances of individual layers and the surface resistance on inside
   d. Addition of resistances of individual layers and the surface resistances on inside and outside
   e. Product of all individual and surface resistances

32. With the same material is it possible to have different thermal resistances?
   a. No, not possible
   b. Yes, by changing the thickness of the material layer
   c. Only if it's a phase change material
   d. Not a good question

33. **Double glazed units (DGUs) mainly reduce heat transfer due to**
    a. Conduction
    b. Convection
    c. Radiation

34. **RETV is**
    a. Independent of orientation of the dwelling unit
    b. Dependent on the orientation of the dwelling unit walls and windows
    c. Independent of the orientation of walls
    d. Dependent on glazing color

35. **Eco-Niwas Samhita ensures ventilation for residential units in terms of**
    a. Air changes per hour
    b. Openable area to floor area ratio
    c. Number of occupants
    d. All of the above

36. **Eco-Niwas Samhita is to be implemented in a similar manner as green building rating programs**
    a. True
    b. False

37. **U-value of wall**
    a. Accounts for both the climate zone of the site and wall orientation
    b. Does not account for the climate zone of the site, nor wall orientation
    c. Accounts for the climate zone of site but not wall orientation
    d. Accounts for the wall orientation but not climate one of site

38. **RETV of a building block is ___________ by the climate zone of the site.**
    a. Affected
    b. Not affected
    c. Independent
    d. None of the above

39. **Is there any lighting compliance mentioned in ENS?**
    a. Yes, prescribes lux levels
    b. No
    c. Yes, prescribes VLT of glass in relation of WWR
    d. None of the above

40. **Traditional architecture is designed to provide more thermally comfortable environment through greater number of comfort hours than conventional houses.**
    a. True
    b. False
    c. Inconclusive argument

41. **Material choices for reducing RETV result in higher cost of construction**
    a. True
    b. False

   c. Depends on project and site characteristics

42. Changing orientation of the building block(s) on site reduces RETV substantially.
   a. True
   b. False
   c. In most cases where original orientation is east-west and site is located in southern hemisphere
   d. Depends on project and site characteristics

43. In terms of building, EPI stands for
   a. Energy Potential Index
   b. Environment Potential Index
   c. Energy Performance Index
   d. Environment Performance Index

44. Shading is an effective strategy for reducing the RETV or EPI of building in hot and dry climate because
   a. It blocks direct radiation
   b. It reduces heat ingress
   c. Both of the above
   d. None of the above

45. Concrete-based construction has higher energy implications than fly ash brick or burnt-clay brick
   a. True always
   b. False always
   c. True for Indian construction sector
   d. False for Indian construction sector

46. Field studies allow researchers to measure and observe
   a. All environmental parameters known to affect thermal comfort
   b. All physical measurements such as skin temperature, core body temperature, etc easily
   c. Some physical observations related to Clo value and MET rate
   d. Psychological parameters through votes on thermal acceptance and satisfaction

47. Digital simulations studies have shortcoming such as
   a. They are not useful when studying thermal comfort in different comfort systems
   b. They are not useful when studying thermal comfort in different control systems
   c. Their output relies heavily on input and can provide results for incorrect inputs too
   d. They require expensive electronic setups

48. Thermal mannequins can be used in research related to age, gender, and ethnicity variations in thermal comfort
   a. False, because thermal mannequins are not designed to account for race, gender, and ethnicity
   b. True, because thermal mannequins designed to account for race, gender, and ethnicity are available

   c. May be

49. Shortcomings in using thermal mannequins for thermal comfort research include

   a. Requirement an extensive laboratory setup in terms of number of electrical equipment
   b. The equipment and lab set up required is expensive
   c. Reduced possibility of working with multiple natural positions and activities of human body
   d. None of the above

50. Data filtering, validation, and cleaning are additional precautionary steps usually performed before analysing the data

   a. True; Data analysis can be performed without data validation, filtering, and cleaning
   b. False; Data analysis can be performed without data validation but filtering and cleaning the data are mandatory procedures
   c. False; Data analysis can be performed without data filtering but validating the data are mandatory procedures
   d. False; Data analysis can be performed without data validation but filtering and cleaning the data are mandatory procedures

51. Radiant cooling works best in

   a. Warm and humid climate
   b. Cold climate
   c. Hot and dry climate
   d. hot and humid climate

52. Evaporative cooling is best suited for

   a. Warm and humid climate
   b. Cold climate
   c. Hot and dry climate
   d. hot and humid climate

53. For radiant cooling, nighttime sky conditions should be

   a. Cloudy
   b. Clear
   c. Dark
   d. Foggy

54. In sensible cooling process, the humidity ratio

   a. Decreases
   b. Increases
   c. Remains constant
   d. Reaches its maximum value

55. Ground cooling technology cannot offer

   a. Regulation of relative humidity without additional system
   b. Quick cooling
   c. Precision in temperature control
   d. All of the above

56. Low energy cooling technologies___________chemicals with global warming potential

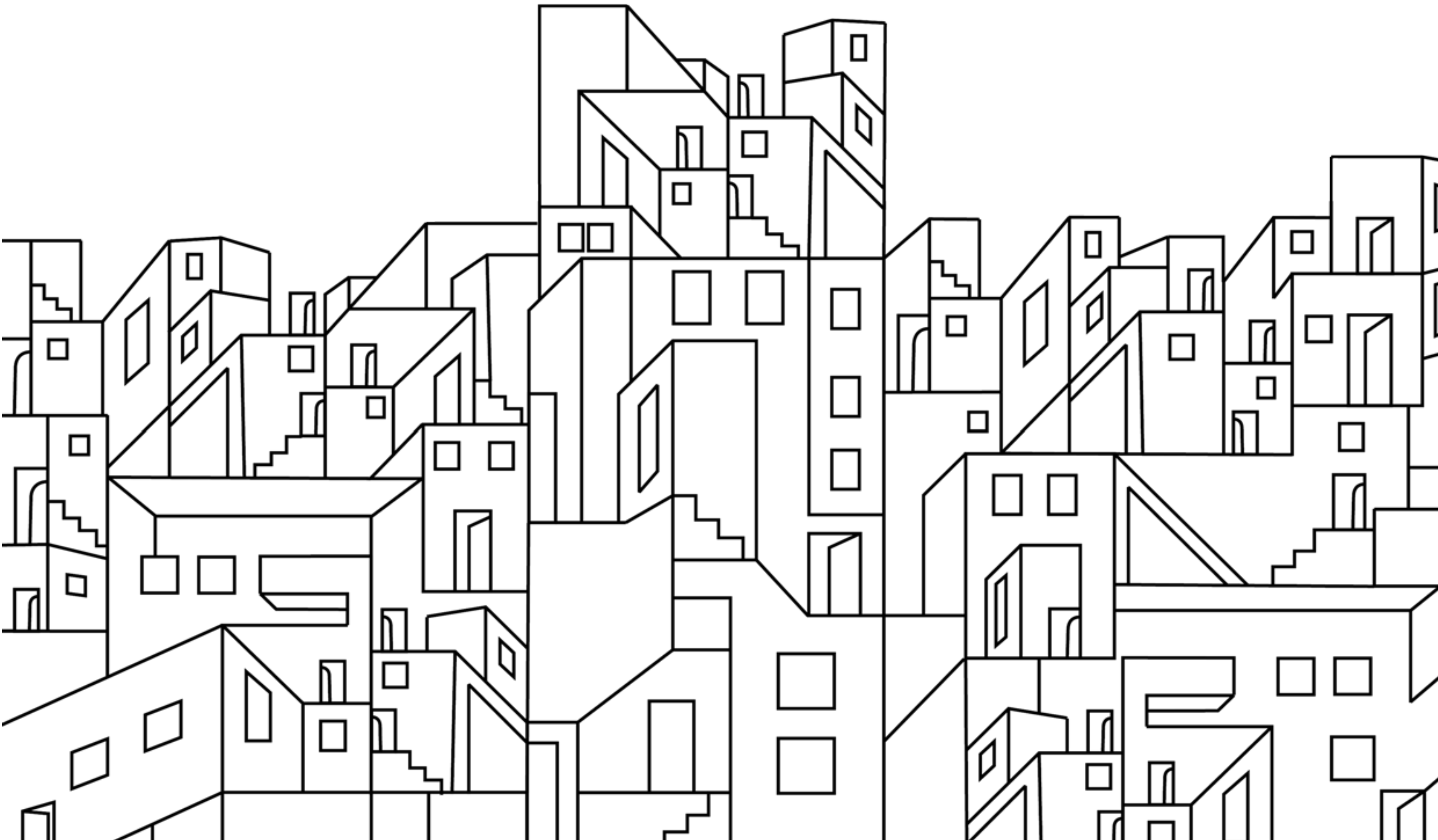
   a. Always contain
   b. Occasionally contain
   c. Have nothing to do with

57. Diffusers in displacement ventilation cooling technology are located

   a. In the ceiling
   b. In structural elements like beam
   c. In walls just above the floor level

11

BIBLIOGRAPHY



1. ASHRAE. (2004). ANSI/ASHRAE Standard 55- *Thermal Environment Conditions for Human Occupancy*. Atlanta: American Society of Heating, Refrigeration and Air-Conditioning Engineers.
2. ASHRAE. (2013). *Standard 55 – Thermal Environmental Conditions for Human Occupancy*.
3. ASHRAE. (2020). Standard 55 – *Thermal Environmental Conditions for Human Occupancy*. Retrieved from https://www.ashrae.org/technical-resources/bookstore/standard-55-thermal-environmental-conditions-for-human-occupancy
4. ASHRAE. (2021). *ASHRAE Handbook*. Retrieved from https://www.hindawi.com/journals/jobe/contents/year/2021/
5. Auliciems, A. (1969a). Effects of weather on indoor thermal comfort. *International Journal of Biometeorology*, 13(2), 147-162.
6. Baker, N., & Standeven, M. (1997). A behavioural approach to thermal comfort assessment. *International Journal of Solar Energy,* 19, 21-35. doi:10.1080/01425919708914
7. Bardhan, R., & Debnath , R. (2017). *Evaluating building material based thermal comfort of a typical low-cost modular house in India.* Retrieved from DOI: 10.1016/j.matpr.2017.11.087, https://linkinghub.elsevier.com/retrieve/pii/S2214785317323258
8. BEE. (2016). *Design guidelines for energy-efficient multi-storey buildings - warm and humid climates*. Retrieved from http://www.beepindia.org/sites/default/files/resources/Residential Guidelines_Warm-Humid Climates.pdf
9. BEE. (2021). *Building Heat Transfer.* Retrieved from https://www.beepindia.org/wp-content/uploads/2021/12/Building-Heat-Transfer_Web.pdf
10. BEE. (2021). *External Movable Shading Systems (EMSyS) Manual.* Retrieved from https://www.beepindia.org/wp-content/uploads/2021/12/EMSYS-Manual_Web.pdf
11. BEE. (2021). *Handbook of Replicable Design for Energy Effecient Residential Buildings*. Retrieved from https://beeindia.gov.in/sites/default/files/BEE_Handbook of Replicable Designs for Energy Efficient Residential Buildings.pdf
12. Bhanware, P., Sunger, V., & Maithel, S. (2020). Assessing Thermal Performance of Building Envelope of New Residential Buildings Using RETV. *Energise 2020: Energy Innovation for a Sustainable Economy Paper Proceedings* (pp. 28-34). New Delhi, India: Alliance for an Energy Efficient Economy (AEEE). Retrieved from https://www.beepindia.org/wp-content/uploads/2013/12/Energise-2020_RETV-Assessment.pdf
13. BIS. (2016). *National Building Code*. Retrieved from https://www.bis.gov.in/index.php/standards/technical-department/national-building-code/
14. BMTPC. (2011). *GFRG panel PAC*. Retrieved from BMTPC: http://www.bmtpc.org/DataFiles/CMS/file/PDF_Files/22_GFRG-Panel-RCF.pdf
15. BMTPC. (2014). *LGFSS PAC BMTPC*. Retrieved 2022, from BMTPC: https://bmtpc.org/DataFiles/CMS/file/PDF_Files/28_PACS_%20LGFSS.pdf
16. BMTPC. (2017). *Expanded polystyrene core panel system(EPS) is the potential construction technology for mass housing.* Retrieved 2022, from https://twitter.com/bmtpcdelhi/status/907828179225673728
17. Boerstra, A. C. (2016). *Personal Control over Indoor Climate in Offices: impact on comfort, health and productivity.* Eindhoven: Eindhoven University of Technology. Retrieved from https://research.tue.nl/files/31668559/20160908_Boerstra.pdf
18. Boerstra, A., van Hoof, J., & van Weele, A. (2015). A new hybrid thermal comfort guideline for the Netherlands: background and development. *Architectural Science*

Review, 58(1), 24-34.

19. Brager, G. S., & de Dear, R. J. (2003). Historical and Cultural Influences on Comfort Expectations. In *Buildings, culture and environment: Informing local and global practices* (pp. 177-201).
20. Bureau of Energy Efficiency. (2018). *Eco-Niwas Samhita 2018 Part I: Building Envelope*. Retrieved from www.econiwas.com: https://www.econiwas.com/pdf/publication/ECBC_BOOK_Web.pdf
21. Cândido, C., de Dear, R., & Lamberts, R. (2011). Combined thermal acceptability and air movement assessments in a hot humid climate. *Building and Environment*, 46(2), 379–385. doi:http://doi.org/10.1016/j.buildenv.2010.07.032.
22. CARBSE. (2013). *CARBSE Assembly U-factor Calculator*. Retrieved from CARBSE: https://carbse.org/research-tools/
23. CEN . (2007). Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. *EN 15251:2007*. Brussels: CEN (European Committee for Standardization.
24. CEN. (2019). Energy performance of 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. *EN 16798*. CEN (European Committee for Standardization.
25. Chetia, S., Maithel, S., Jaboyedoff , P., Lall, A., Bhanware , P., & Gupta , A. (2016). *A Case Study on Design of Thermally Comfortable Affordable Housing in Composite Climate : Simulation Results & Monitored Performance*. Retrieved from https://www.beepindia.org/wp-content/uploads/2013/12/Energise-2020_Smart-GHAR-Case-Study.pdf
26. CIBSE. (2015). *Guide A Environmental Design*. Retrieved from https://www.cibse.org/knowledge/knowledge-items/detail?id=a0q20000008I79JAAS
27. Cook, M., Shukla, Y., Rawal , R., Loveday, D., Faria, L., & Angelopoulos, C. (2020). Low Energy Cooling and Ventilation for Indian Residences: Design Guide. *LECaVIR Design Guide*. Loughborough University, UK and CEPT Research and Development Foundation (CRDF), India. Retrieved from https://carbse.org/wp-content/uploads/2020/02/LECaVIR_Report_17feb20-Final.pdf
28. CRDF. (2020). *Thermo-Physical-Optical Property Database of Construction Material*. Retrieved from https://beta.unglobalpulse.org/wp-content/uploads/2017/05/3rd-Research-Dive.pdf#page=29
29. de Carli, M., Olesen, B. W., Zarrella, A., & Zecchin, R. (2007). People's clothing behaviour according to external weather and indoor environment. *Building and Environment*, 42(12), 3965-3973. doi:10.1016/j.buildenv.2006.06.038
30. de Dear, R. J., Brager, G. S., & Cooper, D. (1997). *Developing an Adaptive Model of Thermal Comfort and Preference - Final Report on ASHRAE RP - 884*. Macquarie University, Sydney. Retrieved from https://www.sydney.edu.au/architecture/documents/staff/richard_de_dear/RP884_Final_Report.pdf
31. de Faria, L. C., Cook, M., Loveday, D., Charalampos, A., Manu, S., & Shukla, Y. (2018). Sizing natural ventilation systems for cooling The potential of NV systems to deliver thermal comfort while reducing energy demands of multi-storey residential buildings in India. *PLEA 2018 Smart and Healthy within the 2-degree Limit*, (pp. 218-223). Hong Kong.

32. DeKay, M., & Brown , G. (Wiley, 2014). *Sun, Wind, and Light: Architectural Design Strategies*. Retrieved from ISBN: 9780470945780, https://www.amazon.in/Sun-Wind-Light-Architectural-Strategies/dp/0470945788
33. Dili, A., Naseer , M., & Varghese, Z. T. (2010). *Thermal comfort study of Kerala traditiopnal residential buildings based on questionnaire survey among occupants of traditional and modern buildings*. Retrieved from https://doi.org/10.1016/j.enbuild.2010.07.004
34. Doctor-Pingel, M., & Vardhan, V. (2017). *Blessing House: Post Occupancy Analysis.* Auroville, India: Centre for Scientific Research (CSR), Auroville. Submitted to the U.S.-India Joint Center for Building Energy Research and Development (CBERD).
35. Doctor-Pingel, M., Vardhan, V., Manu, S., Brager, G., & Rawal, R. (2019). A study of indoor thermal parameters for naturally ventilated occupied buildings in the warm-humid climate of southern India. *Building and Environment*, 151, 1-14. doi:10.1016/j.buildenv.2019.01.026
36. Fanger, P. (1982). *Thermal comfort : analysis and applications in environmental engineering*. Malabar, Florida: R.E. Krieger Pub. Co.
37. Fountain, M., Brager, G., & de Dear, R. (1996, October). Expectations of indoor climate control. *Energy and Buildings,* 24(3), 179-182. doi:10.1016/S0378-7788(96)00988-7
38. Givoni, B. (Wiley, 1994). *Passive Low Energy Cooling of Buildings*. Retrieved from ISBN: 0471284734, https://www.amazon.in/Passive-Energy-Cooling-Buildings-Architecture/ dp/0471284734/ref=sr_1_1? qid=1639977438&refinements=p_27%3ABaruch+Givoni&s=books&sr=1-1
39. GOI. (2017). *EcoNiwas*. Retrieved from EcoNiwas: https://www.econiwas.com/
40. GOI. (2017). *Pradhan Mantri Awas Yojana - Housing for All (Urban) - Credit Linked Subsidy Scheme*. Retrieved from http://mhupa.gov.in/pmay/repository/01_PMAY_Guidelines_English.pdf
41. GOI. (n.d.). *Census 2011*. Retrieved from Census 2011: http://www.censusindia.gov.in/2011census/dchb/DCHB.html
42. GOI. (n.d.). *Energy Efficiency Label for Residential Buildings*. Retrieved from beeindia: https://beeindia.gov.in/sites/default/files/Labelling%20Flyer.pdf
43. GRIHA. (2017). *GRIHA Affordable Housing*. Retrieved from https://www.grihaindia.org/griha-ah
44. Haldi, F., & Robinson, D. (2009). Interactions with window openings by office occupants. *Building and Environment,* 44(12), 2378-2395. doi:10.1016/j.buildenv.2009.03.025
45. Hanssen, M., Hoeks, J., Brans, B., van der Lans, A. A., Schaart, G., van den Driessche, J. J., . . . Schrauwen, P. (2015). *Short-term cold acclimation improves insulin sensitivity in patients with type 2 diabetes mellitus. Nature Medicine,* 21, 863-865. doi:https://doi.org/10.1038/nm.3891
46. Hellwig, R. T. (2015). Perceived control in indoor environments: a conceptual approach. *Building Research & Information,* 43(4), 302-315.
47. Hori, S. (1995). Adaptation to heat. *Japanese Journal of Physiology*, 45, 921-946. doi:https://doi.org/10.2170/jjphysiol.45.921
48. Houghton, F. C., & Yaglou, C. P. (1923a). Determination of the comfort zone. *Journal of the American Society of Heating and Ventilating Engineers*, 29, 361-384.
49. Houghton, F. C., & Yaglou, C. P. (1923b). Determining lines of equal comfort. *Journal of American Society of Heating and Ventilating Engineers*, 29, 163-176.
50. Humphreys. (1978). Outdoor temperatures and comfort indoors. *Batiment*

International, Building Research and Practice, 6(2), 92. doi:https://doi.org/10.1080/09613217808550656

51. Humphreys, M. A. (1976). Field studies of thermal comfort compared and applied. *Journal of the Institution of Heating and Ventilating Engineers*, 44, 5-27.
52. Humphreys, M. A. (1978). Outdoor temperatures and comfort indoors. *Batiment International, Building Research and Practice*, 6(2), 92. doi:10.1080/09613217808550656
53. Humphreys, M., Nicol , F., & Roaf , S. (2020). *Adaptive Thermal Comfort: Foundations and Analysis.* doi:9780367598242
54. IGBC. (2017). *Green Affordable Housing Addendum*. Retrieved from https://igbc.in/igbc/redirectHtml.htm?redVal=showAffordableHousingnosign
55. Indo-Swiss Building Energy Efficiency Project (BEEP). (2021). *Bureau of Energy Efficiency.* Retrieved from Case Study on Green Affordable Housing: Samart Ghar III, Rajkot: https://www.beepindia.org/wp-content/uploads/2021/01/Smart-GHAR_final_0_14.pdf
56. IPCC. (2018). *Anexx II Glossary*. Retrieved from IPCC: https://www.ipcc.ch/site/assets/uploads/2018/02/WGIIAR5-AnnexII_FINAL.pdf
57. ISO. (2005). ISO 7730: 2005,*Ergonomics of the thermal environment — Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria*. Retrieved from https://www.iso.org/standard/39155.html
58. Javed, S., Ornes, I. R., Dokka, T. H., Myrup, M., & Holos, S. B. (2021). Evaluating the Use of Displacement Ventilation for Providing Space Heating in Unoccupied Periods Using Laboratory Experiments, Field Tests and Numerical Simulations. *Energies*, 14(4). doi:10.3390/en14040952
59. Jeyasingh, V. (2010). Concept of Overall Thermal Transfer Value (OTTV) in Design of Building Envelope to Achieve Energy Efficiency. *International Journal of Thermal and Environmental Engineering*.
60. Jones, B., Cook, M., Fitzgerald, S., & Iddon, C. (2016). A review of ventilation opening area terminology. *Energy and Buildings*, 118, 249-258.
61. Kapoor, R., Roulet, C.-A., Maithel, S., & Bhanware , P. (BEE, New Delhi, 2016). *Thermal Insulation of Buildings for Energy Efficiency*. Retrieved from https://www.beepindia.org/wp-content/uploads/2013/12/22.pdf
62. Khan, N. (2013). *Advancements in Sustainable Practices and Innovations in Renewable Energy*. (J. Kaur, Ed.) doi:10.13140/RG.2.1.3240.5201
63. Khan, N. (2013). *Vernacular Architecture and Climatic Control in the extreme conditions of Ladakh.* Retrieved from National conference on Advancements in Sustainable Practices and Innovations in Renewable Energy: DOI: 10.13140/RG.2.1.3240.5201, https://www.researchgate.net/publication/279186605_Vernacular_Architecture_and_Climatic_Control_in_the_extreme_conditions_of_Ladakh_ASPIRE-2013
64. Kjellstrom, T., Maitre, N., Saget, C., Otto, M., & Karimova, T. (2019). *Working on a warmer planet.* International Labour Organization.
65. Loveday, D., Webb, L., Verma, P., Cook, M. J., Rawal, R., Vadodaria, K., . . . Toledo, L. (2016). The Role of Air Motion for Providing Thermal Comfort in Residential/ Mixed Mode Buildings: a Multi-pertner Global Innovtion Initiative (GII) Project. *Proceedings of 9th Windsor Conference: Making Comfort Relevant*. Windsor, UK.
66. Luo, M., de Dear, R., Ji, W., Bin, C., Lin, B., Ouyang, Q., & Zhu, Y. (2016). The dynamics of thermal comfort expectations: The problem, challenge and impication. *Building and Environment*, 95, 322-329. doi:10.1016/j.buildenv.2015.07.015
67. Mahadevia, D., Pathak, M., Bhatia, N., & Patel, S. (2020). *Climate Change,*

Heat Waves and Thermal Comfort—Reflections on Housing Policy in India. doi:10.1177/0975425320906249

68. Maithel, S., Chandiwala, S., Bhanware, P., Rawal, R., Kumar, S., Gupta, V., & Jain, M. (June, 2020). *Developing cost-effective and low-carbon options to meet India's space cooling demand in urban residential buildings through 2050. India Energy Transformation Platform*.
69. Malik , J., & Bardhan, R. (2021). *Thermal comfort perception in naturally ventilated affordable housing of India*. doi:10.1080/17512549.2021.1907224
70. Manu, S., Brager, G., Rawal, R., Geronazzo, A., & Kumar, D. (2018). *Performance evaluation of climate responsive buildings in India: Case studies from cooling dominated climate zones.* Building and Environment. doi:10.1016/j.buildenv.2018.10.063
71. 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,* 55-70. doi:10.1016/j.buildenv.2015.12.019
72. McCartney, K., & Nicol, F. (2002). Developing an adaptive control algorithm for Europe. *Energy and Buildings*, 34(6), 623-635.
73. Ministry of Housing & Urban Affairs, GOI. (2021, January). *PMAY-U.* Retrieved April 2022, from https://pmay-urban.gov.in/uploads/guidelines/60180813309f2-Updated%20guidelines%20of%20PMAY-U.pdf
74. Ministry of Statistics and Programme Implementation, GOI. (2019). *Energy Statistics 2019*. New Delhi: MoSPI, GoI. Retrieved from http://www.indiaenvironmentportal.org.in/files/file/Energy%20Statistics%202019.pdf
75. MOEFCC. (2019). *India Cooling Action Plan*. Retrieved from http://ozonecell.nic.in/wp-content/uploads/2019/03/INDIA-COOLING-ACTION-PLAN-e-circulation-version080319.pdf
76. MoHUA, GoI. (2021). *Light house project at Agartala, Tripura*. Retrieved from GHTC- India: https://ghtc-india.gov.in/Content/pdf/16022021/04_LHP_Agartala_Booklet_15Feb2021_final.pdf
77. MoHUA, GoI. (2021). *Light House Project at Chennai, Tamilnadu*. Retrieved from GHTC - India: https://ghtc-india.gov.in/Content/pdf/16022021/02_LHP_Chennai_Booklet_15Feb2021_final.pdf
78. MoHUA, GoI. (2021). *Light House Project at Indore, Madhya Pradesh.* Retrieved from GHTC - India: https://ghtc-india.gov.in/Content/pdf/16022021/03_LHP_Indore_Booklet_15Feb2021_final.pdf
79. MoHUA, GoI. (2021). *Light House Project at Rajkot, Gujarat*. Retrieved from GHTC - India: https://ghtc-india.gov.in/Content/pdf/16022021/01_LHP_Rajkot_Booklet_15Feb2021_final.pdf
80. MoHUA, GoI. (2021). *Light House Project at Ranchi, Jharkhand.* Retrieved from GHTC - India: https://ghtc-india.gov.in/Content/pdf/16022021/06_LHP_Ranchi_Booklet_15Feb2021_final.pdf
81. MoHUA. GoI. (2021). *Light House Project at Lucknow*, Uttarpradesh. doi:10.7748/ncyp.28.4.70.s53
82. Nicol, F. (2001). Characterising Occupant Behaviour in Buildings: Towards a Stochastic Model of Occupant Use of Windows, Lights, Blinds heaters and fans. *Seventh International IBPSA Conference* (pp. 1073-1078). Rio: International Building Performance Simulation Association. Retrieved from http://www.ibpsa.org/proceedings/BS2001/BS01_1073_1078.pdf

83. Nicol, F., & Humphreys, M. A. (1973). Thermal comfort as part of a self-regulating system. *Building Research and Practice*, 1(3), 174-179.
84. Nicol, F., & Spires , B. (2013). *The limits of thermal comfort: Avoiding overheating in European buildings*. Retrieved from CIBSE: file:///C:/Users/carbse_ra18/Downloads/CIBSE%20TM52%202013%20The%20Limits%20of%20Thermal%20Comfort-%20Avoiding%20Overheating%20in%20European%20Buildings%20NEW%202013%20(1).pdf
85. O'Connor, J. (Design Media Publishing (UK) Limited, 2015). *Architecture & Passive Design*. Retrieved from ISBN: 9881412471, https://www.amazon.in/Architecture-Passive-Design-James-OConnor/dp/9881412471
86. Pallubinsky, H., Kingma, B. R., Schellen, L., Dautzenberg, B., van Baak, M. A., & van Marken Lichtenbelt, W. D. (2017). The effect of warmth acclimation on behaviour, thermophysiology and perception. *Building Research and Information,* 45(7), 800-807. doi:10.1080/09613218.2017.1278652
87. Paolini, R., Zani, A., Poli, T., & Zinzi, M. (2017). Natural aging of cool walls: Impact on solar reflectance, sensitivity to thermal shocks and building energy needs. *Energy and Buildings,* 153, 287-296. doi:10.1016/j.enbuild.2017.08.017
88. Parsons , K. (2019). *Human Thermal Comfort*. Retrieved from ISBN: 9780367261931, https://www.routledge.com/Human-Thermal-Comfort/Parsons/p/book/9780367261931
89. Parsons, K. C. (2002, July). The effects of gender, acclimation state, the opportunity to adjust clothing and physical disability on requirements for thermal comfort. *Energy and Buildings*, 34(6), 593-599. doi:https://doi.org/10.1016/S0378-7788(02)00009-9
90. Pathak , A., Garg, T., & Kumar, S. (2020). *A Policy strategy for decarbonising the building sector- Facilitating Eco-Niwas Samhita implementation in affordable housing*. Retrieved from https://aeee.in/wp-content/uploads/2020/10/Facilitating-Implementation-of-ENS-in-Affordable-Housing.pdf
91. Race, G. (2006). *CIBSE Knowledge Series- Comfort*. doi:ISBN: 9781903287675
92. Radhakrishnan, S., Shanthi, P. R., Nagan, S., & Sundarraja, M. (2016). *Climate Responsive Traditional Architecture of Chettinadu Housing in Tamilnadu, India- A Qualitative and Quantitative Analysis During Summer.* Retrieved from International Journal of Ventilation: DOI: 10.1080/14733315.2011.11683937, http://www.tandfonline.com/doi/full/10.1080/14733315.2011.11683937
93. Rajya Sabha. (2016, March 10). The Real Estate (Regulation and Development) Bill. *THE REAL ESTATE (REGULATION AND DEVELOPMENT) BILL, 2016*. India: Government of India. Retrieved from http://164.100.47.4/BillsTexts/RSBillTexts/PassedRajyaSabha/realest-238-RSP-E.pdf
94. Rajya Sabha. (2016, March 10). *The Real Estate (Regulation and Development) Bill.* Retrieved from http://164.100.47.4/BillsTexts/RSBillTexts/PassedRajyaSabha/realest-238-RSP-E.pdf
95. Rawal, R., & Shukla, Y. (2015). *Potential Energy Savings Using Low Energy Cooling Technologies*. Shakti Sustainable Energy Foundation.
96. Rawal, R., Asrani, S., Shukla, Y., Soldhara, T., Pravalika, S., & Maheriya, B. (2020). *Thermal comfort, Energy consumption and Code Compliance - A study in the context of Affordable Housing In collaboration with Mahila Housing Trust*.
97. Rawal, R., Kumar, D., & Manu, S. (2017). What do traditional pol houses teach us for contemporary dwellings in India. *Proceedings of 33rd PLEA International Conference, Design to Thrive. 1,* pp. 827-834. Edinburgh: NCEUB 2017. Retrieved from https://

plea2017.net/#programmes-container

98. Rawal, R., Maithel, S., Shukla, Y., Rana, S., Gowri, G., Patel, J., . . . Vardhan, V. (2021). *Thermal Performance of walling materials and walling technology. Part I.* Retrieved from https://carbse.org/reports-and-articles/
99. Rawal, R., Poola, V., Sharma, K., Ruyssevelt, P., & Fennell, P. (2019). *Approaches to Urban Stock Model. Ahmedabad, India: Centre for Advanced Research in Building Science and Energy* (CARBSE), Cept University. .
100. Rawal, R., Shukla, Y., Patel , P., Desai, A., & Asrani, S. (2021). *Bridging the gap between Eco Niwas Samhita (ENS) code compliance and implementation: A Case Study of Affordable Housing*. CEPT University, GBPN, CRDF. Retrieved from https://carbse.org/reports-and-articles/
101. Rawal, R., Shukla, Y., Shah, A., Gowri, G., Pathak, B., Sankalpa, & Narendran, M. (2021). *Thermal performance of walling material and wall technology*. Retrieved from http://carbse.org/reports-and-articles/
102. Rawal, R., Shukla, Y., Vardhan, V., Asrani, S., Schweiker, M., de Dear, R., . . . Somani, G. (2022). Adaptive thermal comfort model based on fields studies in five climate zones across India. *Building and Environment*. doi:10.1016/j.buildenv.2022.109187
103. Sala, M., Gallo, C., & Sayigh , A. (Elsevier, 1999). *Architecture - Comfort and Energy*. Retrieved from https://www.elsevier.com/books/architecture-comfort-and-energy/sala/978-0-08-043004-1
104. Samuel, D., Dharmasastha, K., Nagendra , S., & Maiya , M. (Vol. 6, 2017). *Thermal comfort in traditional buildings composed of local and modern construction materials.* Retrieved from https://www.sciencedirect.com/science/article/pii/S221260901730078X
105. Schiavon, S., & Lee, K. H. (2013). Dynamic predictive clothing insulation models based on outdoor air and indoor operative temperatures. *Building and Environment,* 59, 250-260. doi:10.1016/j.buildenv.2012.08.024
106. Schweiker, M., Brasche, S., Bischof, W., Hawighorst, M., Voss, K., & Wagner, A. (2014). Development and validation of a methodology to challenge the adaptive comfort model. *Building and Environment*, 49, 336-347. doi:10.1016/j.buildenv.2011.08.002
107. Shukla, Y., Bhanushali, P., Desai , A., & Asrani, S. (2021). *A Policy Strategy for Decarbonizing the Building Sector.* GBPN, CEPT University. Retrieved from GBPN and CEPT University: https://carbse.org/wp-content/uploads/2021/03/Phase-1-report_CEPT_GBPN_PMAY_2021_03_10.pdf
108. Singh, M. K., Mahapatra, S., & Atreya, S. (2009). Bioclimatism and vernacular architecture of north-east India. *Building and Environment,* 44(5), 878-888. doi:10.1016/j.buildenv.2008.06.008
109. Singh, M. K., Mahapatra, S., & Atreya, S. K. (2007). Development of bio-climatic zones in North-East India. *Energy and Buildings*, 39(12), 1250-1257. doi:10.1016/j.enbuild.2007.01.015
110. Singh, M. K., Ooka, R., Rijal, H. B., & Mahapatra, S. (2016). Defining thermal comfort in residential buildings of North-East India. SCA-16 *Science for the people: Mobilizing modern technologies for sustainable development in Asia*, (pp. 118-123). Colombo, Sri Lanka. Retrieved from https://academic.oup.com/endo/article/144/6/2496/2881403
111. Singh, M., Mahapatra, S., & Atreya, S. (2010). Thermal performance study and evaluation of comfort temperatures in vernacular buildings of North-East India.

Building and Environment, 45(2), 320-329. doi:10.1016/j.buildenv.2009.06.009

112. Strengers, Y. (2008). Comfort expectations: the impact of demand-management strategies in Australia. *Building Research and Information*, 36(4), 381-391. doi:10.1080/09613210802087648
113. Sustainable and Smart Space Cooling Coalition. (2017). *Thermal Comfort for All- Sustainable and Smart Space Cooling*. Retrieved from https://shaktifoundation.in/wp-content/uploads/2017/09/Thermal-Comfort-for-All.pdf
114. Szokolay, S. V. (2014). *Introduction to architectural science: The basis of sustainable design*. doi:9781138293854
115. Takahashi, Y., Nomoto, A., Yoda, S., Hisayama, R., Ogata, M., Ozeki, Y., & Tanabe, S.-i. (2021). Thermoregulation model JOS-3 with new open source code. *Energy and Buildings*, 231. doi:10.1016/j.enbuild.2020.110575
116. Taylor, N. A. (2014). *Human heat adaptation. Comprehensive Physiology*, 4(1), 325-365. doi:10.1002/cphy.c130022
117. Technical Committee. (2006). *Indoor environmental input parameters for design and assessment of energy performance of buildings- addressing indoor air quality, thermal environment, lighting and acoustics*. Retrieved from http://www.cres.gr/greenbuilding/PDF/prend/set4/WI_31_Pre-FV_version_prEN_15251_Indoor_Environment.pdf
118. Tewari, S. (2015). Laurie Baker: A model for Sustainable Architectural Design. *Cumulus Mumbai 2015: In a planet of our own - a vision of sustainability with focus on water*, 1. Mumbai.
119. Tuomaala, P., Holopainen, R., Piira, K., & Airaksinen, M. (2013). *Impact of individual characteristics-such as age, gender, BMI, and fitness-on human thermal sensation. Proceedings of the thirteen Internatinal Building Performance Simulation Association conference*, (pp. 2305-2311). Chambery.
120. Urge-Vorsatz, D., Petrichenko, K., Antal, M., Staniec, M., Labelle, M., Ozden, E., & Labzina, E. (2012). *Best Practice Policies for Low Energy and Carbon Buildings. A Scenario*. Center for Climate Change and Sustainable Policy (3CSEP) for the Global Buildings Performance Network.
121. van Marken Lichtenbelt, W., Kingma, B., van der Lans, A., & Schellen, L. (2014). Cold exposure--an approach to increasing energy expenditure in humans. *Trends in Endocrinology & Metabolism*, 25(4), 165-167. doi:10.1016/j.tem.2014.01.001
122. Verma, T., Brar, T. S., & Kamal, M. A. (2017). *Passive Techniques for Achieving Thermal Comfort in the Vernacular Dwellings of Bikaner*. Retrieved from https://www.researchgate.net/publication/344401392_Passive_Techniques_for_Achieving_Thermal_Comfort_in_the_Vernacular_Dwellings_of_Bikaner
123. Wang, Z., Ji, Y., & Ren, J. (2017). Thermal adaptation in overheated residential buildings in severe cold area in China. *Energy and Buildings*, 146, 322-332. doi:10.1016/j.enbuild.2017.04.053
124. Wang, Z., Ji, Y., & Su, X. (2018). Influence of outdoor and indoor microclimate on human thermal adaptation in winter in the severe cold area, China. *Building and Environment*, 133, 91-102. doi:https://doi.org/10.1016/j.buildenv.2018.02.014
125. World Meteorological Organization. (2022). *The Sun's impact on the Earth*. Retrieved from World Meteorological Organization: https://public.wmo.int/en/sun%E2%80%99s-impact-earth#:~:text=variability%20and%20change.-,

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