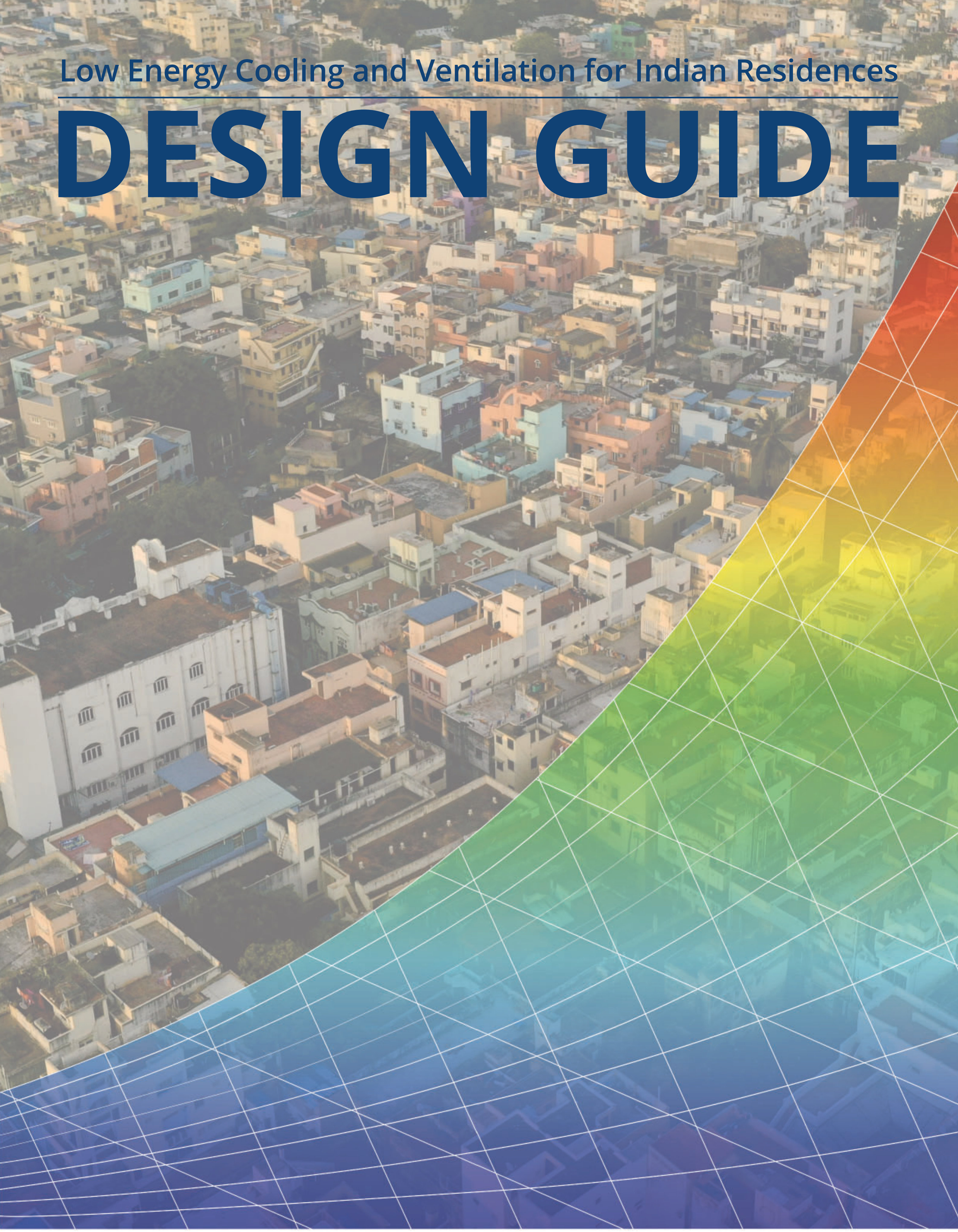
Low Energy Cooling and Ventilation for Indian Residences

DESIGN GUIDE



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LECaVIR

Low Energy Cooling and Ventilation for Indian Residences

DESIGN GUIDE

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Abbreviations

ABL	Atmospheric Boundary Layer
AC	Air Conditioning
ASHRAE	American Society of Heating Refrigerating and Air-conditioning Engineers
CBE	Centre for Built Environment
CEM	Clean Energy Ministerial
CFD	Computational Fluid Dynamics
CIBSE	Chartered Institution of Building Services Engineers
Clo	Clothing Insulation Value
DC	Design Chart
DOE	US Department of Energy
DTS	Dynamic Thermal Sensation
GBPN	Global Buildings Performance Network
HIG	High Income Group
HVAC	Heating Ventilation and Air Conditioning
ICAP	India Cooling Action Plan
IMAC	India Model for Adaptive Comfort
IMAC-MM	India Model for Adaptive Comfort (Mixed-Mode)
IMAC-NV	India Model for Adaptive Comfort (Natural Ventilation)
ISHRAE	Indian Society of Heating Refrigerating and Air-conditioning Engineers
LECaVIR	Low Energy Cooling and Ventilation for Indian Residences
LIG	Low Income Group
MM	Mixed-mode
NBCI	National Building Code of India
NV	Natural Ventilation
NV+	Enhanced Natural Ventilation
ODA	Official Development Assistance
PMAY	Pradhan Mantri Awas Yojana
PPD	Predicted Percentage of Dissatisfied
PPO	Purpose Provided Openings (for ventilation)
RCC	Reinforced Cement Concrete
RH	Relative Humidity
SRI	Surface Reflective Index

Nomenclature

A_f – free area of the openings for NV [m^2]
A_{eff} – effective open area of the openings for NV [m^2]
A_{inlet} – total area of inlet openings [m^2]
A_{outlet} – total area of outlet openings [m^2]
A_{room} - Room floor area [m^2]
α - exponent based on the terrain roughness [-]
C – opening shape coefficient [-]
C_d – discharge coefficient [-]
C_p – specific heat capacity of air [J/kg K]
C_p– pressure coefficient [-]
ΔC_p– pressure coefficient difference [-]
$\Delta T_{inside\text{-}outside}$ – T_{inside} to $T_{outside}$ temperature difference [°C]
g – acceleration due to gravity [m/s^2]
h_a – vertical distance between the centres of the openings [m]
k – exponent based on the terrain roughness [-]
$\dot{m}_{total}$ – total airflow through the openings due to wind and buoyancy forces [m^3/s]
$\dot{m}_b$ – airflow due to buoyancy forces [m^3/s]
$\dot{m}_w$ – airflow due to wind forces [m^3/s]
Q_{total} – total heat gains [W]
ρ – density of air [kg/m^3]
Pa – dynamic pressure [Pa]
q – ventilation rate [m^3/s]
q_a – ventilation rate achieved [m^3/s]
q_{rec} – ventilation rate recommended for thermal comfort [m^3/s]
T_{inside} – temperature inside [°C]
$T_{outside}$ – temperature outside [°C]
$T_{int,aver}$ – average internal air temperature [°C]
$T_{out,aver}$ – average external air temperature [°C]
$T_{i,CSP}$ – cooling setpoint [°C]
$\bar{t}$ – average value of the internal and external temperature [°C]
V_{ref} – mean wind velocity at 10m height [m/s]
V_r – wind speed [m/s]
V_z – wind speed at height ‘Z’ [m/s]
U - wind speed [m/s]
Z – height above ground [m]

This publication is dedicated to Dr Narendra K. Bansal.

FOREWORD

'We scorn all that is cheap.... This air we breathe is so common, we care not for it; nothing pleaseth but what is dear.' [1] Robert Burton (1621)

It is a huge pleasure to be invited to write the Foreword for this extremely timely and very necessary guide, the product of a collaboration between two very distinguished centres for research into building environments, the Building Energy Research Group at the School of Architecture, Building & Civil Engineering at Loughborough University in the UK and the Centre for Advanced Research in Building Science and Energy (CARBSE) at CEPT University in Ahmedabad, India. The issues are complex, the phenomena sometimes counter-intuitive, so the legendary intuition of the natural born architect will not be enough. As the authors record, some 30% of total energy consumption in the Indian built environment is consumed by artificial cooling. The associated carbon dioxide emissions are projected to rise in a business-as-usual scenario by up to 700% by 2050 completely counter to the ambition to achieve a zero carbon economy worldwide by 2050. The authors emphasize that 'providing cooling without the use of energy intensive air conditioning will be critical to avoiding irreversible climate change'.

But in North America and increasingly in Western Europe we have become accustomed to being in wholly artificial environments in glassy public buildings, regardless of the climate outside. The 'air we breathe' is mechanically cooled, dehumidified, rehumidified, reheated and blown at us by millions of fans at colossal cost in electrical energy. India must not repeat the mistakes of the West and this guide shows that it need not. The bizarre practice of generating artificial cold environments actually has a distasteful and now much suppressed provenance, the no doubt well-intended response of early Modernists to negate warmer environments to spare the 'climate-oppressed', unquestionably absorbing their contemporary climate determinists' damning diagnoses of all climates except the Cool Temperate of England and Germany. Leading determinist Ellen Semple wrote in 1911,

'Where man has remained in the Tropics, with few exceptions he has suffered arrested development. His nursery has kept him a child.... without the respite conferred by a bracing winter season....' [2]

This is astounding to the modern reader, it shocks my master's students, but her analysis was widely believed across the West. The unestablished Yale academic Ellsworth Huntington (1876-1947), the exact contemporary of Willis Carrier, the 'inventor' of air conditioning, popularized an extreme climate determinism across the United States through a barrage of publications through Yale University Press. Carrier and rivals' air conditioning machines could cocoon transplanted colonials in their familiar Cool Temperate environment and limit, Semple and Huntingdon argued, their 'moral degradation'. The idea of the chilly interior originally the stems from this Victorian and Edwardian belief, should be rejected without reservation.

It also explains, perhaps, why have modern Western societies and their architects contracted out the responsibility for delivering 'good' air in their interior spaces to a specialised component of the construction industry, the world of conventional

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1. P.75 Robert Burton (1621) 'Some Anatomies of Melancholy', in the essay 'Quantity of Diet a Cause'. Reproduced by Penguin Books, 2008, p.75.
2. Ellen Semple 1911 'Influences of Geographic Environment on the Basis of Ratzel's System of Anthropo-Geography',

mechanical and electrical engineers and subcontractors. It is devoted to the technology of making artificial environments and it justifies this position by thorough 'denunciation' of pre-modern practices as 'unsafe', 'uncomfortable' and 'primitive', a classic historicist Whiggish position. Architects have been complicit in this. But design can remove the need for this artificial world as this Guide clearly shows through the delightful Art and Science of Building Physics. The primitive is revealed as being highly sophisticated, elegant in its economy. In urban settings, despite various well-known challenges, natural ventilation has the potential to provide comfortable environments in a wide range of climatic regions around the world. In fact, under certain climatic conditions, it can be considered one of the most effective and low carbon strategies, requiring, in its simplest form, only a modest temperature difference and/or a light breeze.

In the West the behaviours and attitudes of the supply side are atrophied in a persistent social practice, a dull and repetitive way of building in discrete packages which certainly include the internal environment. Its historical intent and roots are long forgotten but stuck in the psyche of an indifferent commissioning class. This is maintained by networks of risk-shedding consultants, bound by intensely defensive contractual agreements and served by an aggressive industry driven by an immense vested interest in maintaining the status quo. But if my colleagues' modelling of the changing climate is only half right, who will want to own a glass tower anywhere in thirty years which is wholly dependent on a huge energy-consuming life support machine. They ¬will be a liability. This Guide points to a quite different way of building. The science is proven but the design community has not translated this available knowledge into practice. Two things are required to scale up best practice in natural ventilation: policy, and training - in fact both are required.

This Guide provides the much needed information on both policy and training and I commend it to you unreservedly.

C. Alan Short
President of Clare Hall Cambridge
The Professor of Architecture,
University of Cambridge, UK

1.1 About Low Energy Cooling and Ventilation for Indian Residences (LECaVIR)

Achieving long term sustainable growth, whilst ensuring a secure energy supply and combating climate change, is a problem that demands worldwide attention and international collaboration. It must be solved against a backdrop of an increasing global population, relentless urbanisation, degradation of air quality and yet higher expectations of better living standards; matters that are especially pertinent in rapidly developing economies like India. The way in which these interconnected challenges are addressed will shape the future of our planet.

Substantive global collaborative initiatives, which are supported at national government level, have been launched to address these challenges. Mission Innovation (MI), launched in November 2015, aims *"to accelerate the pace of clean energy innovation to achieve performance breakthroughs and cost reductions* ..."(Mission Innovation 2015). It is supported by the European Union and 20 individual countries, including India and five other ODA countries, notably China. MI seeks to double investment in clean energy R&D over the next 5 years. India plans to increase funding from USD 72 million to USD 145 million and, like the UK, has a focus on industry and buildings. The Clean Energy Ministerial (CEM), which is supported by the EU and 24 countries worldwide, including India and 5 other ODA countries, recently launched the Advanced Cooling Challenge (Advanced Cooling Challenge 2020). This global campaign aims *"to inspire governments and industry to make, sell, promote, or install super-efficient air conditioner or cooling solutions that are smart, low global warming potential, and affordable*". Advanced energy-efficient cooling solutions to increase quality of life in India are the focus of this research project.

The demand for residential air conditioning is driven by better living standards, higher thermal comfort expectations, greater disposable income and urbanisation, which leads to dense high-rise apartment buildings. Today, 31% of the Indian population of 1.3 billion live in urban areas; by 2050 this will increase to 50%, or 992million people (United Nations 2016). The floor area of India's residential stock will increase by over 500% by 2030 and space cooling currently represents 30% of total building energy consumption (Kumar et al. 2011) with sales of air conditioners in the residential sector increasing by a similar rate each year. If unchecked, the CO2 emissions from Indian buildings could increase by 700% by 2050 (Shnapp and Laustsen 2013) so strategies that provide cooling without the use of energy intensive air conditioning will be critical to avoiding irreversible climate change.

The international development importance of curbing the growth of conventional air conditioning systems is undeniable. In India for example, some of the most populous metropolitan areas – Mumbai, Delhi and Calcutta – are in hot and humid regions. In such cities, the electricity demand for space cooling comprises up to 60% of the summer peak load and this threatens an already overstretched electricity supply system. Currently, Indian peak demand exceeds the supply capacity by 9%, and supply curtailment is common. On 31st July, 2012 India suffered the biggest blackout in world history with 620 million people, half the country's population, without power (India blackouts 2012). An unreliable power supply threatens businesses and social cohesion and harms the economy; it also deters inward investment by overseas organisations.

Increased wealth and urbanisation are trends observed in many emerging economies; so the increased use of air conditioning is a global phenomenon. For example, it is estimated that the global energy demand of in-room air conditioners purchased between 2010 and 2020 will be more than 600 billion kilowatt-hours by 2020 . Such huge energy demands make it much more difficult to provide a low-carbon, reliable, secure and affordable energy supply.

The LECaVIR project explored the prospects for reducing energy demand for residential air conditioning through the avoidance of refrigerant-based air conditioning, the advancement of technological developments and the delivery of new design guidance. The research evaluated the potential of natural ventilation (NV) and low energy cooling, combined with the judicious use of air conditioning within an overall, digitally controlled mixed-mode (MM) strategy for the hottest and most humid locations. Whilst Indian cities are the focus, many of the strategies developed will be applicable globally in ODA countries with similar climatic conditions, notably China, Brazil, South America and South-East Asia.

1.2 About this design guide

This design guide is a product of the LECaVIR research project and is divided into two parts: Part A presents the LECaVIR concepts and provides a background to thermal comfort and natural ventilation within the context of Indian residences. The intention of Part A is to equip practitioners, designers and operators with all the information required to specify LECaVIR and undertaken initial concept design work. Part B provides further details on how to undertake appropriate sizing for a LECaVIR system, and how to develop an appropriate control strategy for mixed mode ventilation.

LECaVIR

PART A: CONCEPTS

2.1 Indian climatic zones

Buildings are designed and constructed to provide comfort and to protect human beings from unfavourable environmental conditions such as heat, cold, rain, and sun. The key environmental parameters that affect the performance of buildings are solar radiation, ambient temperature, humidity, precipitation, wind, air quality and sky condition. Some of these parameters are also used in the criteria that define the climatic zones based on the prevailing conditions. Regions with similar environmental characteristics are categorized into one climate zone. The criteria used to categorize the Indian climate into five zones are provided in Table 1 (National Building Code of India, 2005). The geographic distribution of these is shown in Figure 1.

Having data for the climate zone in which a building is being designed or refurbished is important for building designers, enabling them to develop climate-responsive designs with acceptable indoor comfort and minimum energy demand. In general, the servicing strategies for the India climate zones are: cooling for the Hot-Dry, Warm-Humid and

Table 1: Criteria for climate classification of India. Source: SP 7: NBCI 2005

Climate Zone	Mean Monthly maximum temperature (°C)	Relative Humidity (%)
Hot - Dry	>30	<55
Warm - Humid	>30	>55
	>25	>75
Temperate	25-30	<75
Cold	<25	All Values
Composite	This applies when six months or more do not fall within any of the above categories	

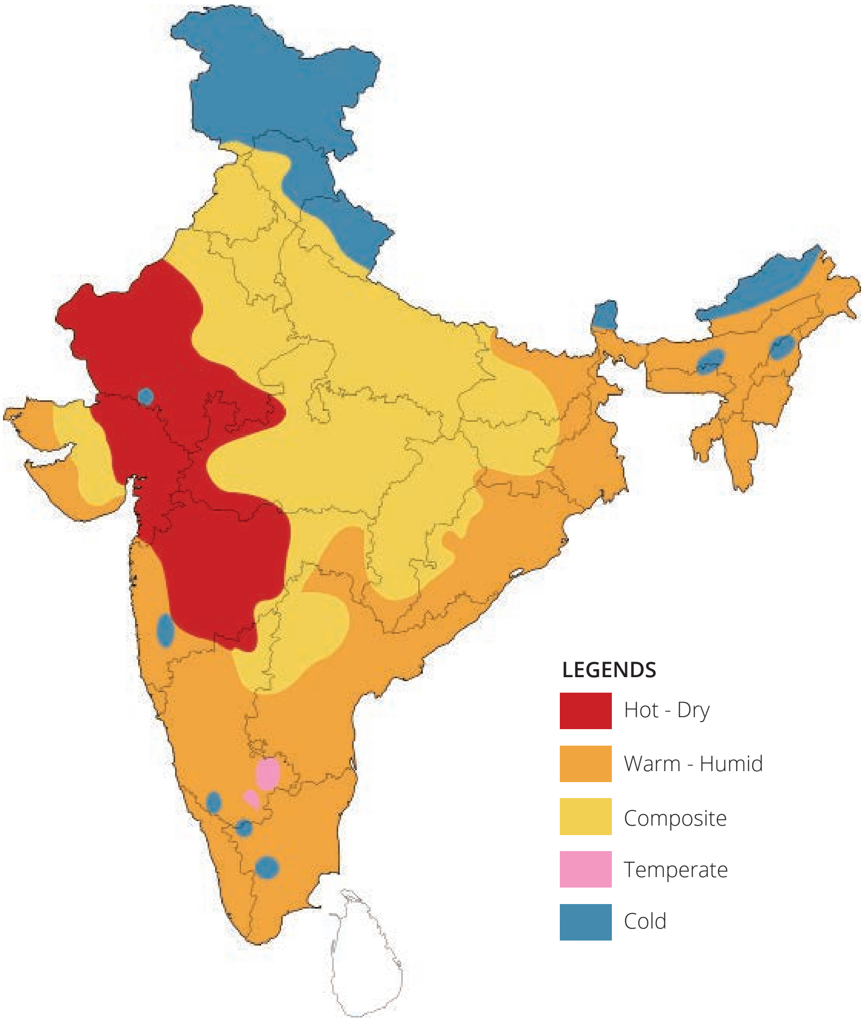


Figure 1: Climate zone map of India. Source: ECBC, Part B, fig.2 (2005)

Temperate zones; cooling and heating for the Composite zone; and heating for the Cold zone. As can be seen in Figure 1, most locations fall under three climate zones: Hot-Dry; Warm–Humid; and Composite. This classification confirms that India is a cooling-dominated country. Those locations in the Cold and Temperate climate zones are also areas which have sparse population. For this reason, this design guide focuses on the Hot-Dry, Warm-Humid and Composite climate zones to explore their low-energy cooling potentials.

2.2 Operating modes for thermal comfort in Indian Residences

The IMAC (India Model for Adaptive Comfort) is a thermal comfort model developed for Indian conditions based on the data from thermal comfort surveys of office buildings across India (Manu et. al., 2016). The IMAC model uses the outdoor temperature and relative humidity to categorise the outdoor conditions into nine modes of operation (Figure 2) and determine the most suitable operating mode (Table 2). This categorisation is available for 56 Indian cities. The upper and lower limits of temperature (T_U and T_L respectively), change for each day and each location since they are derived from the 30-day running mean of outdoor dry-bulb temperature. This model utilizes weather data from the Indian Society of Heating Refrigeration and Air-conditioning Engineers (ISHRAE) (in: Climate. OneBuilding.Org, 2014) and has been integrated into the National Building Code of India (Standards, 2016).

The calculated number of comfort hours in a year for different operating modes as per IMAC-MM is shown in Figure 3 for eight representative Indian cities located in three climatic zones: Mumbai, Chennai, Kolkata and Pune (warm-humid), Ahmedabad (hot-dry), and New-Delhi, Hyderabad and Jaipur (composite). These eight cities fall within the Indian top ten for both population (in: census2011.co.in, 2011) and gross domestic product (GDP) (in: tfipost.com, 2019) and are used as references of location and climate for the application examples in this design guide.

2.3 Adaptive behaviours for thermal comfort in Indian residences

The human body can physiologically adapt to the various climatic conditions, beyond which behavioural adaptations are required for better thermal satisfactions. By modifying their immediate environments, occupants tend to achieve thermal comfort. Operation of building elements such as windows, doors, and building appliances such as fans, provide adaptive opportunities to the occupant to alter their immediate environment. The operation of windows is one of the adaptive measures in most Indian residences. Based on the constantly changing outdoor thermal environmental conditions, occupants either open the windows to allow favourable outdoor air to enter residences or close the windows to prevent the unfavourable outdoor air which adds radiant and convective heat gains to the indoors. In addition to the windows, blinds made

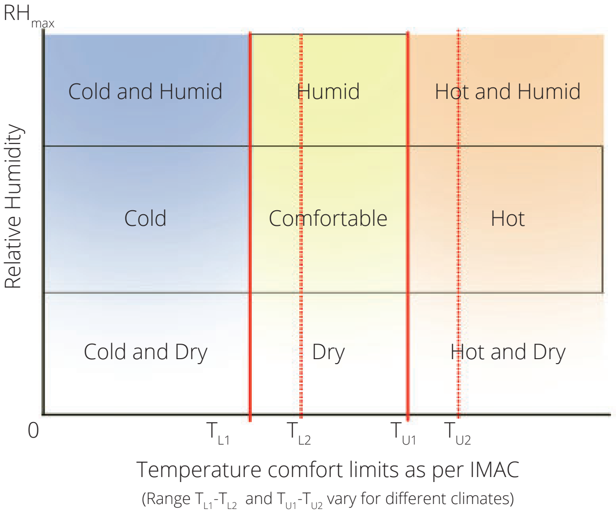


Figure 2: The logic for categorization of annual hours based on temperature and humidity thresholds. Source: Manu et. al. (2016).

Table 2: Conditions for operation modes per the temperature (based on the IMAC models) and 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%

from material such as bamboo placed externally protect windows from direct solar radiation but at the same time provide an opportunity to offer natural ventilation. In summer they block the solar radiation, and by rolling them up during cool winters, the occupant can make use of the available solar radiation. The country's common practice of using ceiling fans induces air movements into the space reducing thermal discomfort and skin moisture. Studies by Nicol, (1974) show that air speeds above 0.25m/s have an equivalent effect similar to reducing the air temperature by approximately 4°C. Another affordable practice alternative to ceiling fans is the use of evaporative coolers. These are small room air coolers specifically used at room level, which uses water to evaporatively cool the space. These coolers are predominantly used in hot and dry climates.

In addition to these adaptations occupants also move between various spaces having varied thermal characteristics such as balconies, porticos, and courtyards. Depending upon the outdoor environmental conditions occupants choose to occupy them. Higher the temperature difference between enclosed spaces and semi-open spaces, the higher the chances of movement of occupants. Movement between various spaces could be during various times of the day or depending upon the season of the year. Modifying the level of clothing insulation values by adding or removing clothes enables the occupant to adapt to the indoor conditions. Consumption of hot and cold fluids, bathing more than once during the day, purposefully changing the metabolic rate by reducing or increasing the activity are some of the adaptive behaviours practiced by occupants.

Typical Indian garments in residences

India has a diverse climate and culture with a awide variety of clothing practices. The clothing insulation or the clo value is modified by a change in attire. Clo value of attire will change based on the material or fabric and the change in the style of attire. These clothing modifications tend to wary with regions, time of the day and can be easily observed in both household wear and work wears. In the warm and humid regions near the coast, people wear light and loose-fitting clothing to facilitate air movements across the clothing. In certain cultures, and economic strata, men even remain bare-chested to maintain comfort. The use of headgears such as turbans to prevent the direct heat falling on the head is well-practiced in most parts of India.

Further, Indian clothing also exhibits a wide range of clothing insulation values or the clo values from research on manikins. Findings on the estimation of clo values for non-western clothing states that Indian female ensembles have the clo values in the range of 0.57 to 0.96 and male ensembles in the range of 0.61-0.99 (Havenith et. al., 2013). The insulation values largely changed with the impact of air velocity, evaporative resistances and the effect of posture and walking motion. This wide range is mostly due to the open weaves and loose fit designs of Indian clothes. Research by Madhavi Indraganti presents the varying clo value of Sarees, which is a unique customizable clothing ensemble worn by most Indian women (Indraganti et al. 2015). This ensemble offers varying clothing insulation depending on the way it is draped over the body, which varies by regions and time of the day and year. The winter ensemble has a clo value ranging

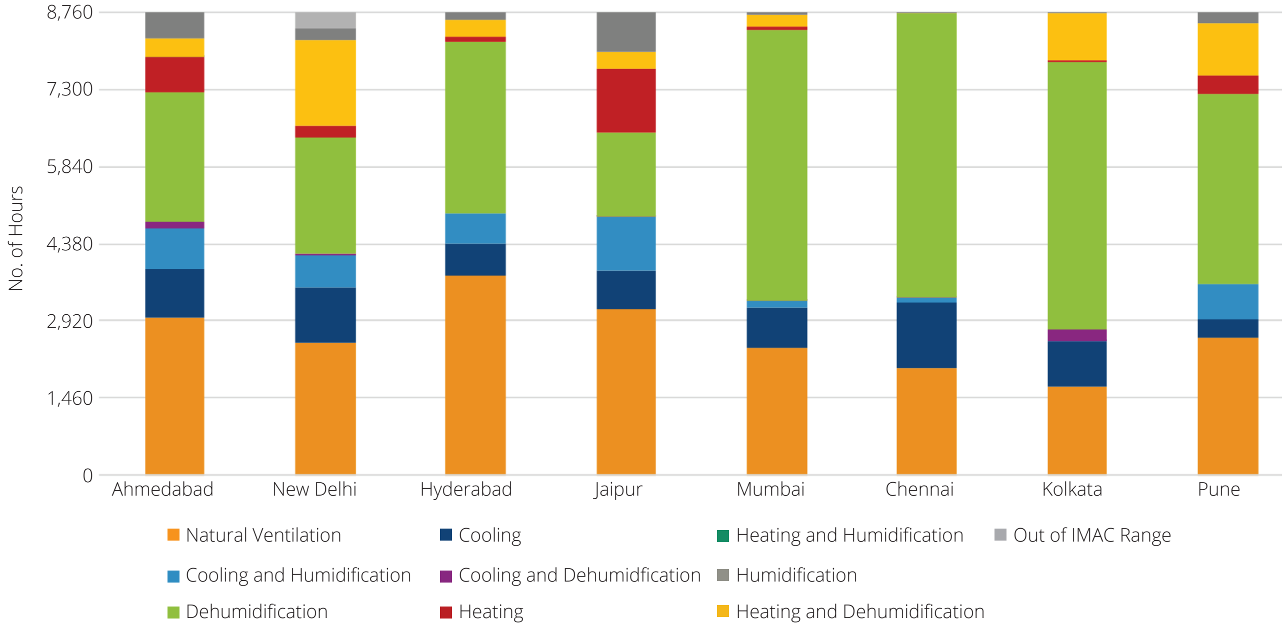


Figure 3: Number of comfort hours in a year for different operating modes as per IMAC-MM for eight Indian cities.

between 1.11 – 1.30 and the summer and monsoon attire has the clo values range between 0.62-0.96. It is also interesting to note that the upper body drape of the saree alone varied the insulation by about 35%.

From the pankhā to the ceiling fan: the tradition of air movement

Use of air movement to improve thermal comfort sensation has been a common adaptive behavior in Indian residences for centuries. Traditional pankhās were used for this purpose. These hand fans were produced with distinct techniques and materials, such as straw, wood, fabric and metals, and in different shapes, demonstrating the diversity of traditional crafts throughout villages and regions (Jatin Das, 2005). In the last century, affordable mechanical ceiling and pedestal fans were introduced in Indian residences. They became a widely used low-energy non-refrigerant-based cooling alternative for maintaining thermal comfort using air movement (India Cooling Action Plan, 2019).

Current typical ceiling fans can produce turbulent downward flow at 203-250 m^3/min and consume from 45W to 80W electric power, depending on the fan shape, material and technology used (ICAP, 2019). The air movement created by a fan does not physically change either the air temperature or the ventilation rates. However, it results in a rise in the acceptable operative temperature which is related to the increase in the air speed (Manu et. al., 2016, Vyas and Apte, 2017, de Faria et. al., 2018)

2.4 Overview of the Indian construction industry for residential buildings

India, a densely populated country, has a range of housing typologies varying between a single plot villa to multi-story apartments. The average housing area ranges from 30 sq.m for units with one bedroom, hall and kitchen owned by the low-income group (LIG) to 400-600 sq.m for units with 5-6 bedrooms owned by High-income group (HIG) (Census 2011). The national average housing area according to PMAY (Pradhan Mantri Awas Yojana (Urban)) is 24-35sq.m. The household sizes vary between 3-5 occupants in most of the major Indian cities, with the national average being 4.2 occupants. In this guide, our major focus is on the apartment typology, commonly with 3-16 floors with typical construction that is followed across all the urban areas in the country.

Each dwelling unit is an RCC framed structure, with various wall constructions such as burnt brick, fly ash blocks, Aerated concrete blocks (ACC) and concrete block. The windows are operable, generally, a single pane clear glass with a wooden or aluminum framework with horizontal fixes. The windows have the sill at 0.9m and lintel at 2.1m from the floor level and are shaded with a horizontal overhang of 300-600m depth. The roof is made of RCC with low SRI coating on the top surface, to reflect solar radiation preventing heating of the structure. Although these typical residential construction practices perform reasonably well in most climates, the concept of building insulation and ventilation were never considered at construction. In hotter regions, insulation of the building envelop reduces the heat gains into the indoor spaces, making the spaces cool, thereby reducing the energy consumed by air conditioners. On the contrary, in colder regions insulation has the reverse action of trapping the heat inside the envelope keeping the spaces warm and reducing the energy consumed for heating. Ventilating a building helps to renew the fresh air in the space and maintains thermal comfort by


Villas


Pol houses (traditional)


Tenements


Chawls


Apartment (3-5 storey)


High-rise Apartment

Figure 4 Housing typologies in India

drawing in hot or cool air through openings under favourable outdoor conditions. Ventilation being a vernacular practice of India is losing its importance due to the difficulty to control and maintain.

2.5 Limitations for NV

Although natural ventilation is the most affordable and environmentally friendly method to achieve indoor air quality and thermal comfort, rarely used, rarely used effectively due to several challenges. The common challenges are pollution, noise and insects. Most apartment buildings in India have a stilted ground floor with a parking space and many are adjacent to the street. The vehicular emissions and dust from parking and the street enter the habitable space through the operable windows. Adding to these the noise levels from the street, parking, stray dogs and social events contribute to the inconvenience. Metal safety grilles have become business as usual for all window openings for security reasons. The further issue of mosquitos has emphasized on the importance of adding a mosquito mesh to all openings in the residence. However, this design guide offers potential approaches to overcome these challenges.

2.6 LECaVIR flow chart

The flowchart for the LECaVIR design procedure shown in Figure 5, describes the proposed steps in the design of low energy cooling and ventilation systems for Indian residences. The strategies put forward in this design guide are suitable for both new and existing residential buildings. The first step is the assessment of the climatic zone in which the building is located and whether that location has a high demand for cooling. Secondly the climate analysis and dynamic thermal simulation are undertaken to identify the annual number of comfort hours for different operating modes and to determine the desired airflow rates to size the NV openings. The subsequent steps involve designing a central system accounting for natural and mixed-mode ventilation components and testing it with an appropriate control strategy. An optional step on CFD simulations coupled with a dynamic thermal comfort model is used to predict detailed air flow patterns, ventilation rates and resulting thermal comfort sensation. This step would be helpful when assessing the performance of innovative designs as it involves specialized computational simulations that are time consuming and resource intensive.

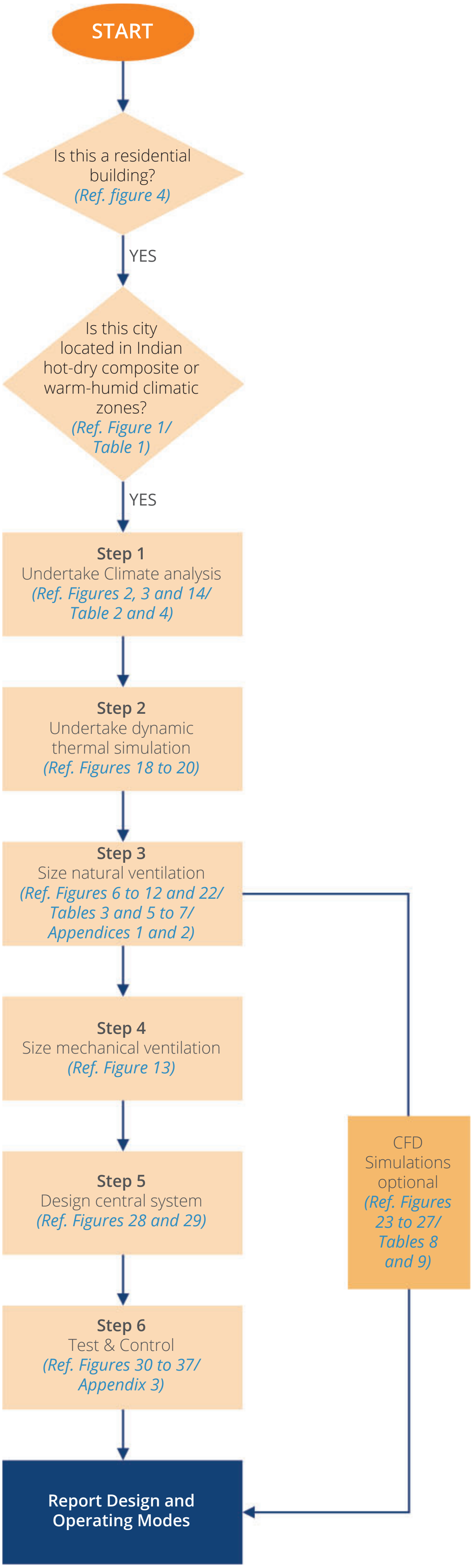


Figure 5: Plan chart for the LECaVIR design procedure

NATURAL VENTILATION AND THERMAL COMFORT PRINCIPLES 3

3.1 Principles of Thermal Comfort

Human thermal comfort is defined as '*that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation*' (ANSI/ASHRAE Standard 55, 2017). Our basic need for thermal comfort indoors is a main driver of building energy demand worldwide, and the aim of built environment designers is to deliver thermal comfort to occupants as energy-efficiently as possible.

Standards for thermal comfort design (ANSI/ASHRAE Standard 55; BS EN ISO 7730) are largely based upon scientific and engineering principles developed by Fanger (1970), in which heat exchange between the human body and its surroundings is related to the thermal sensation experienced, via the '*predicted mean vote*' (PMV) – the vote you would expect from a large group of people exposed to the thermal environment in question. The Fanger approach also allows estimation of the '*Predicted Percentage of Dissatisfied*' (PPD) – the proportion of occupants in a space who are likely to be dissatisfied with their thermal environment. For further details the reader can refer to Parsons (2014). In general, the Fanger-based approach is considered an adequate predictor of thermal comfort in situations where HVAC systems generate the indoor thermal conditions, and the standards present its conditions for application.

However, there is much evidence from field studies to show that people take a more active role in achieving thermal comfort, rather than simply being passive recipients of their thermal environment. Behavioural, psychological and cultural factors, past thermal experiences, and availability of adaptive opportunities as afforded by particular building designs, all play a part in establishing people's thermal comfort sensations that are reported as acceptable. This is termed '*adaptive thermal comfort*' and it offers a more '*dynamic*' approach that can be used for environments with operable windows that open to outdoors, and that are controllable by the occupant, the so-called '*free-running*' situations in buildings. Here, PMV is not the best predictor of thermal comfort, and the adaptive approach better describes the conditions that people find comfortable, considering their adaptive behaviours. The approach gives the ranges of indoor temperatures that are likely to be acceptable to occupants of such buildings in relation to prevailing outdoor temperatures. For complete details, the reader is referred to Humphreys and Nicol (1997), Nicol and Humphreys (2002), Parsons (2014) and Földváry et. al. (2018).

People's past thermal experiences, cultural factors and the availability of adaptive opportunities afforded by buildings, can all potentially affect the range of indoor temperature conditions that can be considered as acceptable. As a result of this, models for adaptive comfort have been developed from field studies in different parts of the world. The Indian Model of Adaptive Comfort (IMAC) developed by Manu et al (2014, 2016) has been adopted into the National Building Code of India (Standards, 2016). The LECaVIR project uses IMAC as the basis for thermal comfort evaluation in residences, where natural ventilation and mixed mode situations prevail.

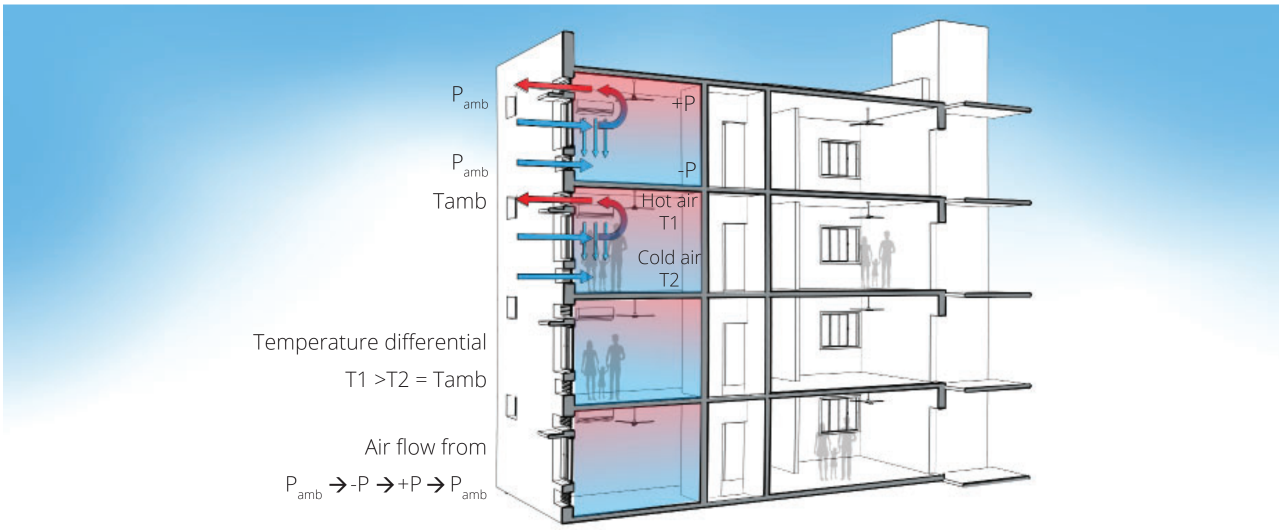


Figure 6: Buoyancy-driven natural ventilation (+P are positive pressure regions relative to the negative pressure regions denoted by -P).

3.2 Natural ventilation principles

When designing buildings it is necessary to ensure that any occupied spaces will be adequately ventilated. This is a relatively straight-forward task when designing using mechanical ventilation as we can use properties of the installed fans and ducts to determine the likely ventilation rate. However, predicting ventilation rates resulting from a *natural ventilation* system is not as simple.

Various terms and phrases have been used to define natural ventilation. In this guide we will use the following definition.

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.

Note that natural ventilation (and indeed all ventilation) should be intentional and controlled. It should not be confused with *infiltration* which is the unintentional and uncontrolled movement of air through cracks and gaps in the fabric of the building envelope.

Natural air movement through a building and the airflow patterns this generates, depends on the size of the driving forces. Although the forces which drive natural ventilation are constantly changing, the theory which follows assumes that conditions are constant. That is, the theory is true for steady state ventilation and represents a '*snapshot*' in time.

The stack effect, or *buoyancy force*, is brought about when temperature differences exist between indoor and outdoor air. In winter, when some buildings are heated, these differences can be quite significant. In summer, however, when outside air temperature is much closer to inside temperature, the driving forces are much smaller. It is designing for stack ventilation in the summer which presents the main challenge for design teams. Very often, design teams strive to ensure that the natural ventilation strategy will perform in the absence of wind, i.e. that the buoyancy forces alone will generate an adequate ventilation flow rate. The principles of buoyancy-driven natural ventilation are shown in Figure 6 below. As warm air rises inside the space a layer of warm (buoyant) air forms at high level. In the absence of wind, this creates a larger hydrostatic pressure in the upper zone of the space relative to that at the same height outside, thereby driving a flow out of the space at high level and drawing cooler air in through openings at low level where the converse is true.

Wind creates complex pressure distributions on the outside of buildings. On the windward side pressure is increased as the wind speed is reduced by the presence of the building. The pressure subsequently decreases as the air flows over and around the building, accelerating as it does so. This is the effect observed around buildings (see figure 7). This pressure distribution around the outside of the building creates pressure differences between inside and outside as illustrated in the figure which drives a ventilation flow. The pressure distribution and the size of the pressure differences depend not only on the wind speed and direction, but also on the shape and form of the building. It is therefore possible to design building features which enhance (or inhibit) wind driven natural ventilation.

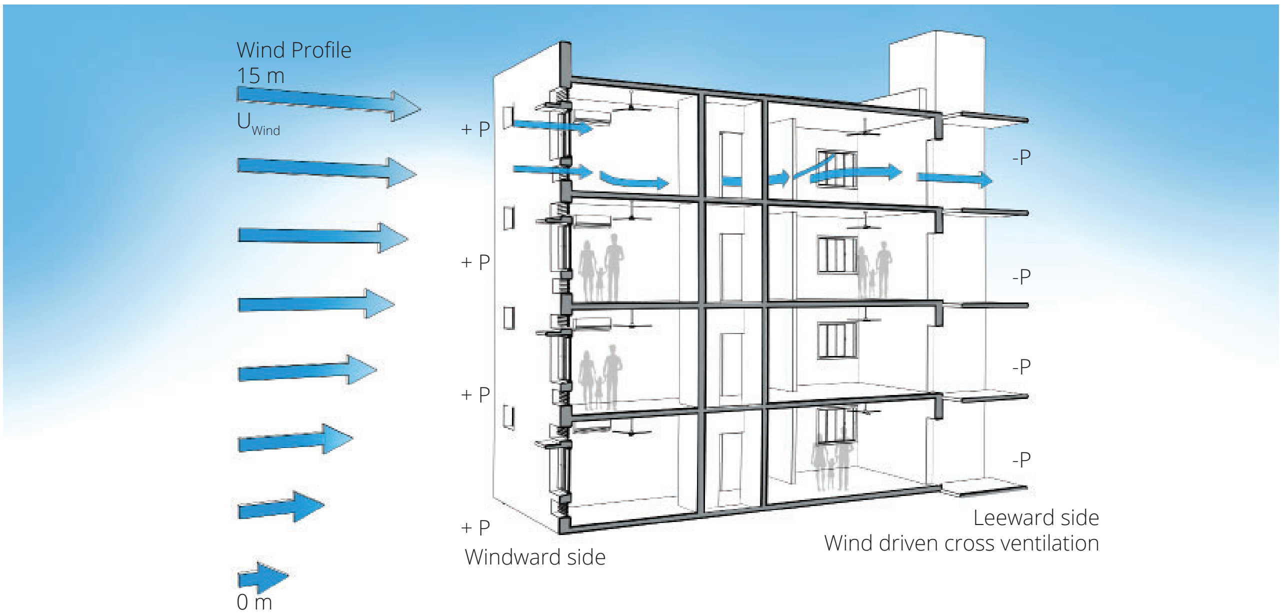


Figure 7: Wind-driven natural ventilation (+P and -P are positive and negative pressure regions relative to the interior).

3.3 Design charts for natural ventilation

It is possible to size openings for natural ventilation without relying on the use of complex and expensive computer simulation techniques. These so-called analytical methods use simple equations to provide designers with good approximations to key design variables. This section presents four design charts (DCs) which can be used to assist in the sizing of ventilation openings to deliver natural ventilation (de Faria et. al., 2019). The design charts are derived from analytical techniques (CIBSE, 2005, and CIBSE, 2010) for the natural ventilation principles previously described in this section.

The design charts provide either the geometrical free area (A_f) of openings as defined in Jones et al (2016) to deliver a recommended air flow rate, or the achieved flow rate for a given free area. The effective area (A_{eff}), which is related to the opening performance, can be calculated using equation 1 (after Jones et al. 2016) for when the value of the discharge coefficient (C_d) of the opening is known. The C_d is a dimensionless number related to the shape of the opening, the air density, the flow Reynolds number, and the wind speed and direction (Heiselberg et. al., 1999, Heiselberg and Sandberg, 2006). In this design guide the values of C_d adopted are: 0.25 for single openings (CIBSE, 2005), 0.61 for multiple openings (CIBSE, 2005), 0.42 for 45° louvres with A_f of 50% (CIBSE, 1986) and 0.32 for typical modular rainproof louvres (e-sgroup.co.uk, 2018).

$$A_{eff} = C_d A_f \qquad (m^2) \qquad (Eq.1)$$

Based on information for inside-outside air temperature difference (ΔT), wind speed (U) and wind pressure co-efficient (ΔCp), the DCs are applicable for a wide range of weather conditions and parameters appropriate for residential buildings located in the selected Indian climatic zones. Examples of application of the design charts are provided in Appendix I of this design guide. The four NV design systems used in this design guide are shown in Figure 8 and shown from Figure 9 to 12: These are considered to be the most common configurations encountered in practice in Indian residences. The corresponding DCs are

- DC-01: buoyancy-driven flow; single-sided ventilation with one opening (Figure 8a and Figure 9)
- DC-02: buoyancy-driven flow; cross-ventilation with multiple openings (Figure 8b and Figure 10)
- DC-03: wind-driven flow; single-sided ventilation with one opening (Figure 8c and Figure 11)
- DC-04: wind-driven flow; cross-ventilation with multiple openings (Figure 8d and Figure 12)

The corresponding rises in the acceptable air temperature with the increase in the air speed is shown in Table 3. These values are derived from the Figure 5.2.3.1 (ASHRAE-55, 2010) and the Figure 5.3.3A (ASHRAE-55, 2017). The first two scenarios (Tr-Ta = -10 and 0°C, respectively, from ASHRAE-55, 2010) show more conservative values than the third one (from ASHRAE-55, 2017), which does not

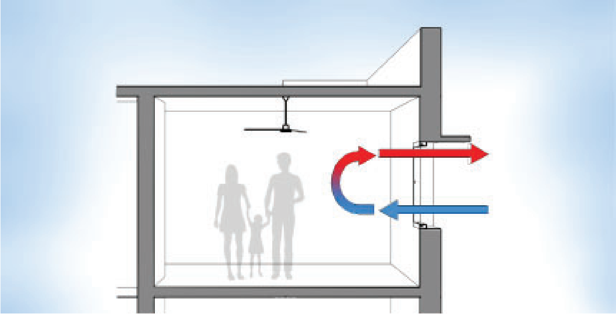


Fig.8a - DC-01

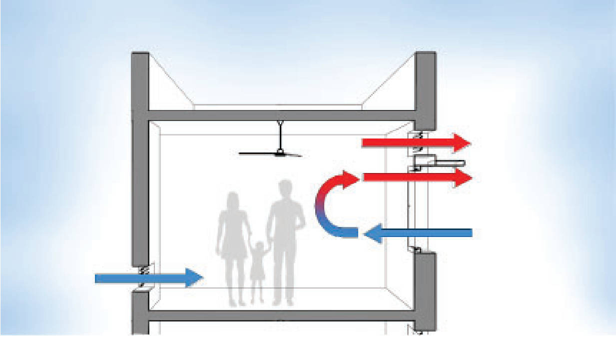


Fig.8b - DC-02

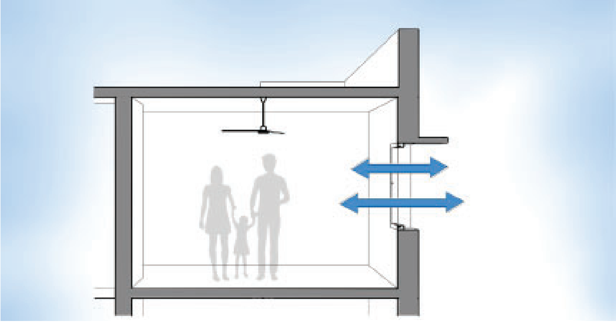


Fig.8c - DC-03

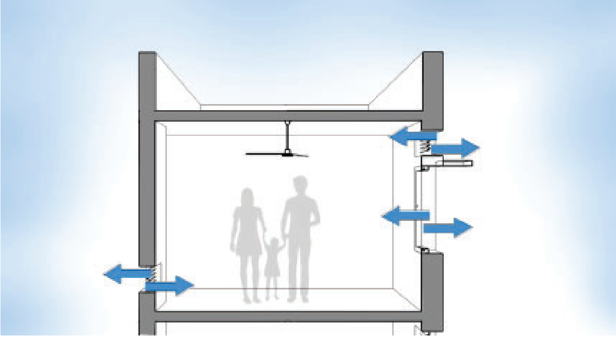


Fig.8d - DC-04

Figure 8: Cross-section sketches of the driving forces for the natural ventilation systems presented in the four design charts. Source: de Faria et. al. (2019).

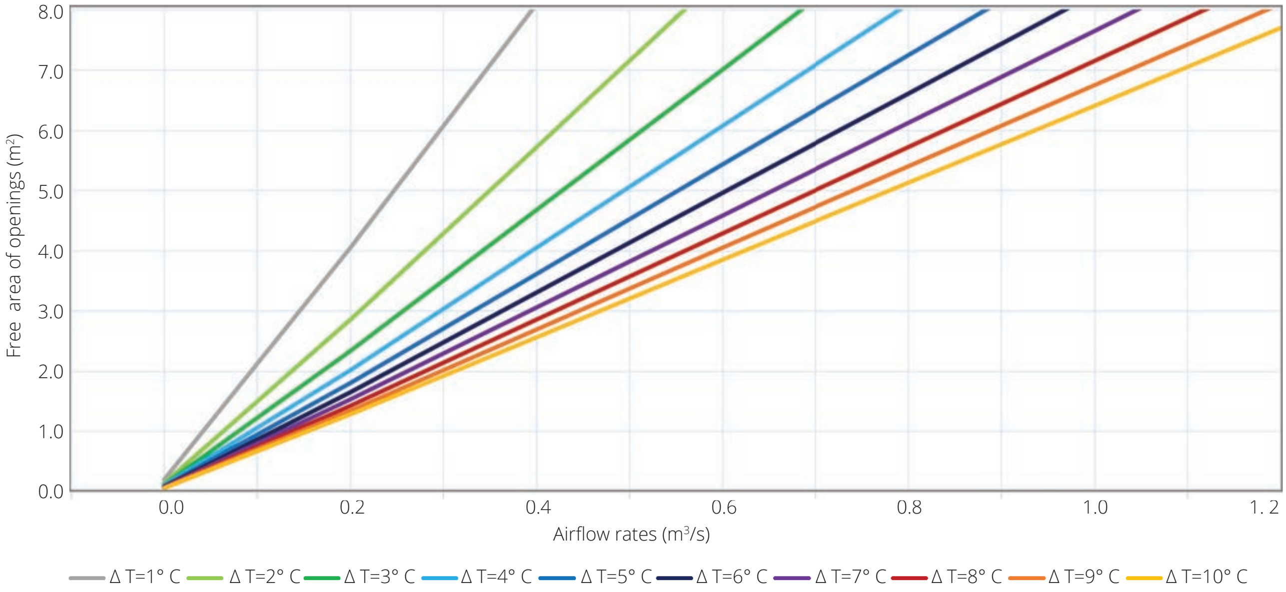


Figure 9: Design Chart DC-01 for single-sided single opening buoyancy-driven flow.

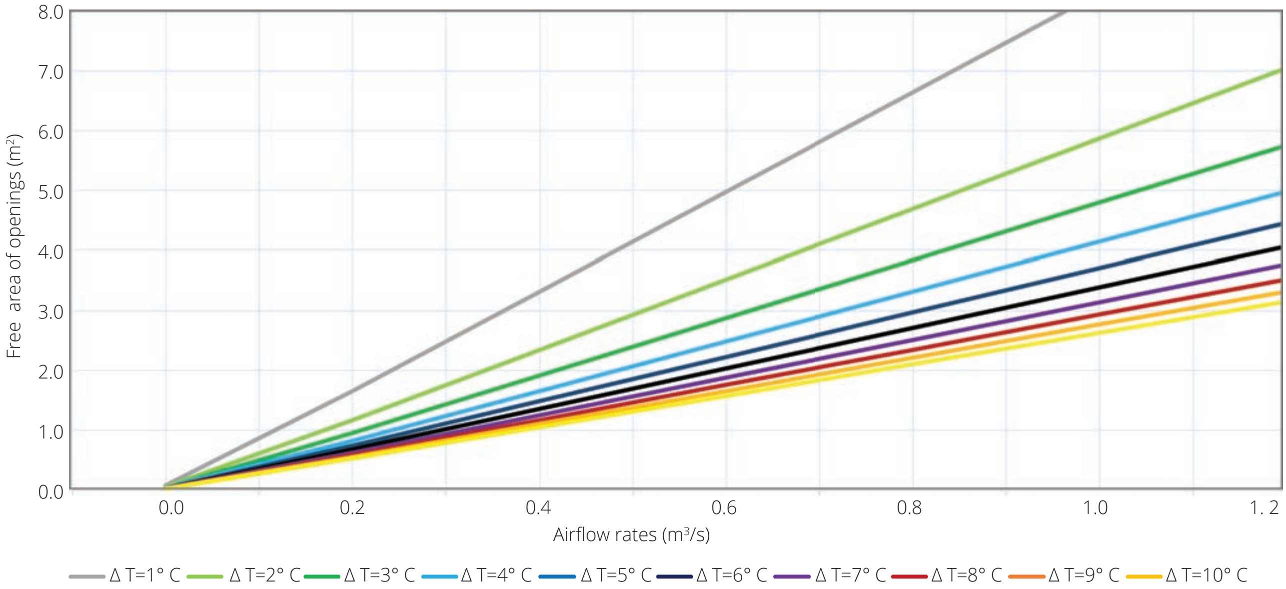


Figure 10: Design Chart DC-02 for multiple openings and buoyancy-driven flow.

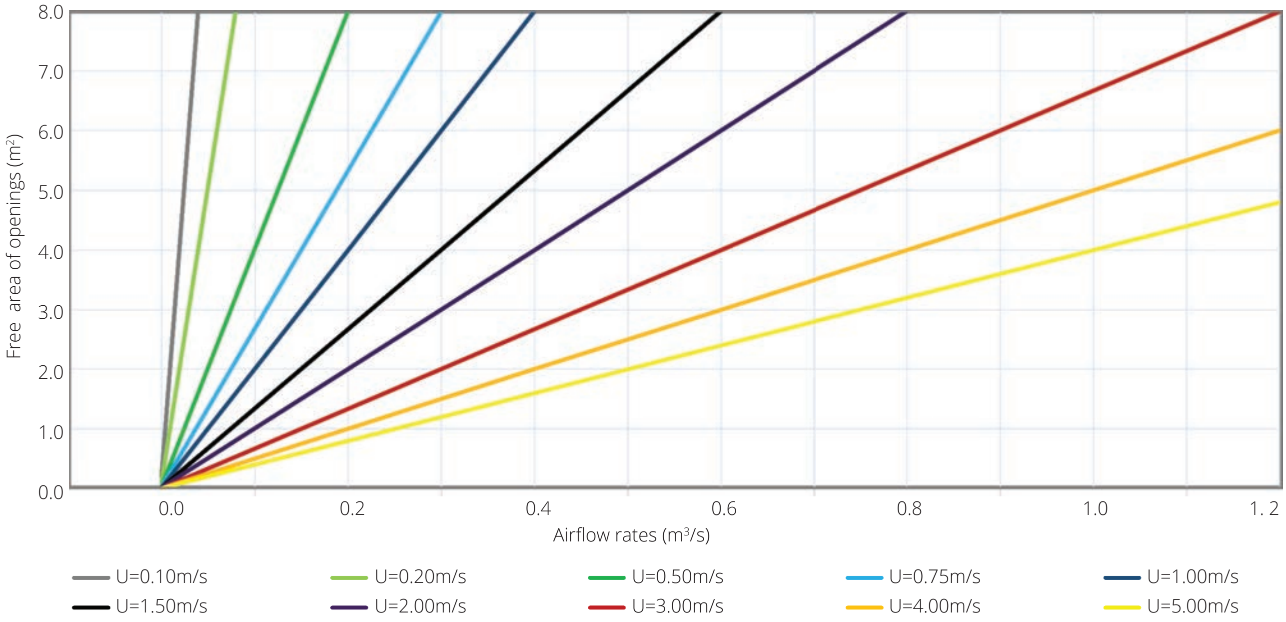


Figure 11: Design Chart DC-03 for single-sided single openings and wind-driven flow.

specify an upper limit to air speed for the situation when occupants have some control over the local environment. While the first two scenarios apply to clothing insulation ranging from 0.50 clo to 0.70 clo and metabolic rates from 1.00 met to 1.30 met, the third scenario applies to 0.50 clo to 1.00 clo and for 1.10 met. These are the scenarios used and quoted in the analysis examples provided in this design guide.

Furthermore, air velocities above 1.8m/s have been reported as comfortable and acceptable by residents of hot-humid climatic zones (Indraganti et. al., 2012, Mihara et. al., 2019). However,this design guide utilizes 1.5m/s as the upper threshold for this analysis due to limited scientific information at the present time.

3.4 Mixed- mode principles

Buildings that are designed with a mixed-mode ventilation strategy rely on natural ventilation for much of the occupied hours but also have integrated mechanical ventilation and cooling systems that are used in certain climatic or internal heat gain conditions. Mixed-mode systems include naturally ventilated buildings that are designed using one of the following approaches as defined by CBE (2007):

- Concurrent mixed-mode (Figure 13a) where both systems operate at the same space at the same time. The mechanical system operates as supplementary ventilation or cooling while the occupants are free to operate the windows based on their personal preference. This strategy is the most common form of mixed-mode ventilation strategy typically employed for open-plan offices and residential buildings.

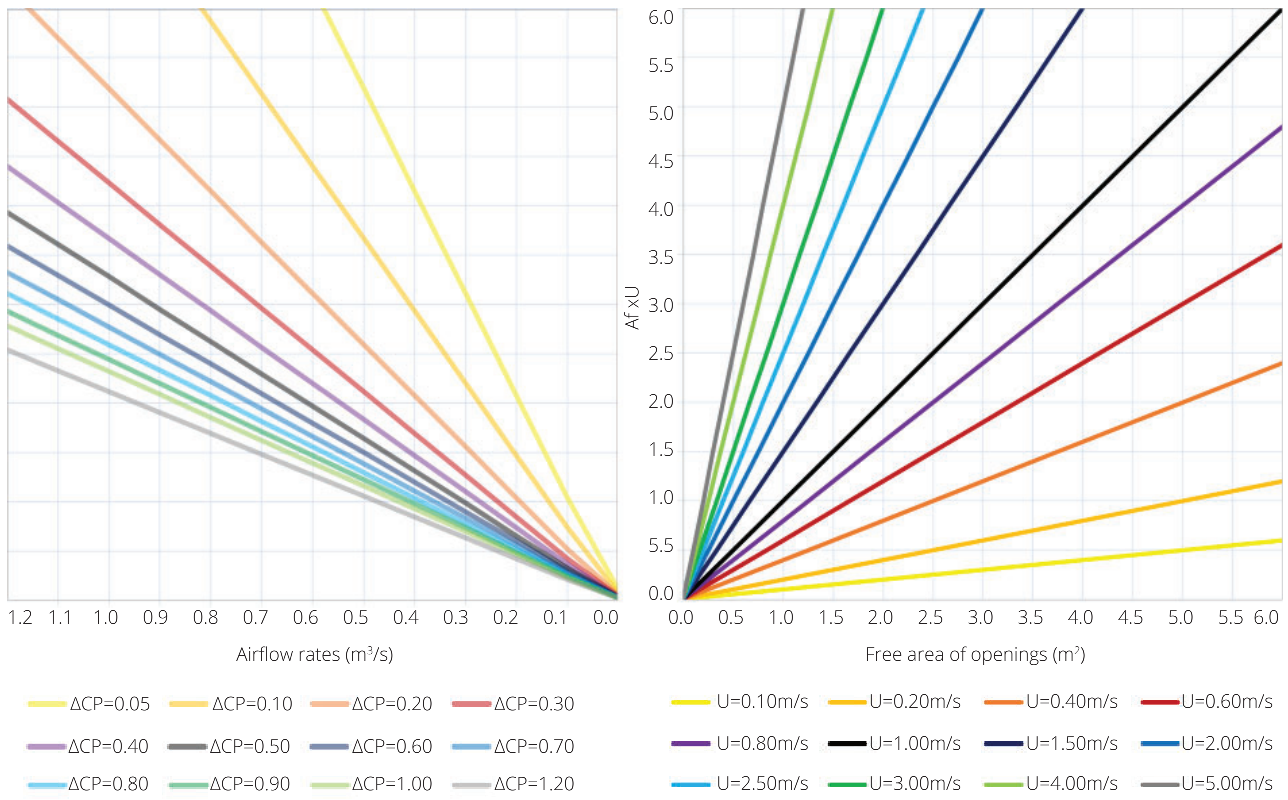


Figure 12: Design Chart DC-04 for multiple openings and wind-driven flow.

Table 3: The corresponding rise in the acceptable air temperature with the increase in the air speed.
Sources: Figure 5.2.3.1 (ASHRAE-55, 2010) and Figure 5.3.3A (ASHRAE-55, 2017).

Fan speed mode	Air speed	corresponding rise in temperature (°C)		
		as per ASHRAE 55-2010 applying: 0.50 clo to 0.70 clo; 1.00 met to 1.30 met		as per ASHRAE 55-2017 applying:
		Tr-Ta = -10	Tr-Ta = 0	0.50 clo to 1.00 clo; 1.10met
off	0.1m/s	-	-	-
I	0.6m/s	1.20	2.00	2.80
II	0.9m/s	1.80	2.70	3.40
III	1.2m/s	2.20	3.30	3.75
IV	1.5m/s	2.50	3.60	4.00

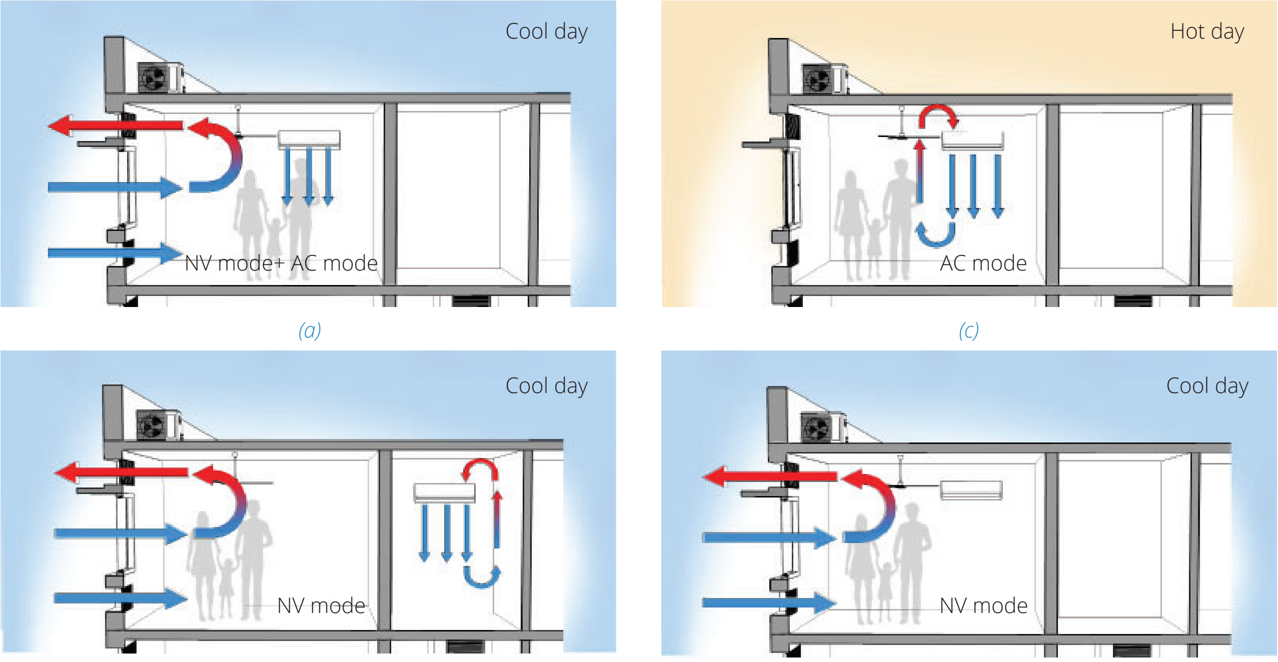
- Change-over mixed-mode (Figure 13b) where the mechanical systems and natural ventilation operate in the same space at different times of the day or year. This approach requires an automated control system to determine which mode should be used at a particular point in time. The selection is based on a variety of input parameters such as outdoor conditions and occupancy. The system operating as change-over MM in a residence can either run automatically or inform the occupants to open or close the windows and switch on/off HVAC systems.
- Zoned mixed-mode (Figure 13c) where the mechanical cooling and natural ventilation operate at the same time but in different spaces of the building. This ventilation strategy is suitable for large office buildings where some offices could use natural ventilation by operating the windows whereas other rooms such as conference rooms may require a mechanical system for fresh air distribution.

Mixed-mode ventilation presents an energy efficient alternative to full air conditioning by capitalising on the potential for natural ventilation when conditions permit. The form of mixed-mode ventilation used in this design guide is change-over mode.

3.5 Control strategies for natural and mixed mode ventilation

Whereas mechanical ventilation systems are controllable by varying fan speeds and supply air temperature, natural ventilation strategies rely solely on the control of openings to determine flow rate, and therefore temperature, in the occupied space. This makes such systems more complex as the driving forces are smaller and less predictable. Natural ventilation control systems use actuated openings and prevailing driving pressures to determine the ventilation flow rate and thus the inside air temperature.

Control systems for mixed mode ventilation have the added complexity of needing to control the switch between a mechanical and a natural ventilation system. There is little guidance available for designers of such systems, hence the need for the work reported here. However, to date, mixed mode control systems have used static setpoint temperatures to switch between natural and mechanical ventilation (Ezzeldin and Rees, 2013). The LECaVIR project proposes the use of dynamic setpoints for this purpose.



(a)

(c)

(b)

(d)

Figure 13: Classification of mixed-mode systems. Concurrent mixed-mode system (a); Change-over mixed-mode system (b); and Zoned mixed-mode system for cool day (c) and for hot day (d)

LECaVIR

PART B: DETAIL DESIGN FOR BUILDINGS

The ability to use natural ventilation for Indian residences depends on the outdoor environmental conditions, which vary with the climatic zone and location. While natural ventilation may not be feasible all year round, at the times when it is feasible, then it is possible to achieve its full potential for that condition if the appropriate strategy is selected.

4.1 Climate analysis for natural ventilation

The ventilation potential based on the outdoor conditions for the eight Indian cities used as references is shown in Table 4. The ventilation potential is calculated using the IMAC-NV and IMAC-MM thermal comfort models (Manu et. al., 2016) as per the criteria described in Chapter 2 of Part A. The ventilation potential is defined as the total number of hours in the year for which NV and MM are feasible.

4.2 Potential to extend hours of NV using the LECaVIR solutions

The LECaVIR solutions are proposed to either deliver the full potential for natural ventilation from the outdoor conditions or to extend this potential and increase the number of hours of the year for which natural ventilation can be used to deliver thermal comfort. The LECaVIR solutions combine designed openings for natural ventilation with the simultaneous use of mechanical ceiling fans to deliver thermal comfort with minimal use of energy. The air movement induced by the fan allows a rise in the acceptable operative temperature which is proportional to the increase in the air speed (this is covered in detail in Chapter 3 of Part A). This combination is referred to in this design guide as LECaVIR solutions for 'enhanced natural ventilation (NV+)'.

The total number of hours of the year for which the outdoor conditions are feasible for natural ventilation, calculated as per the IMAC-MM, and estimated with the LECaVIR solutions for NV+, are shown in Figure 14 for each of the eight Indian cities. This estimation utilizes the values for the corresponding rise in the acceptable air temperature with the increase in the air speed shown in Table 3 for the scenario with $T_{radiant} = T_{air}$ (ASHRAE, 2010) and applies to clothing insulation values ranging from 0.50 clo to 0.70 clo and to metabolic rates ranging from 1.00 met to 1.30 met. This scenario is considered likely to occur in a typical residential environment during daytime and in summer season, with NV operating and without any mechanical cooling source (i.e. a radiant cooling panel). This scenario yields more conservative values than the scenario for when occupants have some control over the local environment (ASHRAE, 2017). This figure also shows the number of hours for which mechanical cooling is required for both the IMAC-MM and the LECaVIR solutions. It is assumed here that the total number of hours for 'natural ventilation plus mechanical cooling', calculated as per the IMAC-MM, will be the same total number of hours for 'natural ventilation plus enhanced natural ventilation (NV+) plus mechanical cooling', calculated as per the LECaVIR solutions for NV+. Therefore, the increase in the number of hours with the LECaVIR solutions for enhanced natural ventilation will correspondingly decrease the same number of hours with mechanical cooling. Furthermore, it is assumed that the LECaVIR solutions will not impact on the number of hours for the following mixed-mode operating modes: Cooling and Humidification, Cooling and Dehumidification, Dehumidification, Heating, Heating and Humidification, Heating and Dehumidification and Humidification. This is assumed because the calculation of the potential hours with the LECaVIR solutions for NV+ does not change the relative humidity thresholds from the IMAC model (shown in Table 2 of Chapter 2, Part A). The sum of the number of hours for all of these other MM operation modes, calculated as per the IMAC-MM, is shown as 'other MM' in Figure 14.

Table 4: Percentage of hours of the year for which natural ventilation is feasible based on outdoor conditions calculated using the IMAC model for NV and MM buildings (Manu et. al., 2016).

City		Mumbai (MUM)	Chennai (CHE)	Kolkata (KOL)	Pune (PUN)	Ahmeda-bad (AHM)	New Delhi (DEL)	Hyderabad (HYD)	Jaipur (JAI)
Indian climatic zone		Warm-Humid	Warm-Humid	Warm-Humid	Warm-Humid	Hot-Dry	Composite	Composite	Composite
IMAC-NV	hours	2,389	1,739	1,588	2,124	1,864	1,767	3,032	2,027
	%	27%	20%	18%	24%	21%	20%	35%	23%
IMAC-MM	hours	2,401	2,026	1,680	2,616	2,977	2,506	3,774	3,137
	%	27%	23%	19%	30%	34%	29%	43%	36%

The detailed number of hours for each of these other MM operating modes is given in Figure 3 of Chapter 2, Part A.

The comparison between the number of hours shown for the IMAC and for the LECaVIR solutions demonstrates that the LECaVIR solutions for NV+ increases the number of hours for which ventilation can operate (and thus reduce the number of hours with mechanical cooling) by an average of 380 hours per year over the eight Indian cities. The initial number of hours per year for mechanical cooling is 824, calculated as per the IMAC-MM and as average over the eight Indian cities. Therefore, the application of the LECaVIR solutions with NV+ have the potential to reduce by 48% the number of hours per year for mechanical cooling as average over the eight Indian cities.

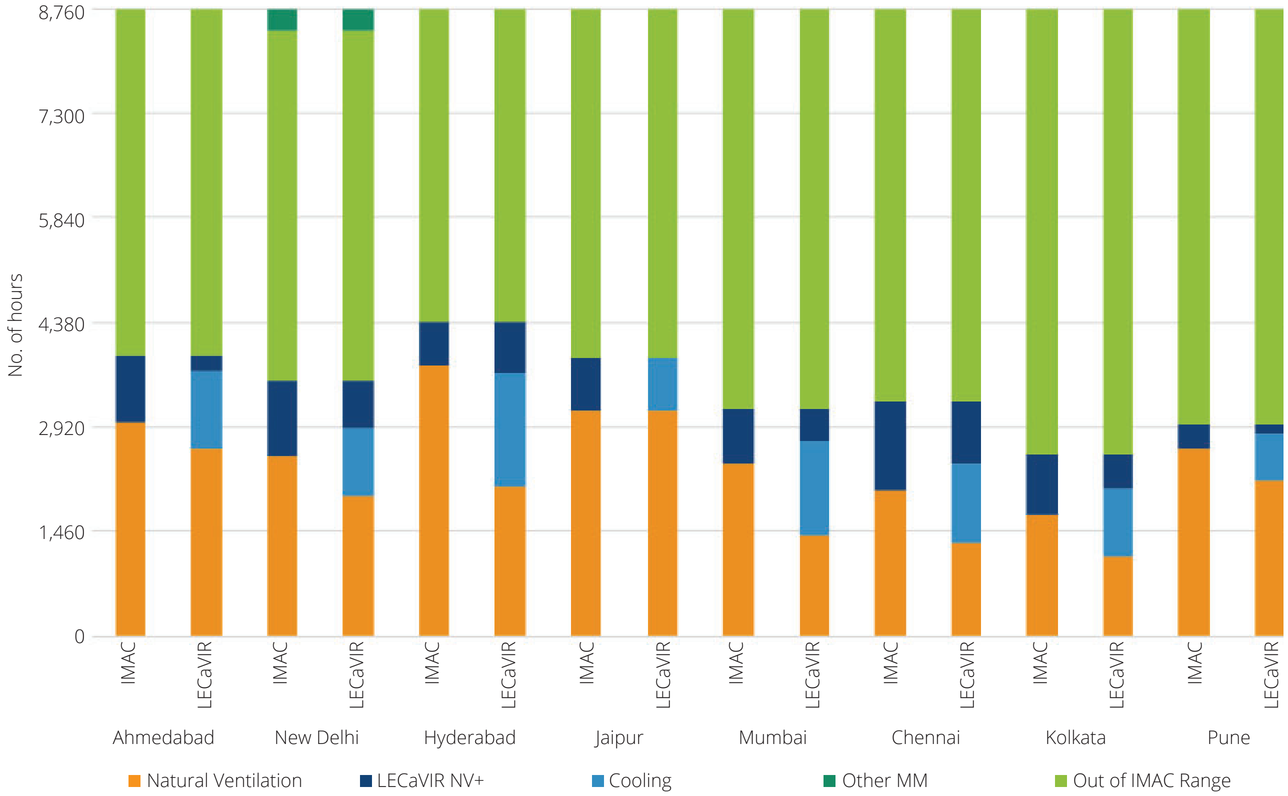


Figure 14: Number of hours in a year using 'natural ventilation, mechanical cooling and other MM', from the IMAC-MM, and using 'natural ventilation, enhanced natural ventilation (NV+), mechanical cooling and other MM', from the LECaVIR solutions for NV+ for eight Indian cities.

5.1 Summary of evidence base and main underlying assumptions employed in this guide

It is useful to remind users of some of the key assumptions and bases that underpin this guidance, and to briefly summarise them here. Identification of suitable outdoor conditions, and estimation of indoor thermal comfort conditions in this guide have been based on the Indian Model for Adaptive Comfort (IMAC), to which the reader is referred for details (Manu et al, 2014; 2016). In brief, the IMAC model has been derived from field studies conducted in sixteen offices across five Indian cities that are representative of five Indian climate zones; three seasons (summer, monsoon, winter) were represented in the field studies, and the offices covered naturally-ventilated, mixed mode, and air-conditioned modes of operation. In the IMAC model, 'mixed mode' means that the building switches from natural ventilation to air-conditioning operation in summer and monsoon seasons; that is, occupants in those buildings experienced natural ventilation for a part of the year and air conditioning at other times (Manu et al, 2015). The IMAC has been integrated into the National Building Code of India (Standards, 2016), and has therefore been used in this guide to select outdoor temperature thresholds for residential indoor thermal comfort. The ranges of 30-day running mean outdoor dry-bulb temperature values upon which IMAC is based were: 12.5-31°C for natural ventilation; 13-38.5°C for mixed mode; these have been adopted within the guidance presented in this document. Based on wider literature review, the range 30-70% RH has been utilised as that considered acceptable for comfort within this guide.

Regarding indoor air speed adjustments (via ceiling fans) made by occupants, the IMAC study incorporates this adaptive behaviour for all the naturally-ventilated and mixed mode buildings in that study. Observations generally showed an increase in indoor operative temperature with increasing mean indoor air velocity. In view of the uncertainties in relation to air temperatures acceptability at higher air velocities(ASHRAE Standard 55,2017; Cheng & Ng, 2006; Indraganti et al, 2012; Yingxin et al, 2015; Mihara et al, 2019) this design guide has taken an indoor air velocity of 1.5m/s as its upper limit.

5.2 Apartments for case study application

In this section the apartments used as case studies for the application of the LECaVIR solutions are presented. Two representative apartments were selected from the Global Buildings Performance Network (GBPN) report for India (Rawal & Shukla, 2014). Both the apartments comprise two bedrooms, a hall/living area and kitchen (2BHK). The apartment 2BHK Case-1 (Figure 15) has 85.0m^2 of built area and 60.0m^2 of carpet area, and the apartment 2BHK Case-2 (Figure 16) has 97.0m^2 of built area and 68.0m^2 of carpet area.

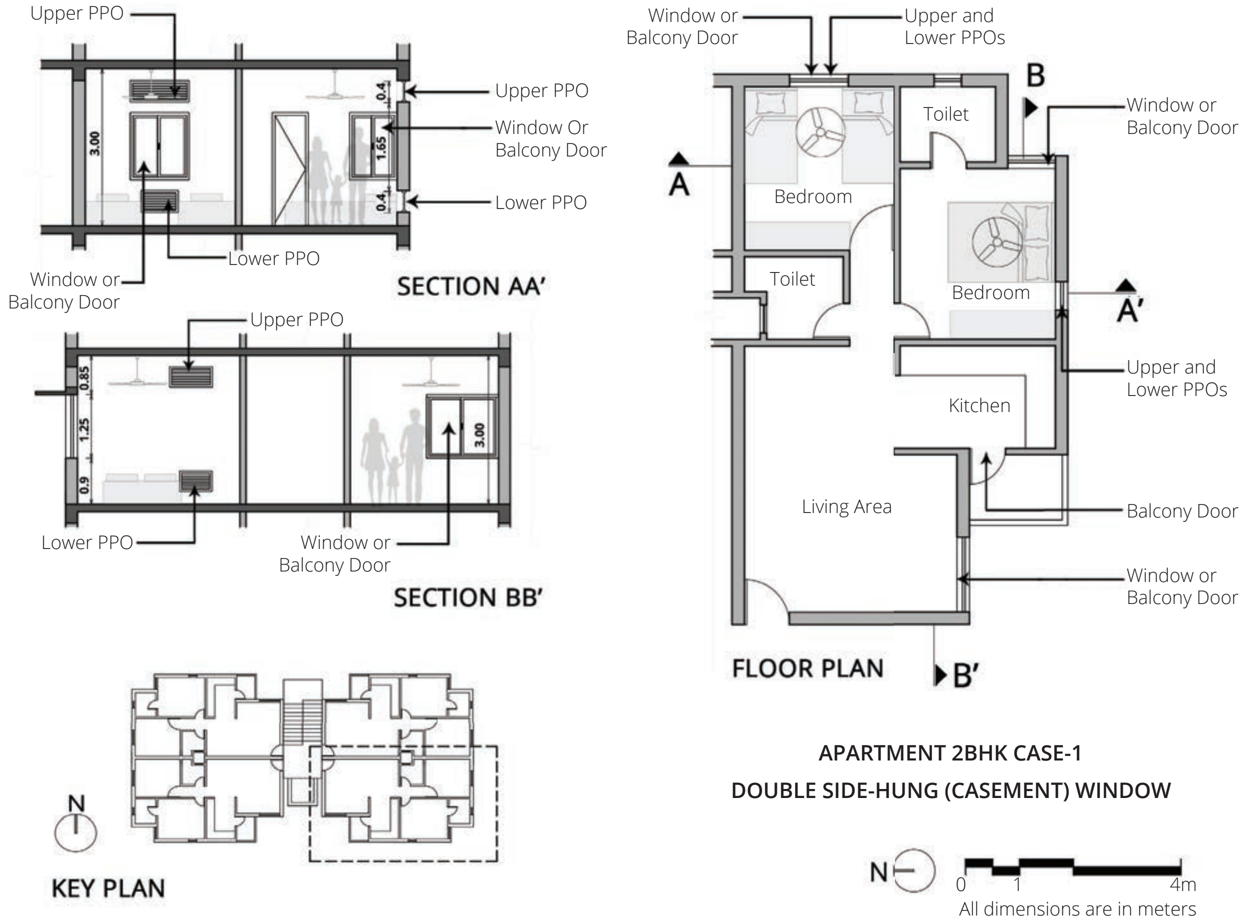


Figure 15: Case study apartment 2HBK Case-1 (Source: Rawal & Shukla, 2014): the floor plan with suggested layout (Fig. 15a), cross-section A-A (Fig.15b) showing the horizontal sliding (sash) windows and louvres of the auxiliary PPOs for ventilation.

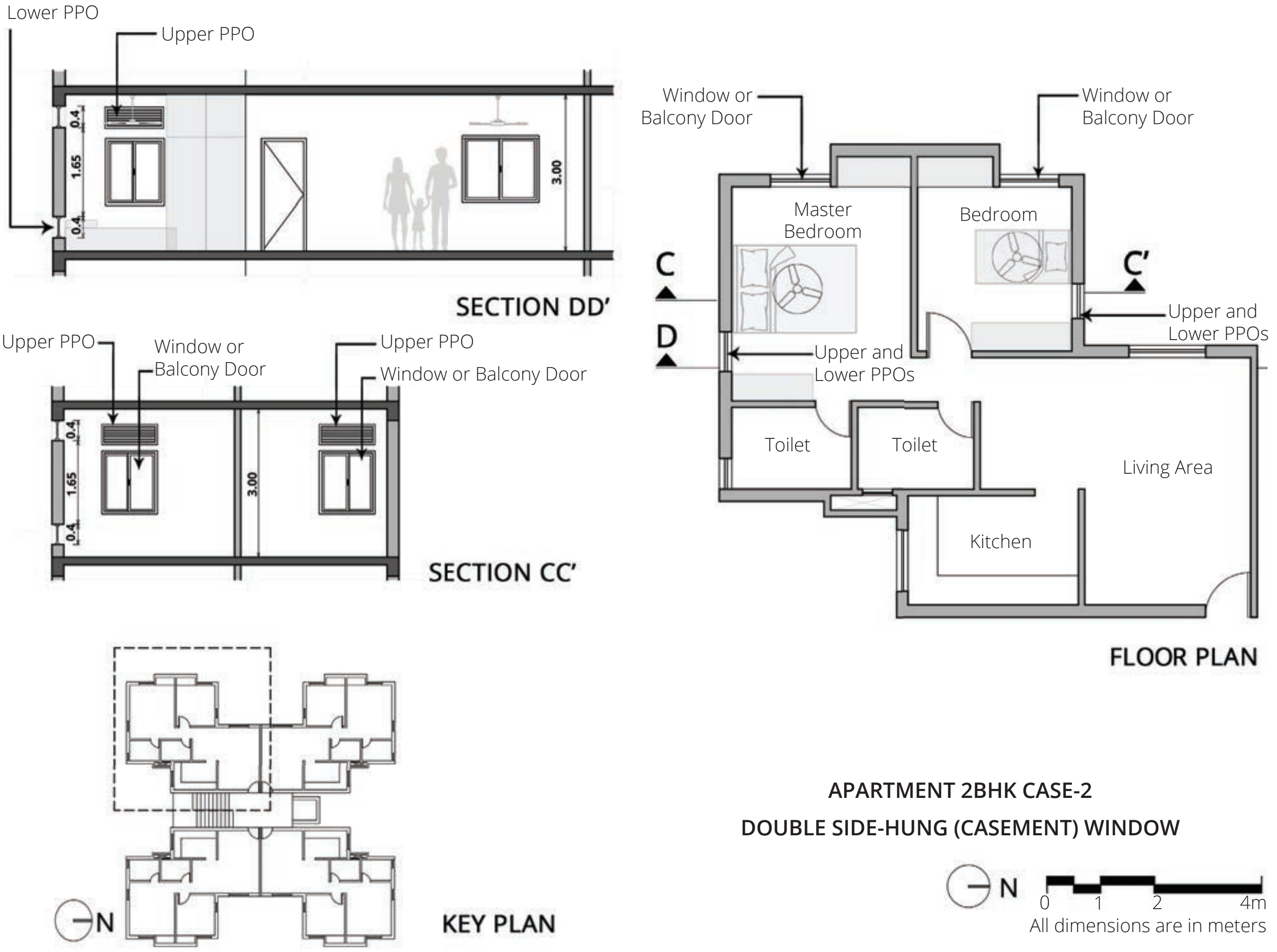


Figure 16: Case study apartment 2HBK Case-2 (Source: Rawal & Shukla, 2014): floor plan with suggested layout (Fig. 16a) and cross-section A-A (Fig.16b) showing the horizontal sliding (sash) windows and louvres of the auxiliary PPOs for ventilation.

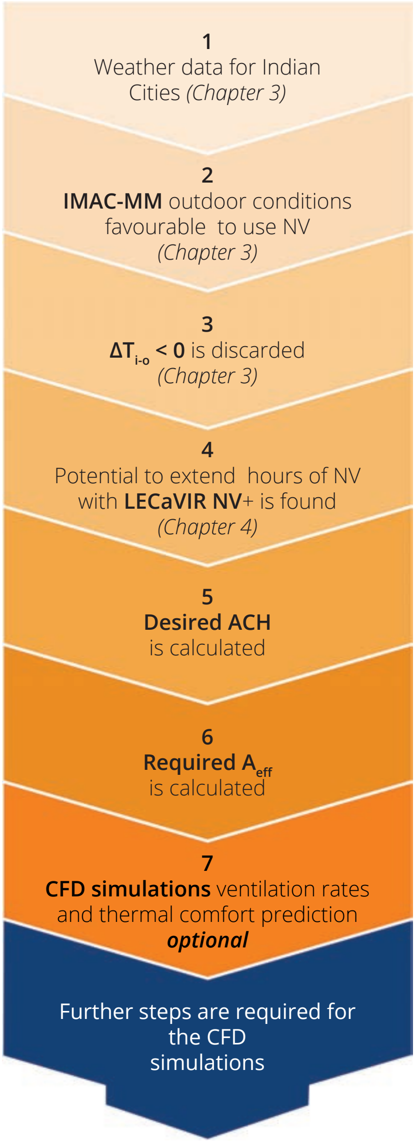


Figure 17: Steps to size the openings for the LECaVIR solutions for NV+ for Indian cities.

5.3 Steps in the application of the LECaVIR solutions NV+ for the case study apartments

This section describes the steps required to size the openings for the LECaVIR solutions to deliver thermal comfort with enhanced natural ventilation for two case study apartments for each of the eight Indian cities considered. The seven steps required for this task are shown in Figure 17. Further steps may be necessary when computational fluid dynamics (CFD) simulations, suggested as optional analysis, are performed. These further steps will be described later in this section.

The first four steps are covered in the previous chapters of this design guide. Step 5 consists of the identification of the ventilation rates which will be used to size the openings for ventilation, carried out in step 6. Step 7 consists of performing CFD simulations coupled with a model for prediction of thermal comfort sensation. The CFD simulations are used to verify if the recommended ventilation rates are being delivered by the LECaVIR solutions and if these airflow rates are sufficient to provide thermal comfort for the occupants. This last step is listed as optional since this type of simulation may not be required for all projects.

Recommended ventilation rates for thermal comfort for the case study apartments

The ventilation rates shown for the eight Indian cities in this design guide were calculated using dynamic thermal simulations, and the hours of the year for

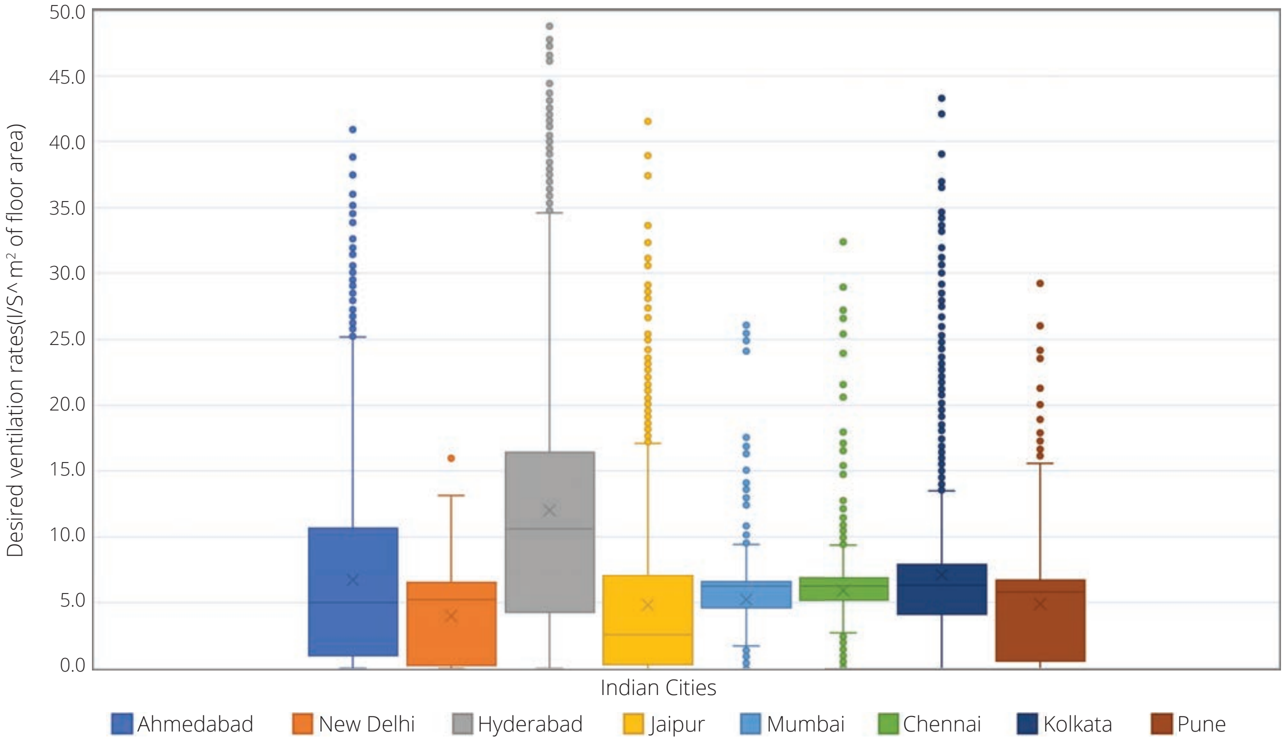


Figure 18: Recommended ventilation rates for the master bedroom (MB) calculated for the hours of the year for which outdoor conditions allow NV to happen.

which outdoor conditions permit natural ventilation were identified using criteria from the IMAC-MM. The rates are provided in Figure 18 for the master bedroom, Figure 19 for the small bedroom, and Figure 20 for the hall/living and kitchen area. The metric to inform the recommended ventilation rates is based on the ratio between the recommended flow rate and the floor area for each room as determined by dynamic thermal simulations for the case study apartments. This unit allows the identification of the ventilation rates based on the floor area for any room size and apartment layout (although these values are derived from the two-bedroom case study apartments shown in Figure 15 and Figure 16). The ventilation rates used for sizing the openings for the application examples and for the analysis of the performance of the LECaVIR solutions are shown in Table 5 and were calculated using values found at the 95th percentile of these figures (see schematic chart in Figure 21).

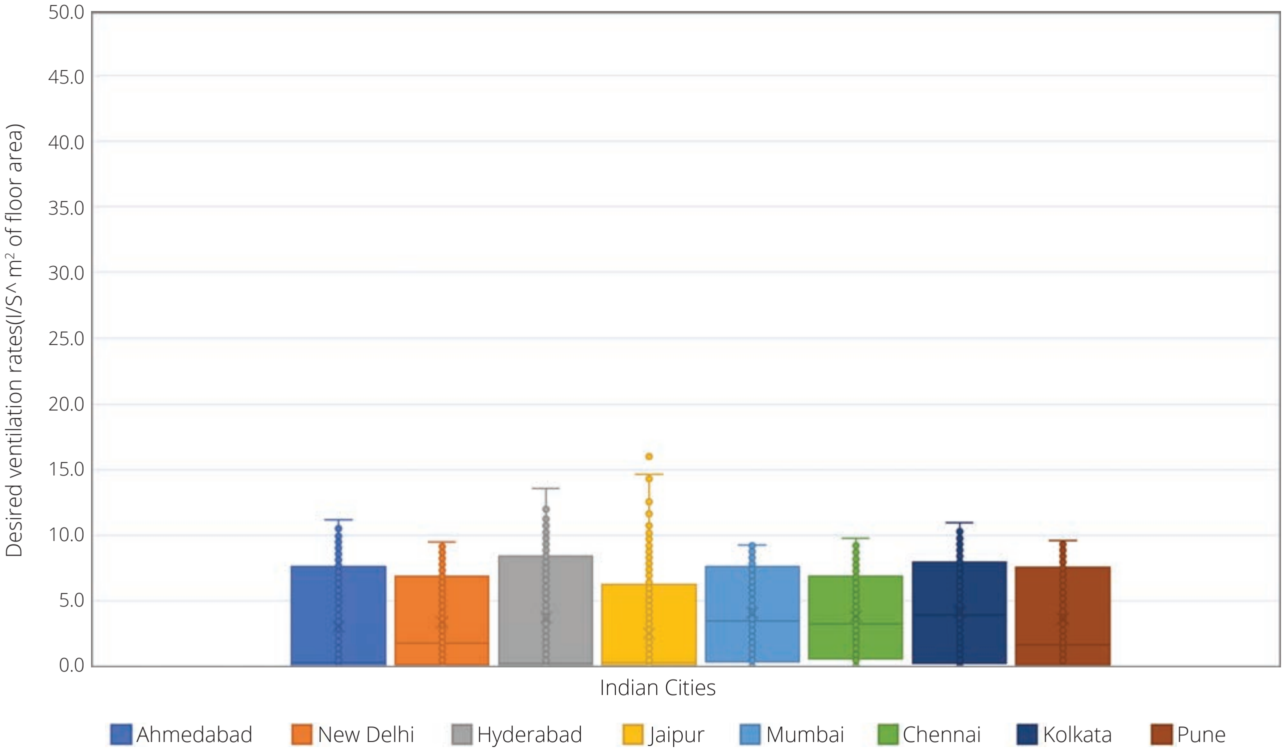


Figure 19: Recommended ventilation rates for the small bedrooms (SB) calculated for the hours of the year for which outdoor conditions allow NV to happen.

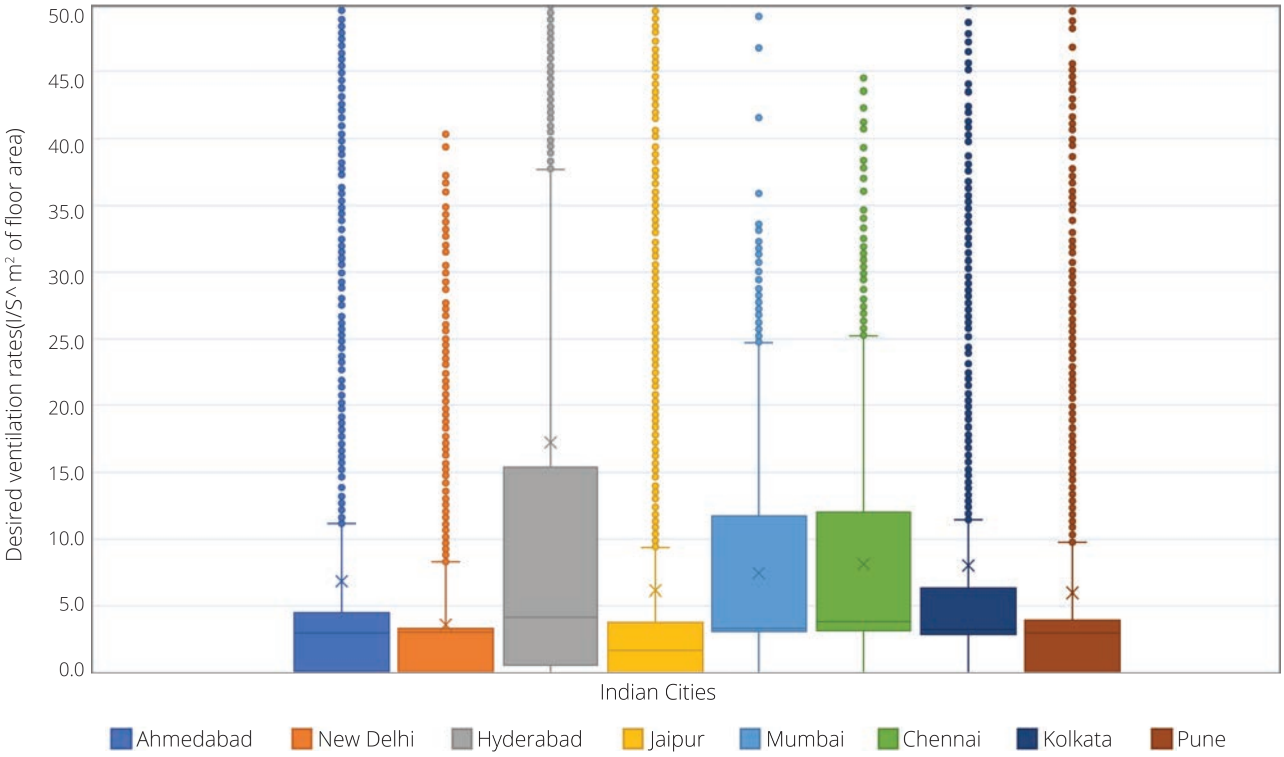


Figure 20: Recommended ventilation rates for the hall with open kitchen (given as m3/min^m2 of floor area) calculated for the hours of the year for which outdoor conditions allow NV to happen.

Table 5: Desired ventilation rates, given as m3/s, for the master bedroom (MB), the small bedroom (SB) and the hall with open kitchen (H+K) for the hours of the year for which outdoor conditions allow NV to happen, and calculated with the values at the percentile 95% found in Figure 18(MB), Figure 19(SB) and Figure 20(H+K).

case study apartment	room	AHMEDABAD		NEW DELHI		HYDERABAD		JAIPUR		MUMBAI		CHENNAI		KOLKATA		PUNE	
		m³/s	ACH	m³/s	ACH	m³/s	ACH	m³/s	ACH	m³/s	ACH	m³/s	ACH	m³/s	ACH	m³/s	ACH
2BHK Case-1	MB	0.23	27	0.09	10	0.35	41	0.17	20	0.09	10	0.10	11	0.22	26	0.13	15
	SB	0.21	27	0.08	10	0.32	41	0.16	20	0.08	10	0.09	11	0.20	26	0.12	15
	H+K	0.66	29	0.48	21	1.04	46	0.57	25	0.71	31	0.69	31	1.06	47	0.85	38
2BHK Case-2	MB	0.34	27	0.13	10	0.53	41	0.26	20	0.13	10	0.14	11	0.33	26	0.19	15
	SB	0.23	27	0.09	10	0.36	41	0.17	20	0.09	10	0.10	11	0.22	26	0.13	15
	H+K	0.70	29	0.51	21	1.12	46	0.61	25	0.76	31	0.74	31	1.14	47	0.91	38

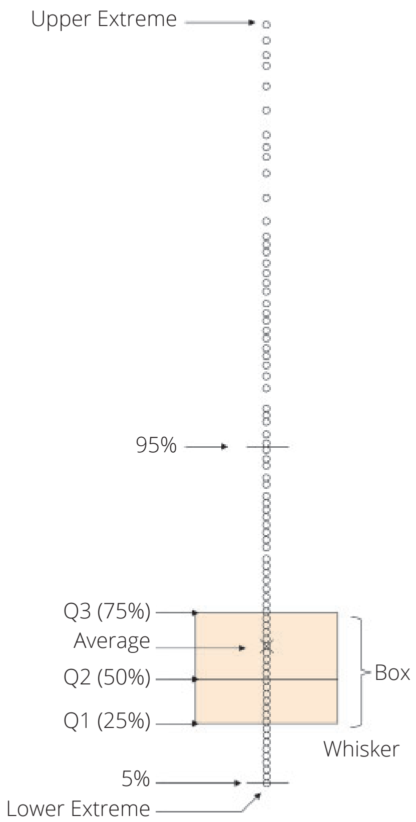


Figure 21: Schematic example of a graph showing the percentiles for the displayed values.

Opening sizes, types and arrangements for efficient NV systems

To deliver the ventilation rates identified for the rooms of the two case study apartments, the proposed openings for the LECaVIR solutions for NV+ combine either a window or a balcony door with two purpose provided openings (PPOs) for ventilation (such as louvred dampers). The PPOs are placed: one at low level near the floor, and another at high level, near the ceiling to maximise buoyancy forces. A schematic representation of the LECaVIR openings is provided in Figure 22.

The ratios between floor area and the area of PPO (A_f), provided in Table 6, are used to size the openings to deliver the calculated recommended ventilation rates. These ratios are given for the master bedroom, for the small bedroom and for the combined open plan living room and kitchen and for the eight Indian cities used as example. Two suggestions of opening types and sizes for the apartment 2BHK Case-1 and for Ahmedabad using the recommended ventilation rates from Figure 18, Figure 19 and Figure 20 and the ratios in Table 6 are given as an example in Table 7.

The suggestions of opening types and sizes for all Indian cities covered in this design guide for both apartment layouts are provided in Appendix 2.

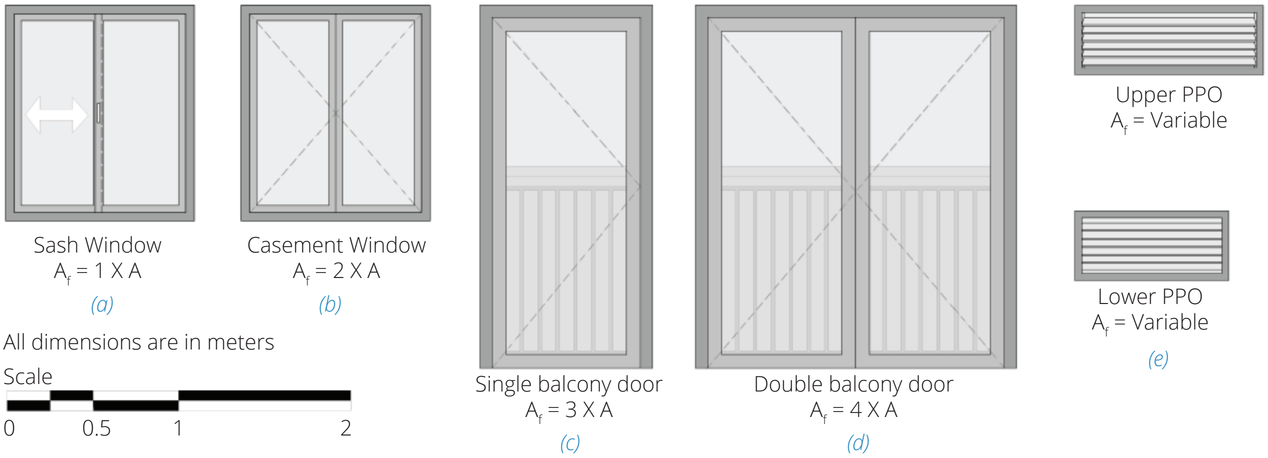


Figure 22: Schematic view of LECaVIR openings for ventilation: sash window (a), casement window (b), single balcony door (c), double balcony door (d) and PPOs for ventilation (e) (Source: de Faria et al., 2018).

Table 6: Ratios between effective open area for the openings for ventilation (A_f) and floor area to size the openings for natural ventilation.

	room	LECaVIR openings opening type	opening area / floor area	Ahmedabad	New Delhi	Hyderabad	Jaipur	Mumbai	Chennai	Kolkata	Pune
2BHK Case-01	MB	upper PPO	$(m^2 A_f / m^2 A_{room})$	0.12	0.12	0.19	0.10	0.19	0.19	0.18	0.09
		window/balcony door	$(m^2 A_f / m^2 A_{room})$	0.07	0.09	0.18	0.05	0.22	0.17	0.21	0.05
		lower PPO	$(m^2 A_f / m^2 A_{room})$	0.03	0.02	0.03	0.02	0.02	0.02	0.03	0.02
	SB	upper PPO	$(m^2 A_f / m^2 A_{room})$	0.14	0.19	0.20	0.12	0.20	0.22	0.20	0.10
		window/balcony door	$(m^2 A_f / m^2 A_{room})$	0.11	0.16	0.19	0.08	0.30	0.34	0.22	0.08
		lower PPO	$(m^2 A_f / m^2 A_{room})$	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
	H+K	window/balcony door	$(m^2 A_f / m^2 A_{room})$	0.07	0.09	0.19	0.05	0.09	0.12	0.19	0.06
2BHK Case-02	MB	upper PPO	$(m^2 A_f / m^2 A_{room})$	0.09	0.09	0.13	0.07	0.13	0.13	0.12	0.07
		window/balcony door	$(m^2 A_f / m^2 A_{room})$	0.06	0.07	0.14	0.04	0.16	0.12	0.16	0.04
		lower PPO	$(m^2 A_f / m^2 A_{room})$	0.02	0.01	0.02	0.02	0.01	0.01	0.02	0.01
	SB	upper PPO	$(m^2 A_f / m^2 A_{room})$	0.13	0.17	0.20	0.11	0.18	0.20	0.19	0.10
		window/balcony door	$(m^2 A_f / m^2 A_{room})$	0.11	0.15	0.17	0.08	0.28	0.32	0.20	0.07
		lower PPO	$(m^2 A_f / m^2 A_{room})$	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01
	H+K	window/balcony door	$(m^2 A_f / m^2 A_{room})$	0.06	0.08	0.18	0.05	0.08	0.11	0.18	0.06

Table 7: Two suggestions of opening types and sizes for the apartment 2BHK Case-1 in Ahmedabad.

AHMEDABAD								
case study apartment		A_f (m²)	Suggestion 1			Suggestion 2		
			opening type	dimension (m)		opening type	dimension (m)	
				W1	H1		W1	H1
2BHK Case-01	MB	1.33	upper PPO	2.21	0.60	upper PPO	2.66	0.50
		0.78	window	0.71	1.10	balcony door	0.38	2.05
		0.28	lower PPO	0.79	0.35	lower PPO	0.69	0.40
	SB	1.45	upper PPO	2.41	0.60	upper PPO	2.90	0.50
		1.15	window	1.04	1.10	balcony door	0.56	2.05
		0.18	lower PPO	0.51	0.35	lower PPO	0.45	0.40
	H+K	1.93	balcony door	0.94	2.05	balcony door	0.94	2.05
		1.93	window	1.76	1.10	balcony door	0.94	2.05

Thermal comfort predictions for the LECaVIR solutions for NV+ applied to the case study apartments

This section provides information about the predicted thermal comfort sensation which can be potentially achieved for the case study apartments when the LECaVIR solutions for NV+ are employed. To identify the predicted thermal comfort sensation, transient CFD simulations coupled with a thermal comfort model were performed for the master-bedroom (MB) of the two case study apartments. In these simulations all doors are considered closed due to privacy reasons during night-time occupation. The CFD simulations were performed for two reasons: to calculate the ventilation rates achieved with the proposed LECaVIR solutions for NV+; and to confirm if these rates can deliver acceptable thermal comfort. For this reason, this analysis focused on the most demanding hot weather conditions for which natural ventilation is still feasible. To identify the climatic conditions and the boundary parameters for the simulations, some additional steps (Figure 23) were added to the initial seven steps provided to

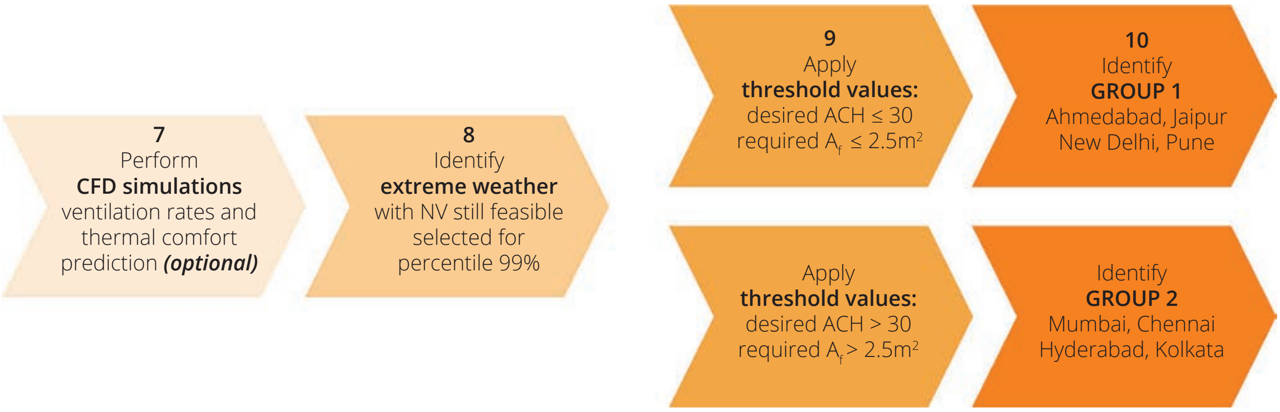


Figure 23: Further steps used in this design guide to group the Indian cities based on extreme weather conditions to be simulated in CFD coupled with thermal comfort model.

size the openings for the LECaVIR solutions for NV+, shown in Figure 17. With the new steps, the eight Indian cities used as examples in this design guide are assembled into two groups. This is done to reduce the total number of CFD simulations whilst maintaining the integrity of the analysis. Group 1 (G1) comprises Ahmedabad, New Delhi, Jaipur and Pune, and Group 2 (G2) comprises Mumbai, Chennai, Hyderabad and Kolkata. The airflow rates identified for extreme weather condition for each city and the averaged values for each assembled group (considered as targets for the CFD simulations) are shown in Table 8, for Group 1, and Table 9, for Group 2.

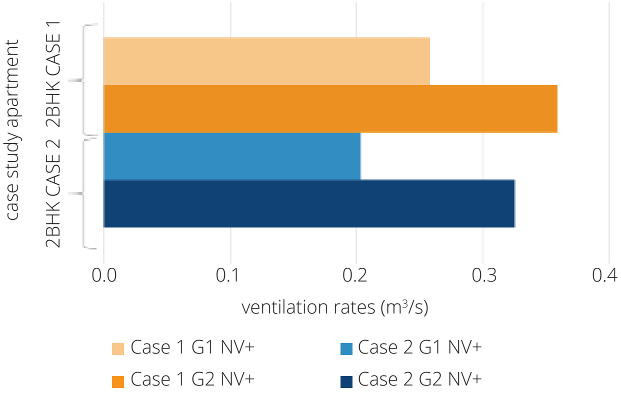


Figure 24: Ventilation rates from the CFD simulations for the master bedroom of the two case study apartments and for two hot weather scenarios.

The ventilation rates for the master bedroom of the case study apartments from the CFD simulations are shown in Figure 24. These results show that, with the LECaVIR solutions for NV+, the achieved airflow rates range from $0.20m^3/s$ to $0.36m^3/s$ for both case study apartments and exceed the target minimum values set as $0.18m^3/s$ for the Indian cities in Group 1 and $0.35m^3/s$ for the Indian cities in Group 2.

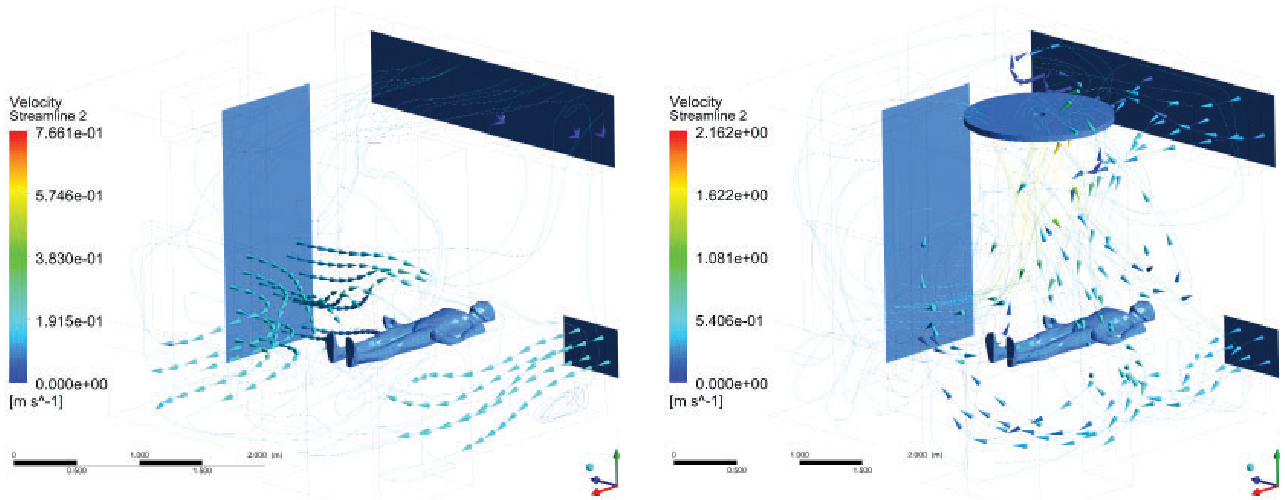
Figure 25 illustrates the airflow streamlines produced in the CFD simulations for two scenarios: without the ceiling fan (Fig.25a) and with the ceiling fan (Fig.25b). The openings in these 3D models for the MB of the apartment 2BHK Case-1 combine a balcony door with two PPOs for ventilation and have the dimensions suggested by the LECaVIR solutions for NV+ for the Indian cities in Group 2.

Table 8 Desired ventilation rates for the master bedroom (MB) of the apartment 2BHK Case-1 for the Indian cities arranged in Group 1. Rates were calculated for the hours of the year for which outdoor conditions allow NV to happen, and calculated with the values

	city	**Ahmedabad**	**New delhi**	**Jaipur**	**Pune**	**Averaged values for group 1**	**Thresholds for group 1**
	Climatic region	**Hot dry**	**Composite**	**Composite**	**Warm humid**		
Desired airflow rates	(ACH)	28	19	24	15	22	- desired ACH ≤ 30
	(m^3/s)	0.24	0.16	0.21	0.13	0.18	

Table 9 Desired ventilation rates for the master bedroom (MB) of the apartment 2BHK Case-1 for the Indian cities arranged in Group 2. Rates were calculated for the hours of the year for which outdoor conditions allow NV to happen and calculated with the values

	city	**Mumbai**	**Chennai**	**Hyderabad**	**Kolkata**	**Averaged values for group 1**	**Thresholds for group 2**
	Climatic region	**Warm humid**	**Warm humid**	**Composite**	**Warm humid**		
Desired airflow rates	(ACH)	34	35	55	37	40	- desired ACH > 30
	(m^3/s)	0.29	0.30	0.47	0.32	0.35	



(Fig.25a) *(Fig.25b)*

Figure 25: Airflow pattern inside the MB of the case study apartment 2BHK Case-1 for two LECaVIR openings solutions for the Indian cities in Group 2: with NV (Fig.25a); and with NV+ (Fig.25b).

The resulting streamlines for the scenario without the fan show a typical pattern for buoyancy-driven flow, i.e. the air rises and leaves the space at high level, drawing cooler, ambient air in at low level.

This pattern is modified in the scenario with the fan, in which the turbulent vortices break down the temperature stratification and the inlet/outlet direction are influenced by the mechanical fan. The streamlines in Figure 25b show that the air enters through both the low level and the high level openings. Conversely, both scenarios show streamlines of cooler air coming from outside through the openings positioned at low level and flowing above the bed. This illustrates that, with the suggested set of openings, cross-ventilation occurs in the absence of wind and with doors closed.

The results for dynamic thermal sensation (DTS, in Figure 26) and for averaged predicted percentage of dissatisfied (PPD, in Figure 27) show that, with the LECaVIR solutions for NV+, the thermal sensation reaches near neutral thermal comfort with only 11% of dissatisfied residents in both case study apartments and for the two groups of Indian cities. The results for DTS and PPD from the CFD simulations coupled with thermal comfort model apply to clothing insulation values ranging from 0.47 clo to 0.56 clo and for metabolic rate of 0.80 met (CIBSE, 1986). These parameters were selected to reproduce conditions of a person resting on a bed during summertime. The clo values were calculated employing the model described by Havenith et. al. (1990) which utilizes thermal insulation values for selected clothing ensembles (CIBSE, 2010) and results from the coupled simulation (average skin temperature, ambient temperature, average clothing surface temperature, total dry heat loss from the body surface to the environment).

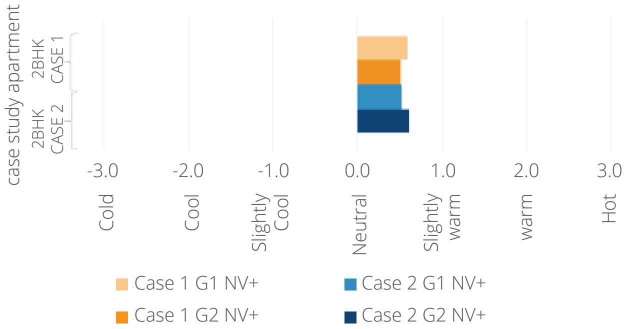


Figure 26: Results for dynamic thermal sensation (DTS) from the CFD simulations coupled with the thermal comfort model for the two case study apartments and for two hot weather scenarios.

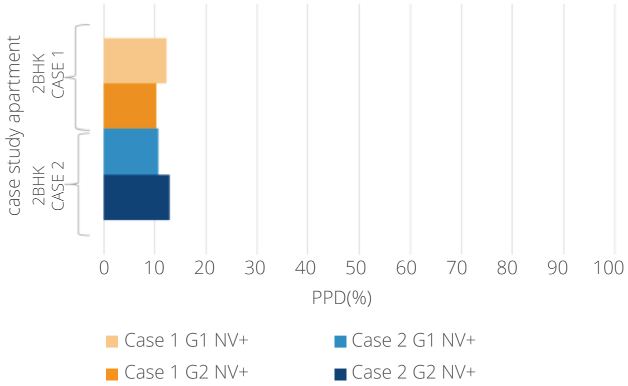


Figure 27: Results for predicted percentage of dissatisfied (PPD) from the CFD simulations for the two case study apartments and for two hot weather scenarios.

The main challenge in the design of control systems in mixed-mode buildings is finding the balance between energy use, indoor thermal conditions, indoor air quality, user satisfaction and robustness. Although users should be freely able to control their own environment, automatic control is preferred in many cases of mixed-mode buildings due to the complexity of the mixed-mode systems. Chapter 6 describes the flexible and self-learning control algorithms developed for effective operation of NV and MM cooling strategies in residential apartment buildings in India.

The chapter is divided into three sections. The first section provides a brief introduction to the control strategies developed during the LECaVIR project. The second section describes the control strategies for natural and mixed-mode ventilation in detail and the third section describes the self-learning algorithms. Additional flowcharts of the developed control algorithms are presented in Appendix 3.

6.1 LECaVIR control strategies

The control strategies for MM residential buildings are developed as a set of stand-alone yet interconnected control modules. These control modules incorporate building and system characteristics and operation patterns as control inputs to control envelope and system components. Applicable control modules should be selected and applied based on the installed envelope and system components in a building.

The following control strategies have been developed as part of the project:

- Building Operation Mode: This control strategy determines suitable operation mode of the building based on prevailing indoor and outdoor conditions.
- NV Components: This control strategy determines operation of NV components, such as windows and dampers, in the building based on set points as well as prevailing indoor and outdoor conditions. Further, a self-learning strategy is developed that utilizes the historical data of ventilation opening position, prevailing outdoor conditions, and prevailing indoor conditions to adjust control algorithms of natural ventilation components.
- Air Circulation Devices: This control strategy determines operation of air circulation devices, such as ceiling and pedestal fans, in the building based on set points as well as prevailing indoor conditions.
- Mechanical System Operation: This control strategy determines operation of the present mechanical cooling systems, such as evaporative cooling system, split air conditioning system, or fan coil units, based on defined cooling set points as well as prevailing indoor conditions. Further, a self-learning strategy is developed that uses the historical data of system operation schedule and indoor temperature to adjust start-up time for air conditioning systems.

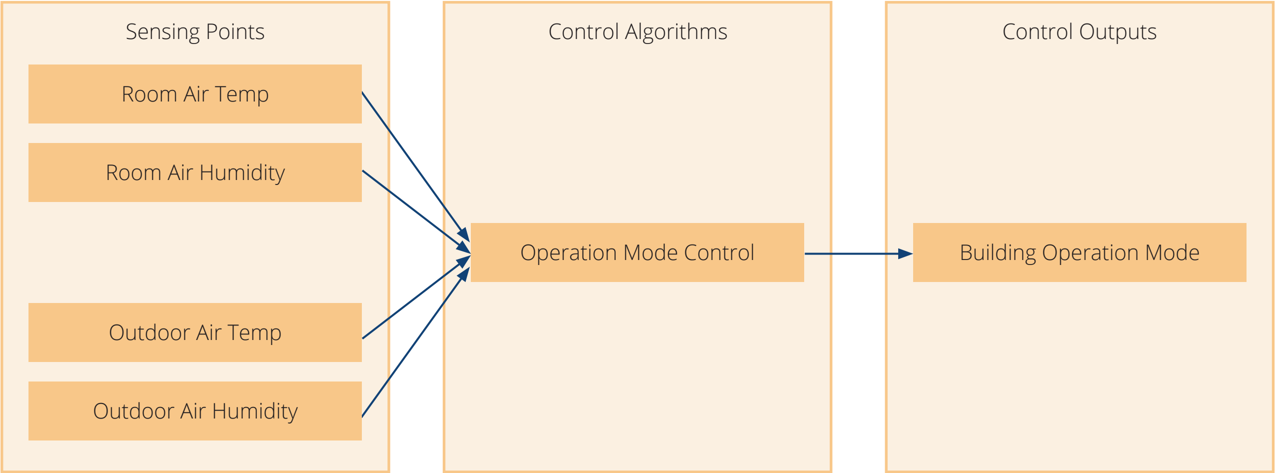


Figure 28: Schematics of Building Operation Mode Control.

6.2 Mixed-mode control algorithms

This subsection describes the developed control algorithms for mixed-mode buildings. The control algorithms are presented in the form of schematics and flow charts with a variety of control parameters in order to control the passive and mechanical systems.

Building Operation Mode

It is critical to determine the suitable operation mode to maximize the energy and comfort benefits in a mixed-mode building. The control strategy needs to effectively determine whether the building should operate in NV, Free-running (FR), or AC mode. Figure 28 shows the schematics of building operation mode control strategy. As shown in the figure, indoor and outdoor conditions are used to determine a suitable operation mode of the building. Once the operation mode is determined, the suitable components can be operated to maintain thermal comfort and indoor air quality inside the building.

Figure 29 shows flowchart of building operation mode control strategy. Firstly, the control strategy checks whether the prevalent outdoor conditions are suitable to maintain comfortable indoor conditions as well as indoor air quality. If the outdoor conditions are found suitable, the building is operated in NV mode. In NV mode, envelope components are modulated to maintain conditions inside the building. If the outdoor conditions are not found suitable to operate in NV mode, the algorithm checks whether the indoor conditions and indoor air quality can be maintained in FR building mode. In the FR mode, active (mechanical) and passive systems are turned off except to maintain a minimum indoor air quality threshold inside the building. If NV or FR mode cannot maintain comfortable conditions inside the building, the building is switched to AC mode. In AC mode, active systems are turned on to maintain comfortable indoor conditions as well as indoor air quality. The air circulation devices are allowed to operated (as required) during all the building operation modes.

The control algorithm is designed to periodically check whether the indoor and outdoor conditions requires switching to a different building operation mode. Different comfort approaches, such as adaptive comfort model or user-defined setpoints, are pre-programmed in the control algorithms to provide flexibility during implementation. Further, the default values can be set in the control algorithms if a specific sensing point is not available in a building.

Operation of NV Components

The NV component operation could have a significant impact on the overall thermal and energy performance of mixed-mode buildings. Hence, it is essential to effectively control the opening of the windows to optimize the performance of the building. Traditionally, operation of NV components are performed by occupants based on prevailing outdoor conditions and their own personal preferences. A few buildings with automated control operate NV component based on fixed

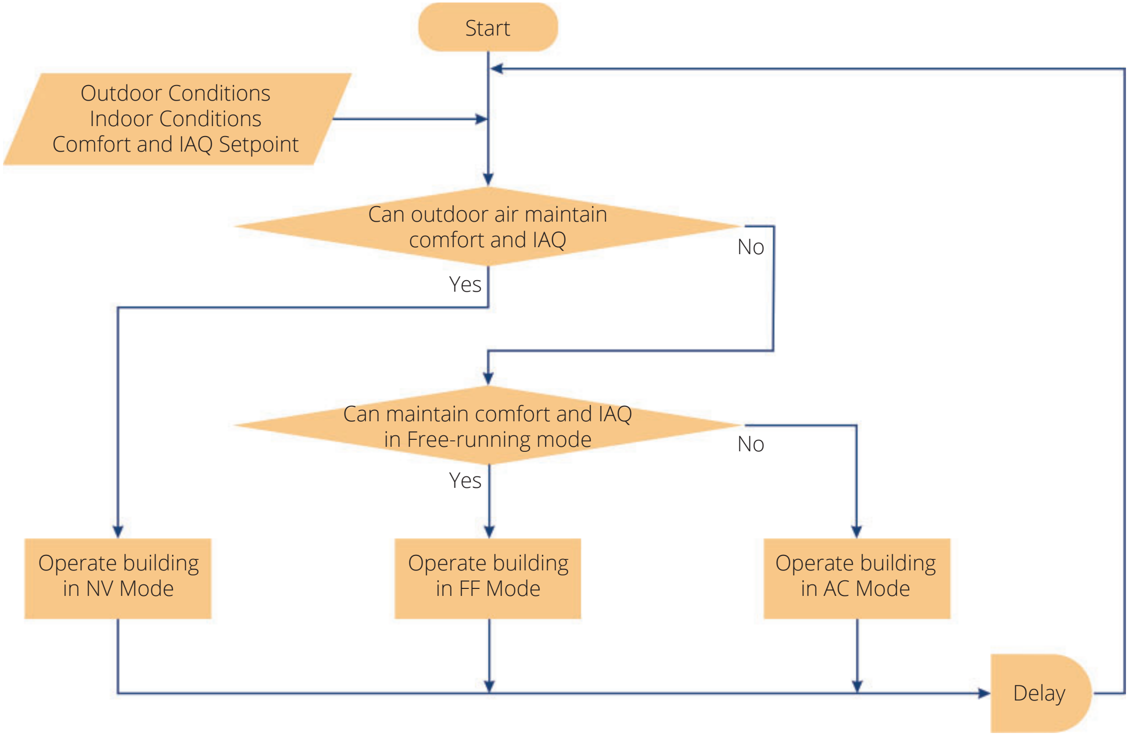


Figure 29: Operation Mode Control Strategy

outdoor temperature thresholds. A new control strategy, developed using building physics, is proposed in this project to control operation of NV components. Figure 30 shows the schematics of the NV component operation strategy proposed in the project.

The proposed control strategy (Figure 31) determines operation of NV components, such as windows and dampers, in the building based on set points as well as prevailing indoor and outdoor conditions. At first, the control strategy calculates the effective opening area needs of the building based on the prevalent indoor and outdoor conditions. Equation 2 is used to estimate the effective opening area of the NV components to achieve comfortable conditions inside the building (CIBSE Guide B, 2005):

$$A_{eff} = \frac{\dot{m}_{total}}{\sqrt{0.05^2 {V_r}^2 + {C_d}^2 \left[\frac{2\left[T_{int,aver} - T_{out,aver}\right] h_a g}{\bar{t} + 273}\right]}} \qquad \text{Eq. 2}$$

The total airflow ($\dot{m}_{total}$) required through the opening is calculated based on the internal temperature and cooling setpoints of the building. Once the effective area requirements are calculated, control strategy checks if the building has sufficient opening area to provide required cooling in the building.

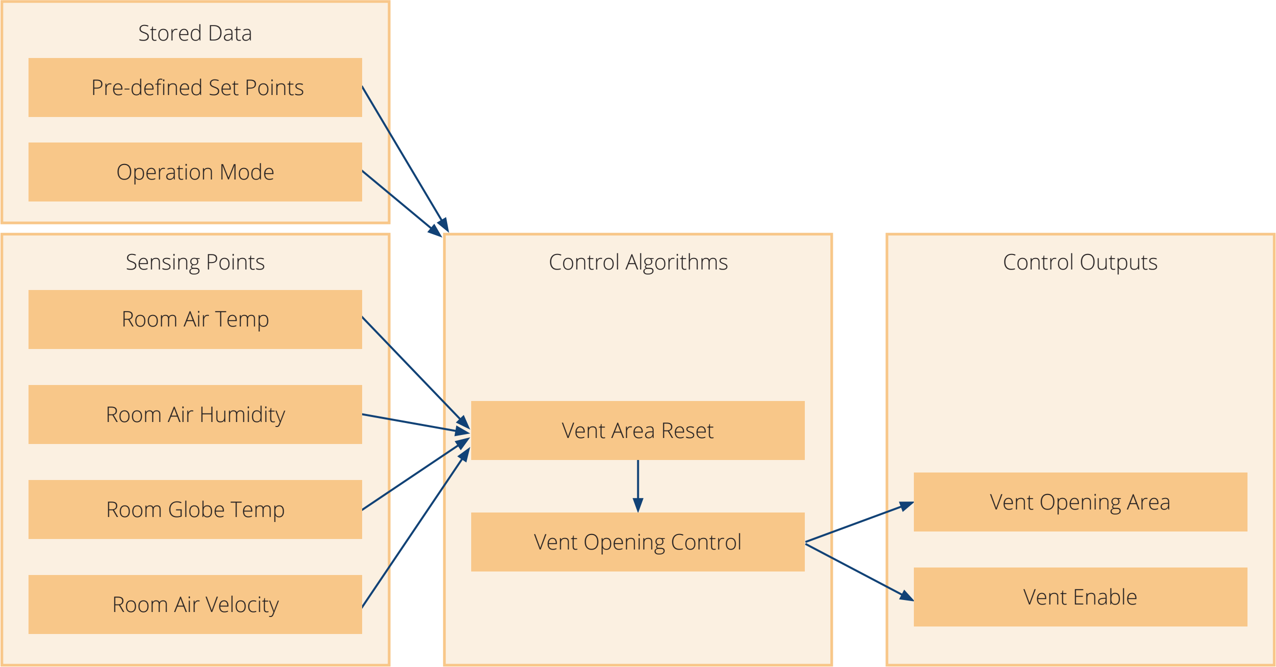


Figure 30: Schematics of Operation of NV Components

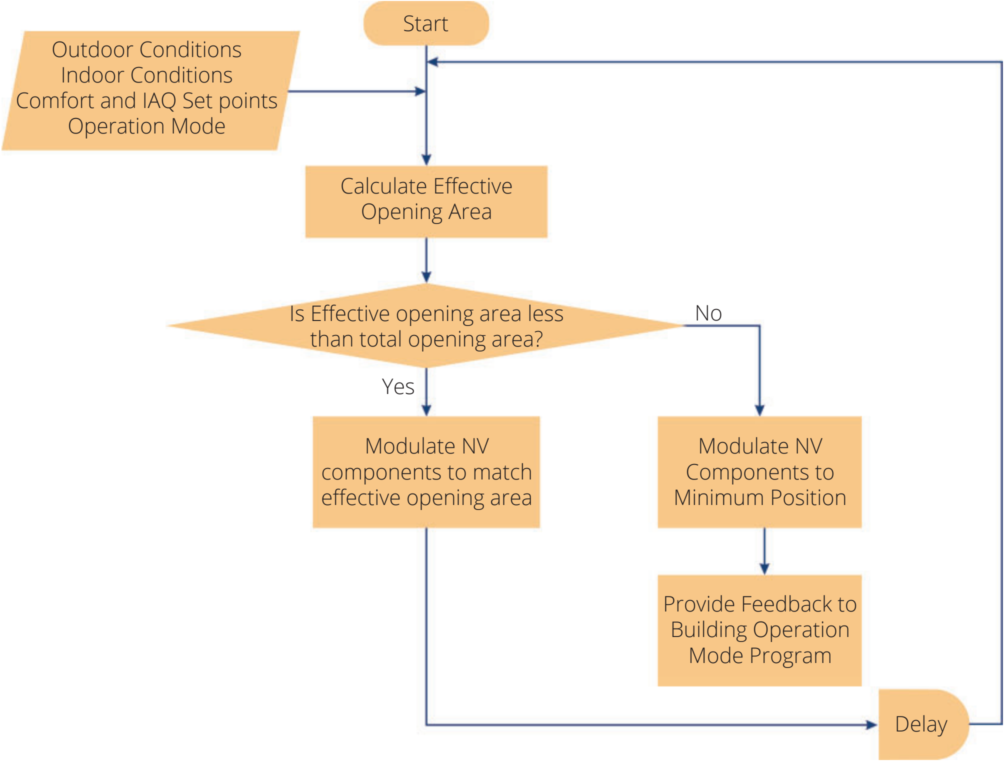


Figure 31: Flowchart of Control Strategy of NV Components

If the available total opening area of all the NV components is less than the calculated effective opening area, the NV components are modulated to minimum position and feedback is provided to the building operation mode indicating that the NV mode is unable to maintain comfort in the building. If the available total opening area of all the NV components is more than the calculated effective opening area, the NV components are modulated to provide cooling to the space.

Dampers, if installed, are opened first in the building. If still more opening area is required, window openings are modulated to match the calculated required effective area for the given conditions. The priority of specific NV components can be set in the control algorithms to allow flexibility of implementation to the control engineers. The control strategy periodically checks whether the indoor and outdoor conditions requires switching to a different building operation mode or adjustment of opening area of NV components.

The self-learning algorithms allow control strategies to adjust and optimize the operation of MM buildings based on specific system and building dynamics. Figure 32 shows the self-learning control strategy developed to adjust the ventilation opening algorithm using the historical data. As seen in the figure, the self-learning strategy utilizes the historical data of ventilation opening position, prevailing outdoor conditions, and prevailing indoor conditions to adjust control algorithms of the natural ventilation components.

At first, the strategy segregates the relevant measurement information from the historical data. Further, the strategy compares the expected benefits of ventilation opening area against the measured data calculated based on indoor and outdoor conditions. Finally, the coefficients are developed using self-learning algorithms to more accurately predict the impacts of the ventilation opening area. These coefficients are then incorporated in Equation 2, to estimate the effective area opening control. The self-learning control strategy allows the control engineers to implement the natural ventilation opening control for a wide variety of mixed-mode building applications.

Operation of Air Circulation Devices

The adjustment of the indoor air velocity is one of the most important behavioural adaption mechanisms for the occupants of a building. Air movement, especially in warm and humid climates, can improve the thermal sensation of occupants (Zhai et al., 2015). This control strategy determines operation of air circulation devices, such ceiling and pedestal fans, in the building based on set points as well as prevailing indoor conditions.

Figures 33 and 34 show the control strategy developed for operation of air circulation devices. The control strategy first calculates air velocity setpoint based on indoor conditions inside the building and findings from the IMAC study (Manu et al, 2014; 2016). The IMAC study derived mean air velocity maintained inside the building at various indoor temperatures. These derived air velocity values are used in the control strategy to calculate the air velocity set points. The speed of air circulation devices are modulated inside the building to maintain indoor air velocity setpoint.

ASHRAE Standard 55 (2010) has quantified the benefits of increased air velocity on operative air

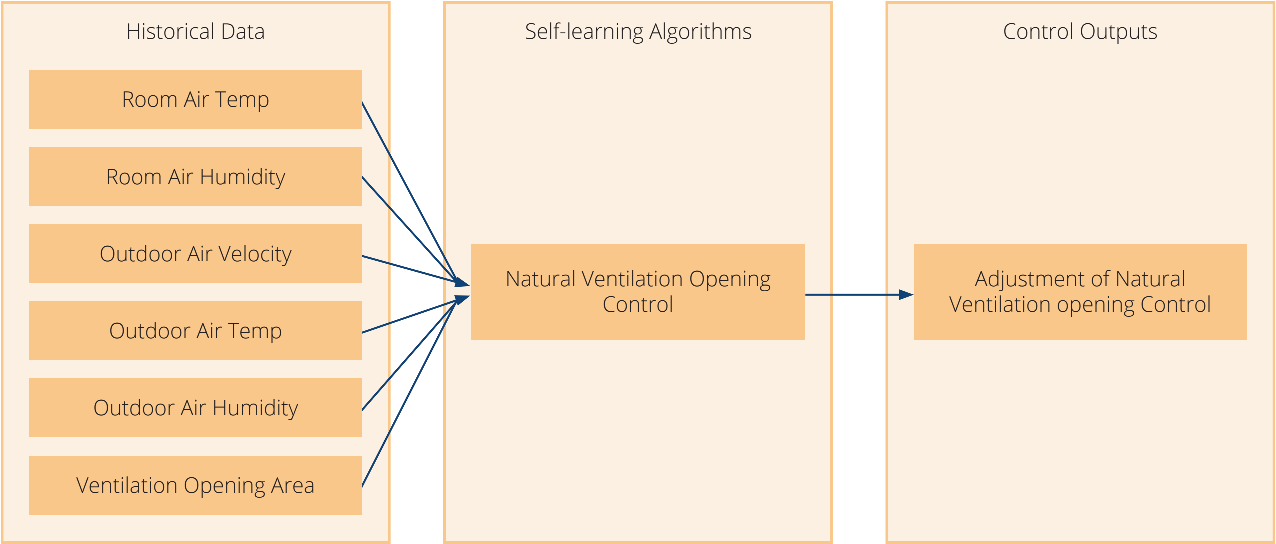


Figure 32: Schematics of the Natural Ventilation Opening Control

temperature limits. In alignment with the standard, when the control strategy enables the air circulation devices, the setpoint temperature is also adjusted to account for the effect of the air movement. For instance, if the initial setpoint without the use of ceiling fan is predicted to 27°C,and if the control strategy operates the ceiling fan at 0.6 m/s, the setpoint is adjusted to include the effect of air movement (1.2°C as per ASHRAE 55-2010) by the algorithm. Hence the final operating setpoint is set to 28.2°C.

Mechanical System Operation

Mechanical air conditioning systems are often the most energy consuming component in a mixed-mode building. Hence, the control strategy needs to be designed to minimize the energy consumption of the active (mechanical) system while maintaining thermal comfort and indoor air quality inside the building. The proposed control strategy determines operation of the common mechanical cooling systems, such as evaporative cooling, split air conditioning, or fan coil units, based on defined cooling set points as well as prevailing indoor conditions. This section explains the control strategy used for split air conditioning systems. Additional flowcharts suitable for evaporative cooling systems and fan coil units are included in Appendix 3.

The split air conditioning system is one of the most commonly used air conditioner systems in Indian residences. Figures 35 and 36 show the control strategy developed for split air conditioning system. The control strategy first calculates the desired room conditions based on the IMAC study (Manu et al, 2014; 2016). Further, the supply air temperature and humidity setpoints are calculated in the control strategy to maintain desired room conditions. Finally, the control strategy then modulates fan speed, supply air temperature, and supply air humidity to maintain room conditions. The split air conditioning system is run in dry mode (low fan speed, compressor on for short periods) when the supply air temperature is above the setpoint plus the dead band.

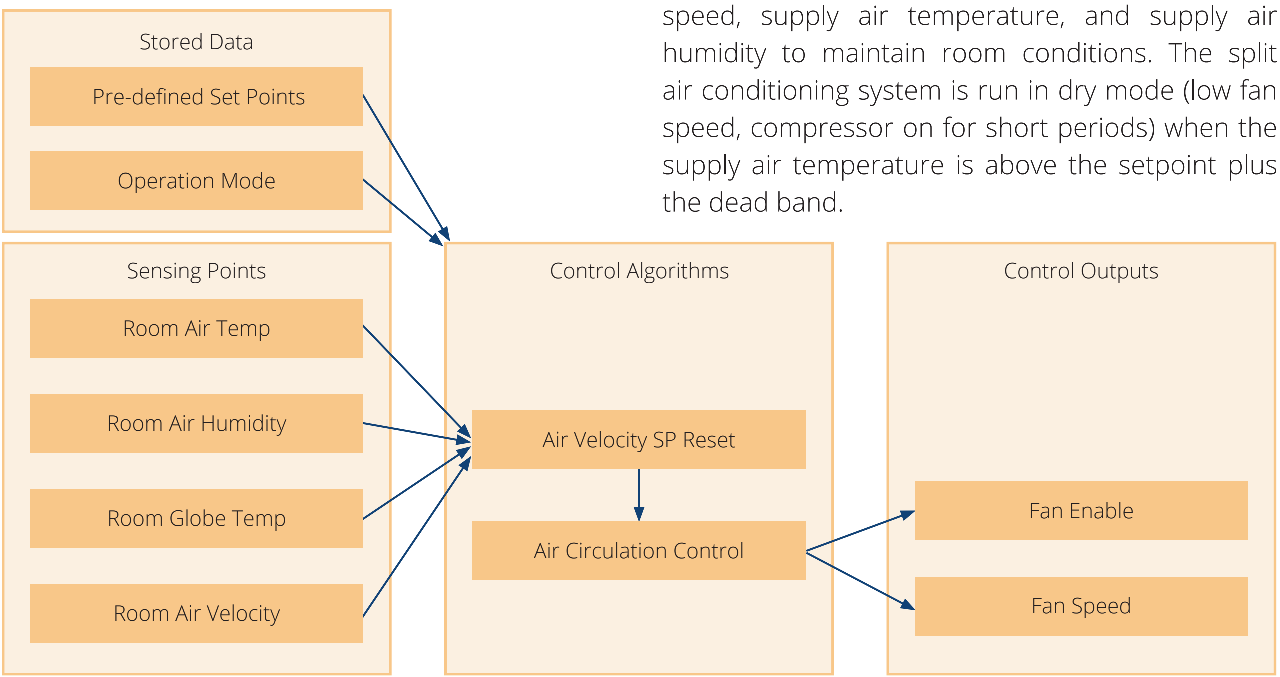


Figure 33: Schematics of Operation of Air Circulation Devices.

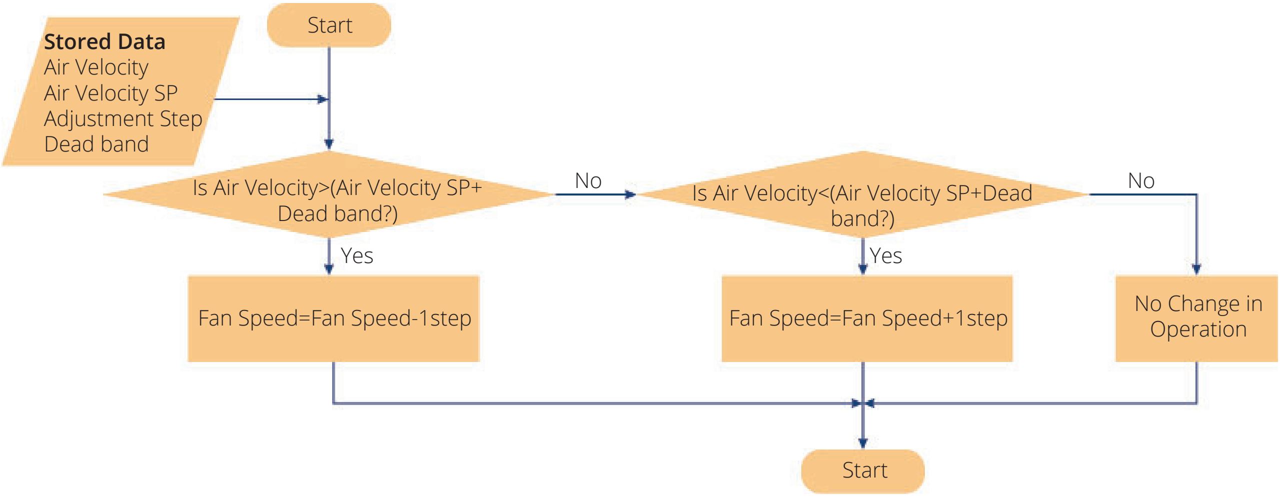


Figure 34: Flowchart for the Operation of Air Circulation Devices.

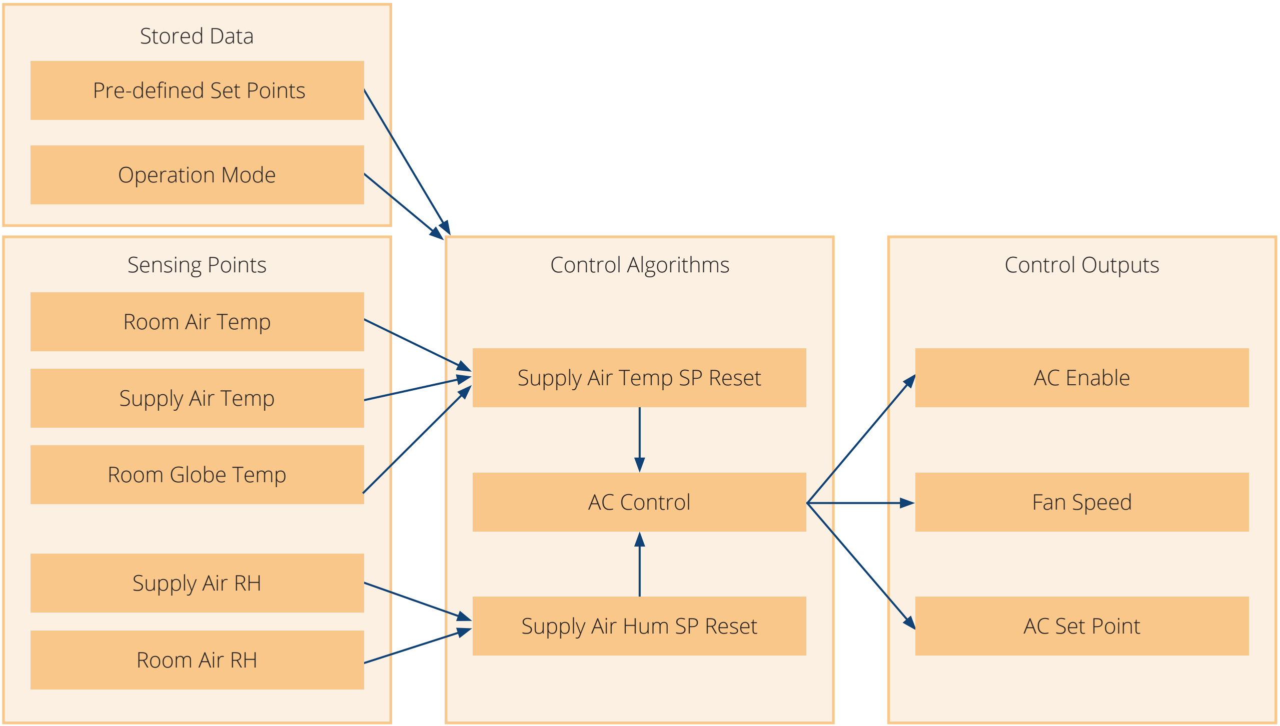


Figure 35: Schematics of Operation of Split Air Conditioning Devices.

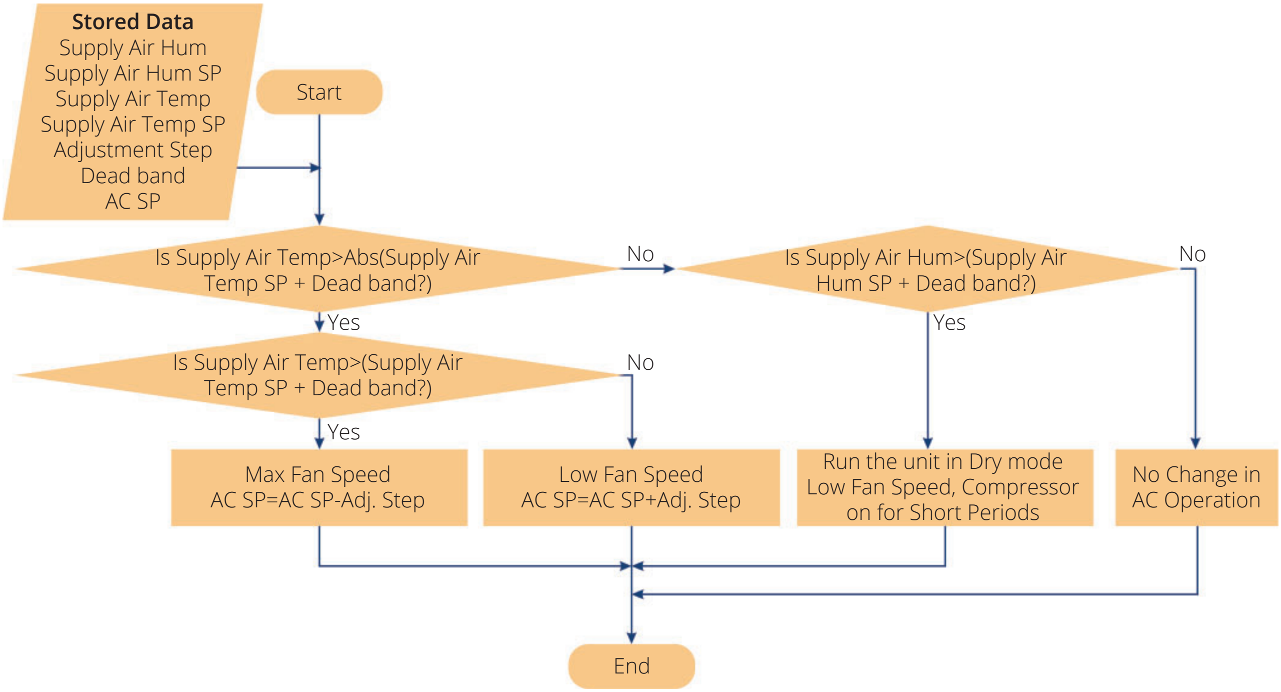


Figure 36: Flowcharts for the Operation of Split Air Conditioning Devices.

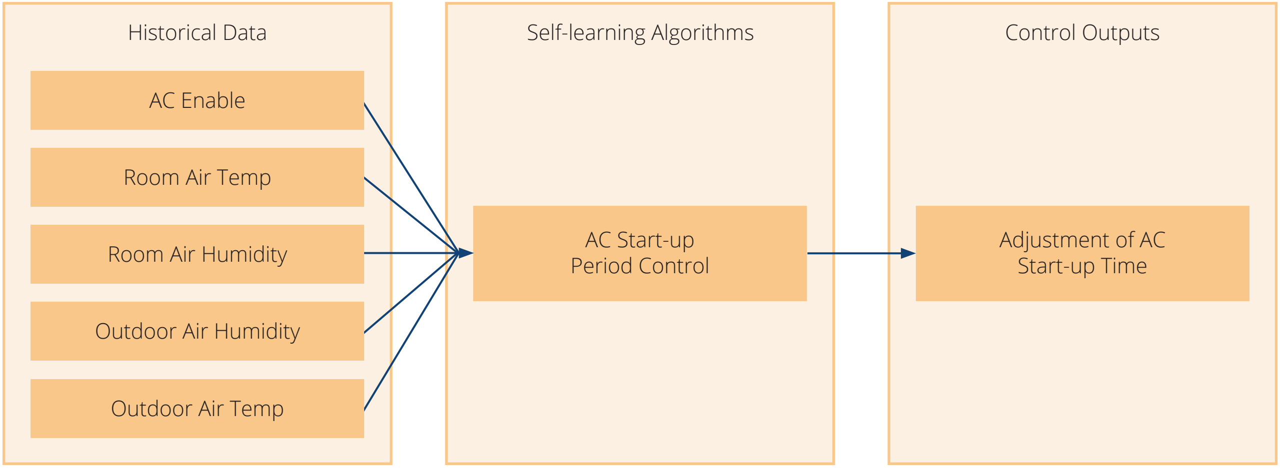


Figure 37: Schematics for the Adjustment of Start-up period for Air Conditioning System.

The self-learning algorithms continuously analyse the historic measurement data gathered by the monitoring system to automatically adapt the control strategies. Figure 37 shows the self-learning control strategy developed to adjust start-up period of the air conditioning system based on the historical data. In this strategy, room air temperature and humidity change is observed in the building each time the air conditioning system is enabled after a long period of inactivity (default value of four hours). The strategy also tracks the historical data of outdoor conditions during the initial operation period. Based on the statistical analysis of the historical data, the self-learning algorithm estimates the time the air conditioning system will need to operate to achieve the setpoint at the prevailing outdoor conditions. The start-up period is then optimized along with the occupancy period to minimize energy consumption of the air conditioning system.

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APPENDICES

Appendix 1

Application of the design charts for NV

The application of the design charts for NV presented in Chapter 3 is demonstrated here. The openings for the master-bedroom of the apartment 2BHK Case-1 (see Figure 15 in Chapter 5 for detail of this apartment) are sized to deliver the recommended airflow rates for each group of assembled Indian cities (see Figure 23 and Table 8 for detail of Group 1 and Table 9 for detail of Group 2, all in Chapter 5). The input parameters used for the demonstration of the design charts are shown in Table 10. The demonstration is shown for DC-01 in Figure A-1, for DC-02 in Figure A-2, for DC-03 in Figure A-3 and for DC-04 in Figure A-4. The free area for the openings calculated with the DCs are shown in Table 12.

- DC-01: buoyancy-driven flow; single-sided ventilation with one opening

$$A_f = \frac{q_{rec}}{C_d}\sqrt{\frac{(T_{inside}+273)}{g\ h_a\ \Delta T_{inside-outside}}} \qquad \text{Eq. 3}$$

The DC-01 is derived from Equation 3 (CIBSE, 2005). For single openings the value for Cd adopted is 0.25 (see section 3.3 for further information). The demonstration of the application of this DC for both groups of Indian cities and for the input parameters shown in Table 10 is shown in Figure A-1.

- DC-02: buoyancy-driven flow; cross-ventilation with multiple openings (Figure 8b and Figure 9)

The DC-02 is also derived from Equation 3 (CIBSE, 2005). Conversely, for multiple openings, the value for Cd adopted is 0.61 (see section 3.3 for further information). The demonstration of the application of this DC for both groups of Indian cities and for the input parameters shown in Table 10 is shown in Figure A-2.

- DC-03: wind-driven flow; single-sided ventilation with one opening (Figure 8c and Figure 10)

The DC-03 is derived from Equation 4 (CIBSE, 2005).

$$A_f \ = q_{rec} \,/ C\ V_z \qquad \text{Eq. 4}$$

The wind speed is calculated based on the height of the opening and the wind profile adjusted according to the terrain roughness. Equation 5 defines the wind speed (Vz) at height 'Z' based on the mean wind velocity at 10m height (Vref) and the characteristics of the roughness of the terrain, employed as an exponent of this power law (Table 11) (Masi, 2005; Cook, 1985). For this demonstration 'city terrain' is adopted in the calculations of Vz (input parameters and calculated values are shown in Table 10).

$$V_z = V_{ref}\ k\ z^{\alpha} \qquad (m/s) \qquad \text{Eq. 5}$$

Table 10: Input parameters used for the demonstration of the design charts.

input parameters	Group 1	Group 2
q_{rec} (m^3/s)	0.18	0.35
$\Delta T_{i\text{-}o}$ (°C)	3.4	2.6
T_{inside} (°C)	31.3	31.0
$T_{outside}$ (°C)	27.9	28.4
V_{ref} (m/s)	1.80	2.03
V_r (m/s)	0.98	1.10
ΔC_p	0.36	0.36
C_d for single openings	0.25	0.25
C_d for multiple openings	0.61	0.61
C for single openings	0.05	0.05
h_a (m)	1.20	1.20
Z (m)	18.00	18.00
α	0.33	0.33
k	0.21	0.21

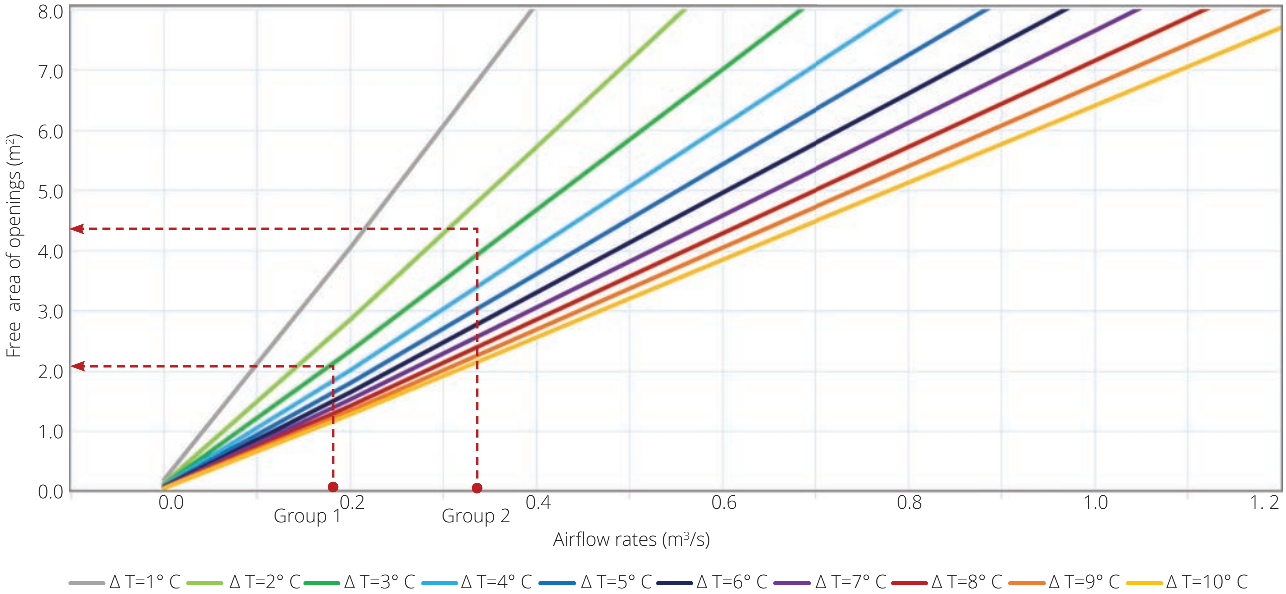

Figure A-1: Demonstration of the application of the DC-01 (buoyancy-driven flow; single-sided ventilation with one opening) for both groups of Indian cities.

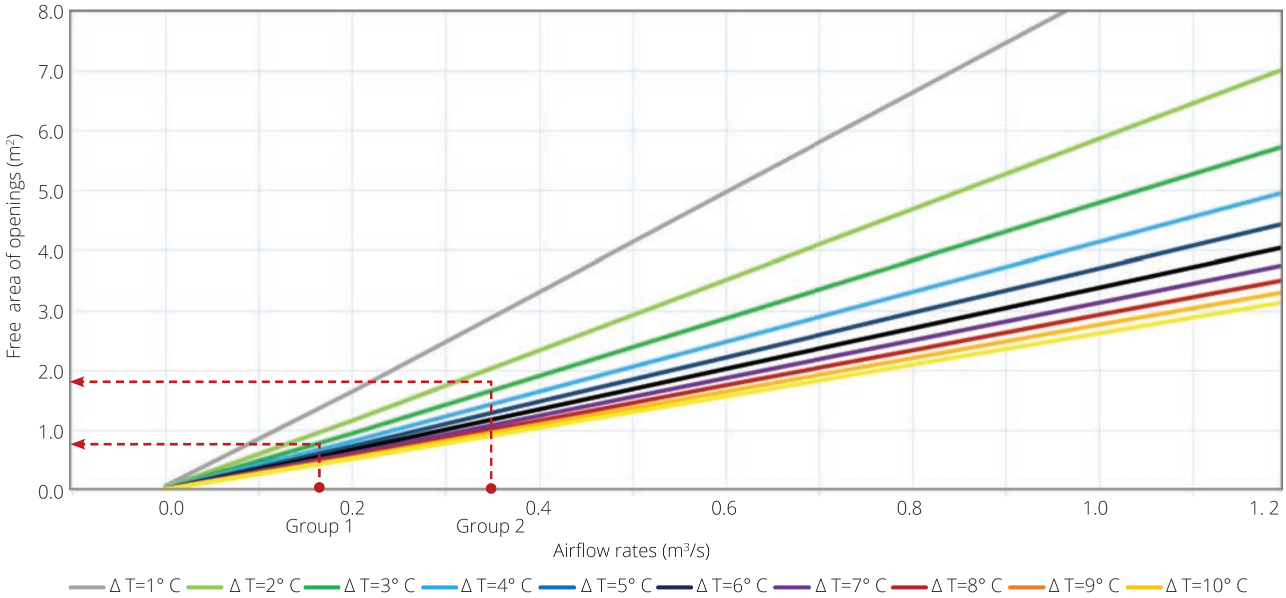

Figure A-2: Demonstration of the application of the DC-02 (buoyancy-driven flow; cross-ventilation with multiple openings) for both groups of Indian cities.

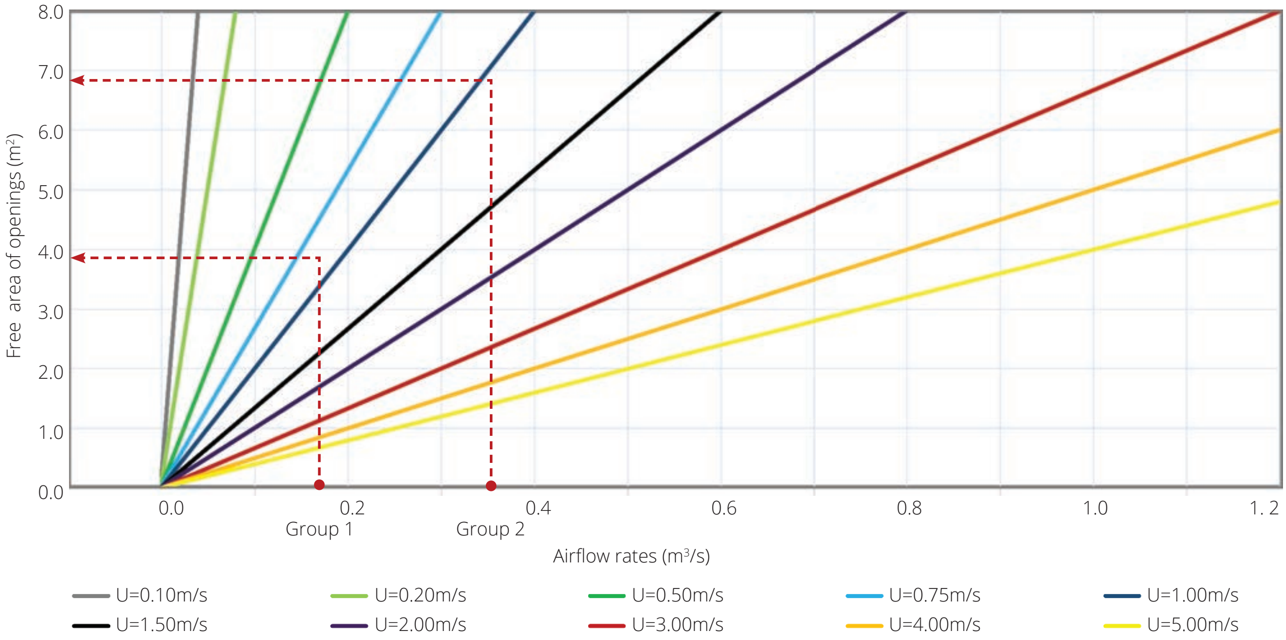

Figure A-3: Demonstration of the application of the DC-03 (wind-driven flow; single-sided ventilation with one opening) for both groups of Indian cities.

Table 11: Exponent values based on the terrain roughness

terrain roughness	α	k
open country	0.17	0.68
few blockages	0.20	0.52
urban	0.25	0.35
city	0.33	0.21

The demonstration of the application of this DC for both groups of Indian cities and for the input parameters shown in Table 10 is shown in Figure A-3.

- DC-04: wind-driven flow; cross-ventilation with multiple openings (Figure 8d and Figure 11)

$$A_f = q_{rec}\,(C_d\,V_z\sqrt{\frac{\Delta C_p}{2}}\,)^{-1} \qquad \text{Eq. 6}$$

The DC-4 is derived from Equation 6 (CIBSE, 2005). Pressure coefficients for orthogonal and oblique wind directions for the building shape used in this design guide are from CIBSE Guide A (CIBSE, 2010). For orthogonal wind and for the floor plan presented in Figure 15 for the 2BHK Case-1 apartment block a pressure coefficient difference (ΔCp) between inlets and outlets of 0.36 is adopted for this application demonstration (see Table 10).

The free areas of the openings calculated utilizing the four design charts provided in this design guide for the recommended airflow rates presented in Table 10 and for both groups of Indian cities are given in Table 12.

Table 12: Free areas of the openings calculated utilizing the design charts for both groups of Indian cities.

A_f (m²)	Group 1	Group 2
DC-01	2.03	4.36
DC-02	0.83	1.79
DC-03	4.02	6.90
DC-04	0.78	1.33

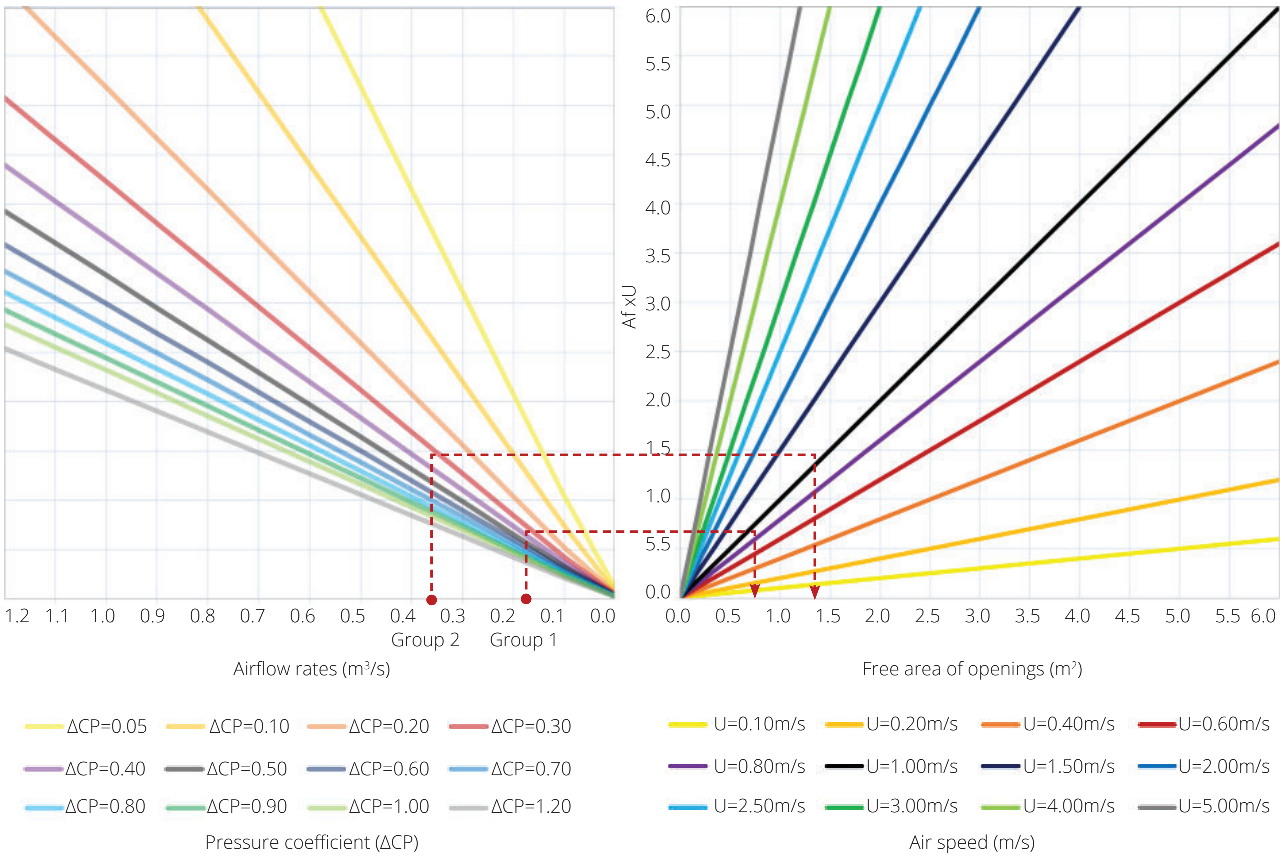

Figure A-4: Demonstration of the application of the DC-04 (wind-driven flow; cross-ventilation with multiple openings) for both groups of Indian cities.

Appendix 2

Suggestions of opening sizes for each case study apartment and for eight Indian cities

Table 13: Suggestion of opening sizes for each case study apartment in Ahmedabad.

AHMEDABAD																	
case study apartment		A_f (m^2)	Suggestion 1			Suggestion 2			case study apartment		A_f (m^2)	Suggestion 1			Suggestion 2		
			opening type	dimension (m)		opening type	dimension (m)					opening type	dimension (m)		opening type	dimension (m)	
				W	H		W	H					W	H		W	H
2BHK Case-01	MB	1.33	upper PPO	2.21	0.60	upper PPO	2.21	0.60	2BHK Case-02	MB	1.45	upper PPO	2.42	0.60	upper PPO	2.42	0.60
		0.78	window	0.71	1.10	balcony door	0.38	2.05			0.91	window	0.83	1.10	balcony door	0.45	2.05
		0.28	lower PPO	0.79	0.35	lower PPO	0.79	0.35			0.28	lower PPO	0.79	0.35	lower PPO	0.79	0.35
	SB	1.45	upper PPO	2.41	0.60	upper PPO	2.41	0.60		SB	1.47	upper PPO	2.45	0.60	upper PPO	2.45	0.60
		1.15	window	1.04	1.10	balcony door	0.56	2.05			1.17	window	1.07	1.10	balcony door	0.57	2.05
		0.18	lower PPO	0.51	0.35	lower PPO	0.51	0.35			0.18	lower PPO	0.51	0.35	lower PPO	0.51	0.35
	H+K	1.93	balcony door	0.94	2.05	balcony door	0.94	2.05		H+K	1.96	balcony door	0.96	2.05	balcony door	0.96	2.05
		1.93	window	1.76	1.10	balcony door	0.94	2.05			1.96	window	0.96	1.10	balcony door	0.96	2.05

Table 14: Suggestion of opening sizes for each case study apartment in New Delhi.

NEW DELHI																	
case study apartment		A_f (m^2)	Suggestion 1			Suggestion 2			case study apartment		A_f (m^2)	Suggestion 1			Suggestion 2		
			opening type	dimension (m)		opening type	dimension (m)					opening type	dimension (m)		opening type	dimension (m)	
				W	H		W	H					W	H		W	H
2BHK Case-01	MB	1.32	upper PPO	2.20	0.60	upper PPO	2.20	0.60	2BHK Case-02	MB	1.44	upper PPO	2.40	0.60	upper PPO	2.40	0.60
		1.01	window	0.91	1.10	balcony door	0.49	2.05			1.14	window	1.03	1.10	balcony door	0.55	2.05
		0.18	lower PPO	0.52	0.35	lower PPO	0.52	0.35			0.18	lower PPO	0.52	0.35	lower PPO	0.52	0.35
	SB	1.90	upper PPO	3.16	0.60	upper PPO	3.16	0.60		SB	1.93	upper PPO	3.21	0.60	upper PPO	3.21	0.60
		1.62	window	1.47	1.10	balcony door	0.79	2.05			1.66	window	1.51	1.10	balcony door	0.81	2.05
		0.19	lower PPO	0.53	0.35	lower PPO	0.53	0.35			0.19	lower PPO	0.53	0.35	lower PPO	0.53	0.35
	H+K	2.48	balcony door	1.21	2.05	balcony door	1.21	2.05		H+K	2.52	balcony door	1.23	2.05	balcony door	1.23	2.05
		2.48	window	2.25	1.10	balcony door	1.21	2.05			2.52	window	2.29	1.10	balcony door	1.23	2.05

Table 15: Suggestion of opening sizes for each case study apartment in Hyderabad.

HYDERABAD																	
case study apartment		A_f (m^2)	Suggestion 1			Suggestion 2			case study apartment		A_f (m^2)	Suggestion 1			Suggestion 2		
			opening type	dimension (m)		opening type	dimension (m)					opening type	dimension (m)		opening type	dimension (m)	
				W	H		W	H					W	H		W	H
2BHK Case-01	MB	2.08	upper PPO	3.47	0.60	upper PPO	3.47	0.60	2BHK Case-02	MB	2.21	upper PPO	3.69	0.60	upper PPO	3.69	0.60
		1.99	window	1.81	1.10	balcony door	0.97	2.05			2.24	balcony door	2.04	1.10	balcony door	1.09	2.05
		0.34	lower PPO	0.98	0.35	lower PPO	0.98	0.35			0.34	lower PPO	0.98	0.35	lower PPO	0.98	0.35
	SB	2.05	upper PPO	3.42	0.60	upper PPO	3.42	0.60		SB	2.19	upper PPO	3.65	0.60	upper PPO	3.65	0.60
		1.88	window	1.71	1.10	balcony door	0.92	2.05			1.92	balcony door	1.75	1.10	balcony door	0.94	2.05
		0.20	lower PPO	0.56	0.35	lower PPO	0.56	0.35			0.20	lower PPO	0.56	0.35	lower PPO	0.56	0.35
	H+K	5.48	balcony door	2.67	2.05	balcony door	2.67	2.05		H+K	5.57	balcony door	2.71	2.05	balcony door	2.71	2.05
		5.48	window	4.98	1.10	balcony door	2.67	2.05			5.57	balcony door	5.06	1.10	balcony door	2.71	2.05

Table 16: Suggestion of opening sizes for each case study apartment in Jaipur.

JAIPUR

case study apartment		A_f (m^2)	Suggestion 1			Suggestion 2			case study apartment		A_f (m^2)	Suggestion 1			Suggestion 2		
			opening type	dimension (m)		opening type	dimension (m)					opening type	dimension (m)		opening type	dimension (m)	
				W	H		W	H					W	H		W	H
2BHK Case-01	MB	1.09	upper PPO	1.82	0.60	upper PPO	1.82	0.60	2BHK Case-02	MB	1.19	upper PPO	1.99	0.60	upper PPO	1.99	0.60
		0.53	window	0.48	1.10	balcony door	0.26	2.05			0.64	window	0.58	1.10	balcony door	0.31	2.05
		0.27	lower PPO	0.78	0.35	lower PPO	0.78	0.35			0.27	lower PPO	0.78	0.35	lower PPO	0.78	0.35
	SB	1.18	upper PPO	1.97	0.60	upper PPO	1.97	0.60		SB	1.20	upper PPO	2.01	0.60	upper PPO	2.01	0.60
		0.85	window	0.78	1.10	balcony door	0.42	2.05			0.88	window	0.80	1.10	balcony door	0.43	2.05
		0.18	lower PPO	0.52	0.35	lower PPO	0.52	0.35			0.18	lower PPO	0.52	0.35	lower PPO	0.52	0.35
	H+K	1.54	balcony door	0.75	2.05	balcony door	0.75	2.05		H+K	1.57	balcony door	0.77	2.05	balcony door	0.77	2.05
		1.54	window	1.40	1.10	balcony door	0.75	2.05			1.57	window	1.43	1.10	balcony door	0.77	2.05

Table 17: Suggestion of opening sizes for each case study apartment in Mumbai.

MUMBAI

case study apartment		A_f (m^2)	Suggestion 1			Suggestion 2			case study apartment		A_f (m^2)	Suggestion 1			Suggestion 2		
			opening type	dimension (m)		opening type	dimension (m)					opening type	dimension (m)		opening type	dimension (m)	
				W	H		W	H					W	H		W	H
2BHK Case-01	MB	2.06	upper PPO	3.44	0.60	upper PPO	3.44	0.60	2BHK Case-02	MB	2.08	upper PPO	3.47	0.60	upper PPO	3.47	0.60
		2.43	window	2.21	1.10	balcony door	1.18	2.05			2.68	window	2.44	1.10	balcony door	1.31	2.05
		0.18	lower PPO	0.51	0.35	lower PPO	0.51	0.35			0.18	lower PPO	0.51	0.35	lower PPO	0.51	0.35
	SB	2.03	upper PPO	3.38	0.60	upper PPO	3.38	0.60		SB	2.04	upper PPO	3.40	0.60	upper PPO	3.40	0.60
		3.01	window	2.74	1.10	balcony door	1.47	2.05			3.07	window	2.79	1.10	balcony door	1.50	2.05
		0.20	lower PPO	0.56	0.35	lower PPO	0.56	0.35			0.20	lower PPO	0.56	0.35	lower PPO	0.56	0.35
	H+K	2.60	balcony door	1.27	2.05	balcony door	1.27	2.05		H+K	2.64	balcony door	1.29	2.05	balcony door	1.29	2.05
		2.60	window	2.36	1.10	balcony door	1.27	2.05			2.64	window	2.40	1.10	balcony door	1.29	2.05

Table 18: Suggestion of opening sizes for each case study apartment in Chennai.

CHENNAI

case study apartment		A_f (m^2)	Suggestion 1			Suggestion 2			case study apartment		A_f (m^2)	Suggestion 1			Suggestion 2		
			opening type	dimension (m)		opening type	dimension (m)					opening type	dimension (m)		opening type	dimension (m)	
				W	H		W	H					W	H		W	H
2BHK Case-01	MB	2.11	upper PPO	3.51	0.60	upper PPO	3.51	0.60	2BHK Case-02	MB	2.18	upper PPO	3.64	0.60	upper PPO	3.64	0.60
		1.82	window	1.65	1.10	balcony door	0.89	2.05			2.01	balcony door	1.83	1.10	balcony door	0.98	2.05
		0.20	lower PPO	0.57	0.35	lower PPO	0.57	0.35			0.20	lower PPO	0.57	0.35	lower PPO	0.57	0.35
	SB	2.16	upper PPO	3.61	0.60	upper PPO	3.61	0.60		SB	2.17	upper PPO	3.62	0.60	upper PPO	3.62	0.60
		3.43	window	3.12	1.10	balcony door	1.67	2.05			3.49	balcony door	3.18	1.10	balcony door	1.70	2.05
		0.24	lower PPO	0.68	0.35	lower PPO	0.68	0.35			0.24	lower PPO	0.68	0.35	lower PPO	0.68	0.35
	H+K	3.50	balcony door	1.71	2.05	balcony door	1.71	2.05		H+K	3.55	balcony door	1.73	2.05	balcony door	1.73	2.05
		3.50	window	3.18	1.10	balcony door	1.71	2.05			3.55	balcony door	3.23	1.10	balcony door	1.73	2.05

Table 19: Suggestion of opening sizes for each case study apartment in in Kolkata.

KOLKOTA

case study apartment		A_f (m^2)	Suggestion 1			Suggestion 2			case study apartment		A_f (m^2)	Suggestion 1			Suggestion 2		
			opening type	dimension (m)		opening type	dimension (m)					opening type	dimension (m)		opening type	dimension (m)	
				W	H		W	H					W	H		W	H
2BHK Case-01	MB	2.00	upper PPO	3.33	0.60	upper PPO	3.33	0.60	2BHK Case-02	MB	2.04	upper PPO	3.40	0.60	upper PPO	3.40	0.60
		2.32	window	2.11	1.10	balcony door	1.13	2.05			2.60	window	2.36	1.10	balcony door	1.27	2.05
		0.30	lower PPO	0.85	0.35	lower PPO	0.85	0.35			0.30	lower PPO	0.85	0.35	lower PPO	0.85	0.35
	SB	2.05	upper PPO	3.42	0.60	upper PPO	3.42	0.60		SB	2.10	upper PPO	3.49	0.60	upper PPO	3.49	0.60
		2.18	window	1.98	1.10	balcony door	1.06	2.05			2.23	window	2.03	1.10	balcony door	1.09	2.05
		0.21	lower PPO	0.59	0.35	lower PPO	0.59	0.35			0.21	lower PPO	0.59	0.35	lower PPO	0.59	0.35
	H+K	5.61	balcony door	2.74	2.05	balcony door	2.74	2.05		H+K	5.70	balcony door	2.78	2.05	balcony door	2.78	2.05
		5.61	window	5.10	1.10	balcony door	2.74	2.05			5.70	window	5.19	1.10	balcony door	2.78	2.05

Table 20: Suggestion of opening sizes for each case study apartment in Pune.

PUNE

case study apartment		A_f (m^2)	Suggestion 1			Suggestion 2			case study apartment		A_f (m^2)	Suggestion 1			Suggestion 2		
			opening type	dimension (m)		opening type	dimension (m)					opening type	dimension (m)		opening type	dimension (m)	
				W	H		W	H					W	H		W	H
2BHK Case-01	MB	1.02	upper PPO	1.70	0.60	upper PPO	1.70	0.60	2BHK Case-02	MB	1.11	upper PPO	1.86	0.60	upper PPO	1.86	0.60
		0.59	window	0.54	1.10	balcony door	0.29	2.05			0.69	window	0.63	1.10	balcony door	0.34	2.05
		0.22	lower PPO	0.62	0.35	lower PPO	0.62	0.35			0.22	lower PPO	0.62	0.35	lower PPO	0.62	0.35
	SB	1.06	upper PPO	1.76	0.60	upper PPO	1.76	0.60		SB	1.07	upper PPO	1.79	0.60	upper PPO	1.79	0.60
		0.76	window	0.70	1.10	balcony door	0.37	2.05			0.78	window	0.71	1.10	balcony door	0.38	2.05
		0.16	lower PPO	0.46	0.35	lower PPO	0.46	0.35			0.16	lower PPO	0.46	0.35	lower PPO	0.46	0.35
	H+K	1.71	balcony door	0.83	2.05	balcony door	0.83	2.05		H+K	1.74	balcony door	0.85	2.05	balcony door	0.85	2.05
		1.71	window	1.55	1.10	balcony door	0.83	2.05			1.74	window	1.58	1.10	balcony door	0.85	2.05

Appendix 3

Flow Charts of Control Algorithms

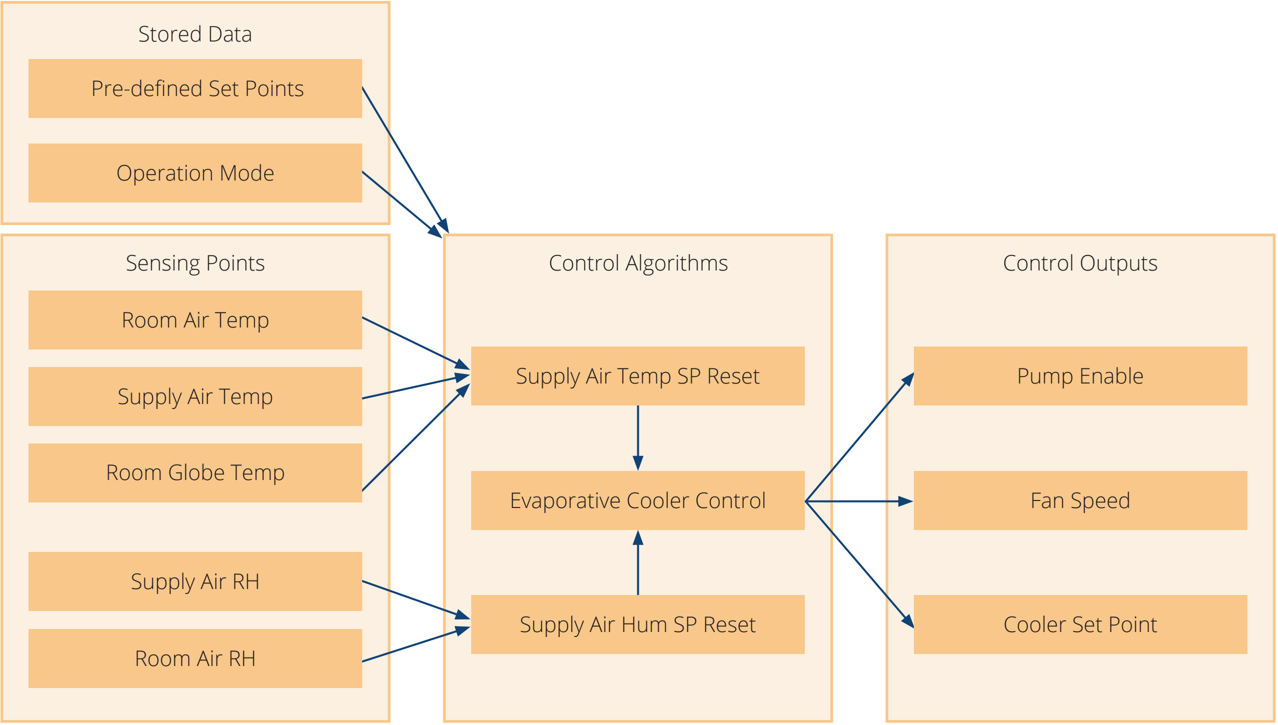

Figure A-5: Schematics of Operation of Evaporative Cooling Devices.

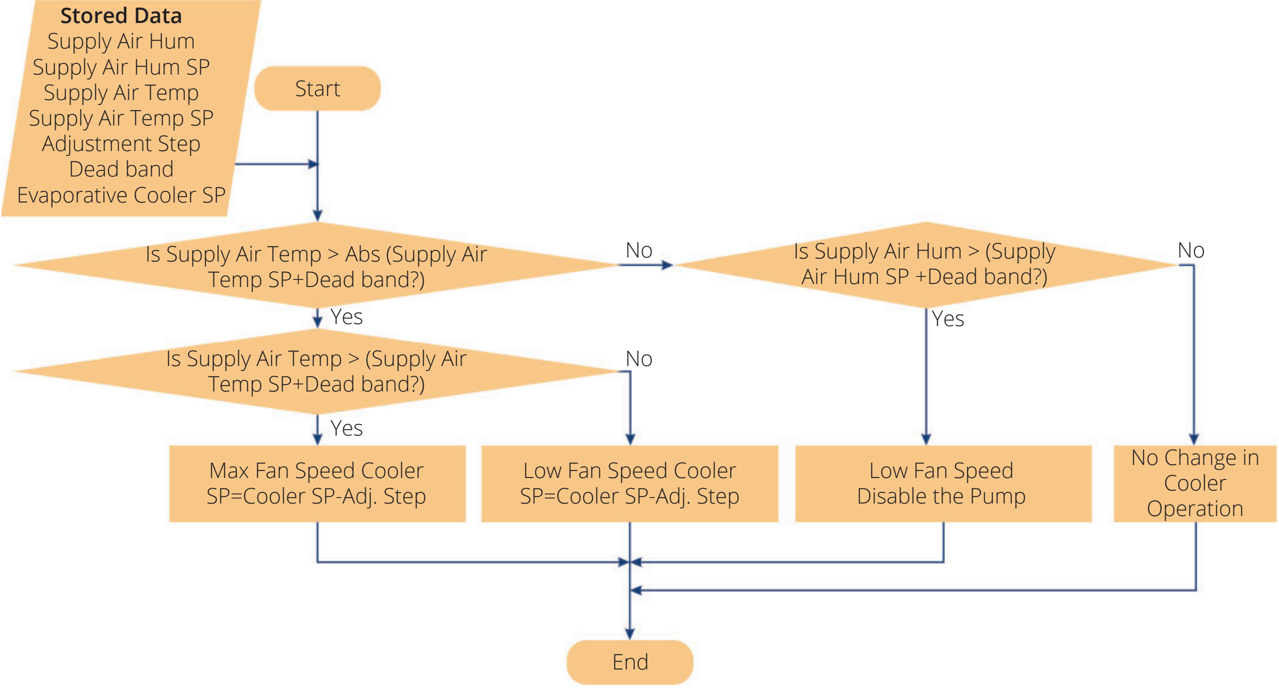

Figure A-6: Flowchart for the Operation of Evaporative Cooler

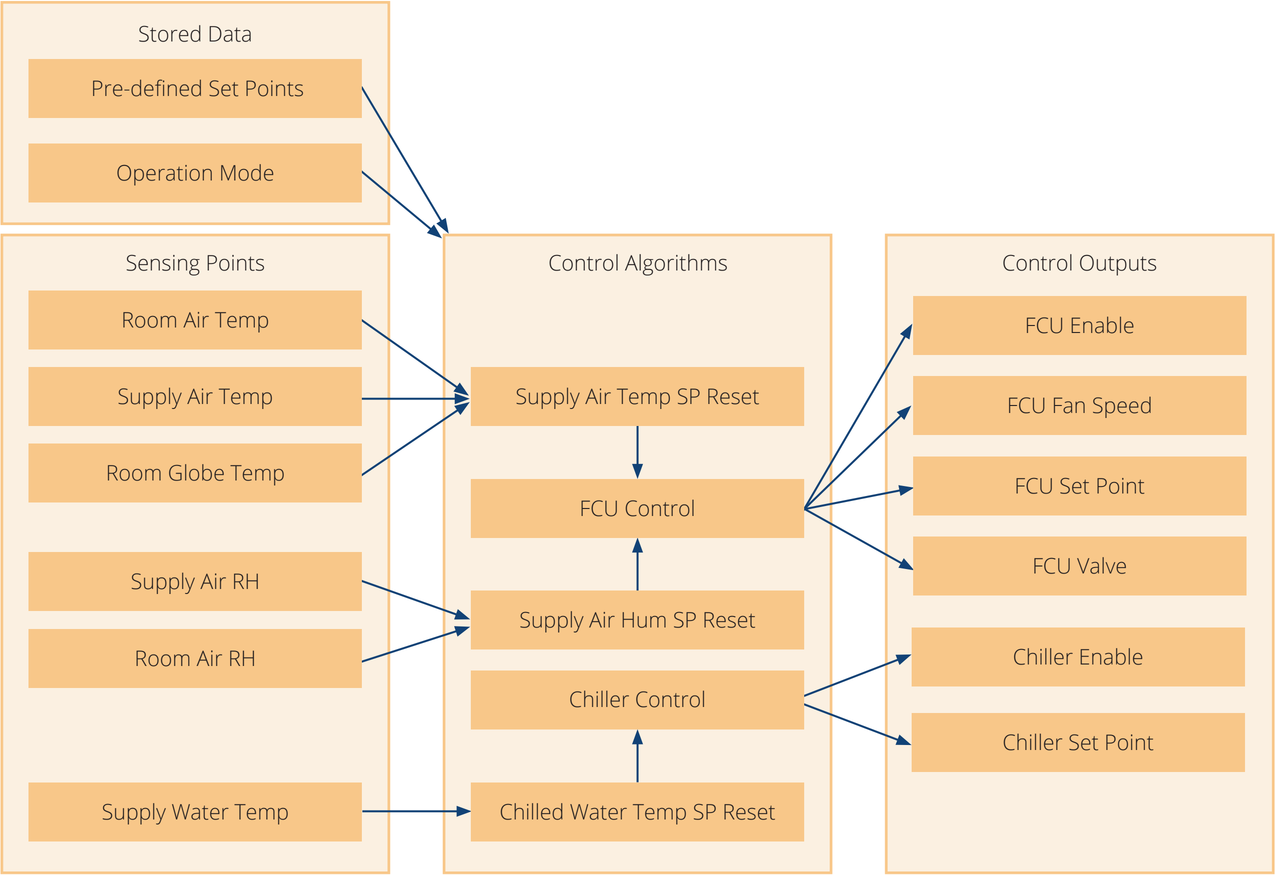

Figure A-7: Schematics of the Operation of Fan Coil Unit Devices with Centralized Air Cooled Chiller.

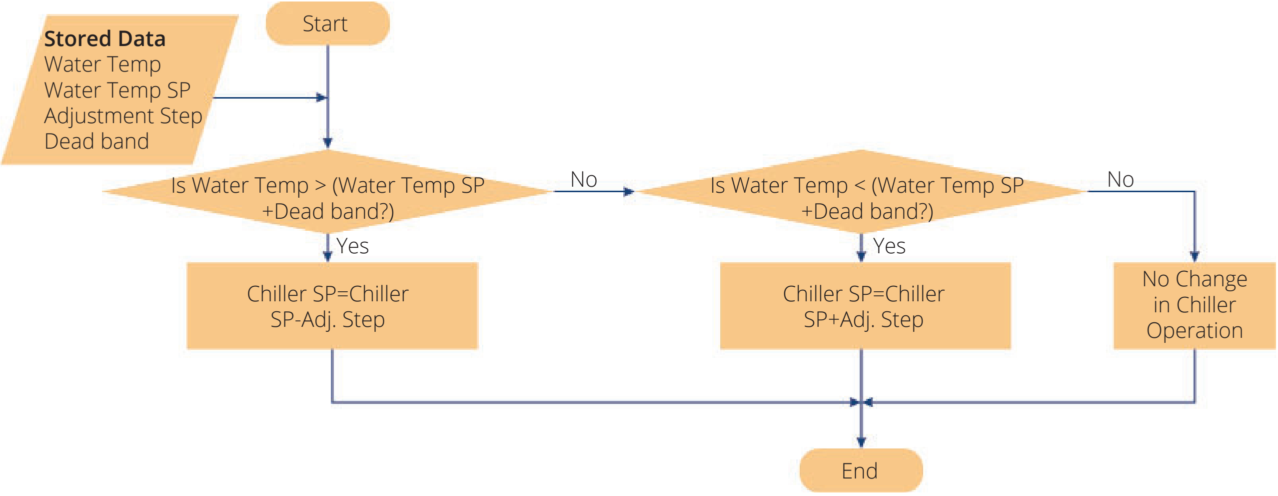

Figure A-8: Flowcharts of the Operation of Fan Coil Unit Devices with Centralized Air Cooled Chiller.

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