# Assessing the Energy-Saving Potential of Passive Strategies in Commercial Buildings in the Top Upcoming Megacities

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A B S T R A C T

*Buildings account for up to 50% of energy consumption in many regions. Heating, ventilation and air-conditioning systems consume half of that energy. Passive cooling strategies can significantly reduce energy use and associated carbon emissions, especially in high-density regions like megacities. This work aims to quantify the energy-saving potential of passive strategies in five upcoming megacities, namely Hyderabad, Bogota, Johannesburg, Bangkok and Chengdu. It assesses the potential of three strategies - natural ventilation, shading and use of appropriate materials. The aspects of energy use, thermal comfort and indoor air quality are combined to identify the strategy and the city with the most energy-saving potential. The study showed that climate and occupancy hours dictated the success of each strategy in each city. The analysis and data presented here can provide guidelines for designing new buildings and retrofitting existing ones before the upcoming population surge.*

## 1. INTRODUCTION

Keeley and Little [1] defines megacities as urban agglomerations with a population of 10 million or more. There were 31 megacities in 2016, and there will be 41 by 2030 [2]. This immense population growth requires an exponential increase in housing and infrastructure. Buildings account for 23-47% of the energy consumption in developing [3] and developed countries [4], meaning they have high potential to curb rising $CO_2$ levels and the associated greenhouse effect, high pollution levels, energy shortages, and several climate issues [5] with all developing technological solutions aiming towards the achievement of zero-energy buildings [6].

With all ten upcoming megacities being in the developing world, economically, also it becomes essential to understand how buildings in these cities can be designed to perform better [7]. As pointed out by Shukla and Zia [8] developing countries often put economic development ahead of emission reduction targets, as in the case of the Indian National Action Plan on Climate Change, which does not mention commitments to reducing carbon emissions [9]. A balance between the two is a highly debated topic when it comes to developing countries.

Chen et al. [10] analyzed the energy consumption patterns of residential buildings across five districts in Hong Kong, aiming to identify the most energy-intensive components and propose targeted passive design strategies accordingly. Space heating/cooling has the most significant impact on building energy use in all cities in their study as well as in the world. Thus, passive or low-energy cooling strategies can significantly reduce the impact buildings have on the environment. Furthermore, Stavrakas and Flamos [10] suggested a demand management system to quantify the benefits of demand flexibility in the residential sector. Strategies such as these would become effective towards building energy management design model as it can influence towards the potential of building consumptions. Several such strategies can be used, of which the impact of shading, mixed-mode ventilation and use of appropriate building materials have been studied here. These three were chosen as they can be applied to one common base model. The strategies vary based on adaptability to periodic changes in the local climate in order to ensure comfortable indoor temperature ranges. Other possible passive strategies can be evaluated in future work following the approach introduced in the present work.

The focus of this study is on megacities, since these are regions of intense energy use, and reducing the consumption in these regions would have a more significant global impact. To date, most studies have been region-specific or climate-specific. The one global study that exists by Chen and Tong [11], does not consider cities that create high impact in terms of those with high square footage of buildings, and rate of growth of the city. Evaluating upcoming megacities further brings about the potential to

use guidelines to plan new buildings in advance appropriately, and not just retrofit existing buildings.

This work aims to predict the energy-saving potential of passive cooling strategies in five of the ten upcoming megacities – namely, Hyderabad, India; Bogotá, Colombia; Johannesburg, South Africa; Bangkok, Thailand; Chengdu, China [2] using Building Energy Simulation (BES). The BES software, IES VE are commonly used to perform building energy performance analysis [12]. This software was used to develop an energy model of a typical office building, According to [13] with passive cooling and apply appropriate settings for each model based on the climate of each city [14]. In addition, as pointed out by Bilgen and Sarıkaya [15], sustainability is based on balancing three main objectives: environmental protection, economic growth and social equity. Energy conservation cannot be with a compromise on the standard of living – of which thermal comfort is a basic necessity [16]. Hence, the impact of the three strategies on energy and thermal comfort were compared with a base model which used only mechanical ventilation. Furthermore, the results for all cities were compared to understand why some cities have more potential than others. The study seeks to provide data for policymakers, building engineers and architects to judiciously design buildings in these cities to achieve global reductions in energy consumption, and thereby minimise the impact on the environment.

## 2. LITERATURE REVIEW

The study by Chen and Tong [11] conducted a comprehensive estimation of the energy-saving potential of natural ventilation (NV) in 1854 locations around the world by calculating NV hours and simultaneously used BES to estimate the energy-saving potential of the world's 60 largest cities. Two key points in this study were the choice of climate classification based on grouping of similarities from different locations, and the use of the adaptive comfort model established by de Dear and Brager [16] instead of fixed upper-temperature thresholds. The study quantified NV hours and energy-saving percentage based on climatic variations and established that subtropical highland climate, (with little variation in temperature and almost

no snowfall), had highest NV hours. Mediterranean, temperate and desert climates were also favourable for natural ventilation. Regions with high temperature and high humidity were most unfavourable. This study was useful in developing a methodology for the present work since it had a similar approach to studying different countries with very different climates.

In terms of region-specific studies, Oropeza-Perez and Østergaard [17] used EnergyPlus simulations to solve overheating issues in a building in Denmark through passive cooling methods. It was observed that there was up to 90% reduction in mechanical ventilation hours. They conducted a similar study in the warm conditions of Mexico [18] and observed that there was 54.4% savings in air conditioning demand through the use of passive cooling techniques. In this case, material use also significantly impacted the cooling. High heat capacity materials had higher saving potential in hot-dry climate, and low heat capacity materials helped lower indoor temperature in hot-humid climates. This was, however, less applicable for very humid conditions. For such regions, it would be advantageous to study vernacular techniques and materials since they are both cost-effective and tailored to the local climate as seen in the study by Beccali et al. [19] for hot-humid climates. While Sivaraman [20] used simulations to determine the potential of traditional passive cooling methods in modern Indian houses. Replacing materials used to traditional materials decreased energy use by 36%, $CO_2$ emission by over 30% and had cost savings of 21%. Pesic et al. [21] used DesignBuilder simulations for buildings in Catalonian cities and found that hybrid ventilation along with night-time ventilation was beneficent to energy-saving in these cities.

Although natural ventilation can improve indoor air quality by reducing pollutants that are indoors, it can also introduce pollutants into the building. People spend 90% of their time inside and 70% of their time in their house [22]. Poor Indoor Air Quality (IAQ) can lead to several health effects and lower productivity of occupants [23]. Particulate matter and oxides of carbon, nitrogen and sulphur can originate both from indoor and outdoor sources [24]. Of these, BES can determine indoor $CO_2$ levels given the outdoor $CO_2$ levels. The change in outdoor $CO_2$

levels over the years creates the need to monitor indoor $CO_2$ concentrations based on current as well as future outdoor $CO_2$ levels.

Poor air quality due to pollutants reduces the capability of a city to use natural ventilation as an energy-saving strategy. Tong et al. [25] proved that the energy-saving potential of NV depends on temperature and humidity, air quality, dependence on fossil fuel, rate of growth of the city and the square footage of buildings in the city. In their study of Chinese cities, many cities lost nearly half the NV hours due to poor air quality. Ben-David and Waring [26] simulated IAQ and energy consumption in offices in 14 U.S. cities and concluded that the impact on IAQ could be kept to a minimum by controlling the mode of delivery of outdoor air (by delivering through an AHU instead of building openings). The work of Chen and Tong [11] overlooks the influence of air pollution on NV potential. There are discrepancies in the NV hours possible in the Chinese city of Zhenzhou [25]. They also mention the high possibility of NV in New Delhi, which is impossible considering it has been named "the world's most polluted big city" by the WHO [27].

While there are a few region-specific studies that take IAQ into consideration [28], there are some which also delve into aspects of environmental and economic benefits of energy-saving using natural ventilation and passive cooling [18]. Tong et al. [25] raised the importance of studying cities that can create a large impact on energy savings due to the high rate of growth/high square footage of buildings. When trying to achieve maximum impact, it becomes essential not to divide the case studies based on climate or location, and to instead focus on cities that would create a larger impact. For this reason, it becomes important to conduct a study of the energy-saving strategies for buildings in future megacities of the world. A study of the energy-saving potential and thermal comfort performance of passive cooling in these upcoming megacities has not been done yet.

## 3. METHOD

Fig. 1 presents an overview of the methodology. It consists of analysing the climatic data towards the creation of the following four different models to enable the analysis that determines the best strategy that would work best for each city.
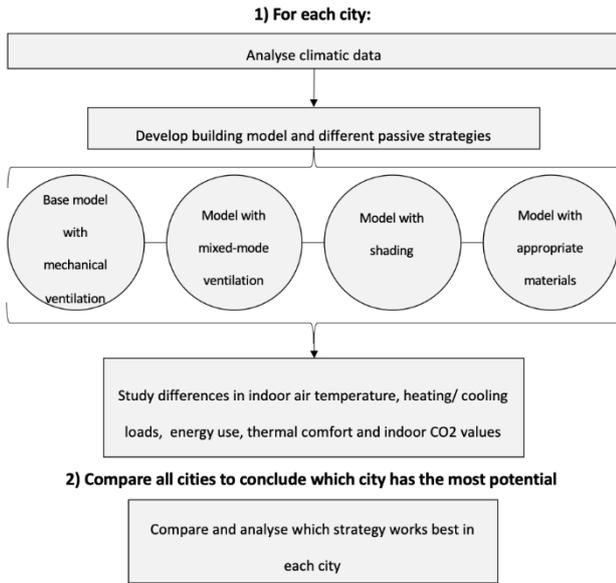
**1) For each city:**

Analyse climatic data

Develop building model and different passive strategies

Base model with mechanical ventilation

Model with mixed-mode ventilation

Model with shading

Model with appropriate materials

Study differences in indoor air temperature, heating/ cooling loads, energy use, thermal comfort and indoor CO2 values

**2) Compare all cities to conclude which city has the most potential**

Compare and analyse which strategy works best in each city

**Fig. 1.** Overview of the methodology.

### 3.1 Theory

This research will use the Building Energy Simulation (BES) to assess the energy performance of the office building with passive cooling strategies. The BES is based on the commercial tool IESVE, which is a dynamic thermal simulation based on the modelling of the heat transfer processes between a building and its microclimate. The three-dimensional modelling of a similar three-storey commercial office building using the IESVE tool was validated in our previous works [29]. Within the tool, the conduction, convection and radiation heat transfer processes for each building component or fabric are modelled individually and incorporated with the model of the heat gains, air exchange and plant within and around a thermal space or room [30]. The methods and approach used to model these processes are summarised here, the equations are derived from the modelling principles adopted in the IES VE simulation software [31]. The time-dependent spatial temperature distribution in a solid without internal heat sources is given by the partial differential equations:

$$W = -\lambda \nabla T \qquad (1)$$

$$\nabla \cdot W = -\rho c_p \frac{\partial T}{\partial t} \qquad (2)$$

where T is the temperature, W is the heat flux vector, $\lambda$ is the conductivity, $\rho$ is the density and $c_p$ is the specific heat capacity. The heat storage in air masses or net heat flow into the air masses Q is modelled by the following equation:

$$Q = c_p \rho_a V \frac{\partial T_a}{\partial t} \qquad (3)$$

where $V$ is the air volume, $\rho_a$ is the air density and $T_a$ is the air temperature.

For the discretisation, the tool uses a finite difference approach to the heat diffusion equation solution, which first replaces the element with a finite number of discrete nodes at which the temperature will be calculated. The nodes are distributed within the layers for the modelling of the heat transfer and storage characteristics for the selected time step. This choice is based on constraints imposed on the Fourier number. Then, the time variable is discretised, and a combination of explicit and implicit time-stepping schemes is adopted in order to alternate nodes of the construction. The convective heat transfer is described by the equation:

$$W_{hf} = K(T_a - T_s)^n \qquad (4)$$

where $W_{hf}$ is the heat flux from the air to the surface, $T_s$ is the mean surface temperature and $K$ and $n$ are coefficients. For forced convection, at sufficiently high air velocities n can be approximated as = 1. For natural convection, although n is usually somewhat greater than 1, its value is often sufficiently close to 1 for the approximation:

$$W = h_c(T_a - T_s) \qquad (5)$$

where $h_c$ is the convective heat transfer coefficient

The heat transfer rate associated with an air stream entering a space is described by equation:

$$Q = Mc_p(T_i - T_a) \qquad (6)$$

where M is the air mass flow rate, $T_i$ is the supply air temperature and $T_a$ is the room mean air temperature.

For the interior long-wave radiation, the net radiant exchange between a surface and the rest of the enclosure is described by the equation:

$$W_{rl} = h_r(T_s - T_{MRT}) \qquad (7)$$

where $W_{rl}$ is the net radiative loss from the surface $h_r$ is the surface heat transfer coefficient for exchange with the MRT node and $T_{MRT}$ is the mean radiant temperature.

For the exterior long-wave radiation, the net long-wave gain for an external surface of inclination $\beta(°)$ is represented by the following:

$$L^*(\beta) = \varepsilon_e\left[L_{skv}(\beta) + L_g(\beta) - \sigma\Theta_e^4\right] \qquad (8)$$

where $\varepsilon_e$ is the emissivity of the exterior surface, $L_{skv}(\beta)$ is the long-wave radiation received directly from the sky, $L_g(\beta)$ is the long-wave radiation from the ground and $\Theta_e^4$ is the absolute temperature of the exterior surface. The tool calculates the solar flux incident on every external building surface at each time-step.

## 3.2 Climate Data and Indoor Conditions

Fig. 2a shows a map created to show the ten upcoming megacities between 2016 and 2030 as estimated [2]. Those marked in red are the ones included in this study (Hyderabad, Bogota, Johannesburg, Bangkok and Chengdu), while those in blue, due to unavailability of weather data for some, have not been included in the study. Other than the fact that all these cities are in developing countries, we also see that they are mostly in the Tropical region or Subtropical region. Most of the energy use in Tropical regions is due to the requirement of air-conditioning almost throughout the year due to high temperatures (and humidity in some cases) and a high level of solar gain. Natural ventilation alone cannot cater to comfort throughout the year, which is why this study considers the use of mixed-mode ventilation as well as other passive strategies.

For each of the selected upcoming megacities, Fig. 2b presents the increase in population over the years and the projected values for the future. According to the [2], the population of these five cities are set to increase by an average of 9% within the upcoming years; with an increase by 13.0% for Hyderabad, 10.7% for Johannesburg, 7.80% for Bangkok, 7.12% for Bogota and 6.50% for Chengdu. Climate data and the indoor conditions are important for analysis [32] of these locations and should be further examined. According to the weather data from Department

of Energy (DOE) [33], the temperature range for the chosen 5 cities (as of 2018) were arranged into a chart, as shown in Fig. 2c. The figure shows average highs and lows as well as design highs and lows to design for extreme conditions.
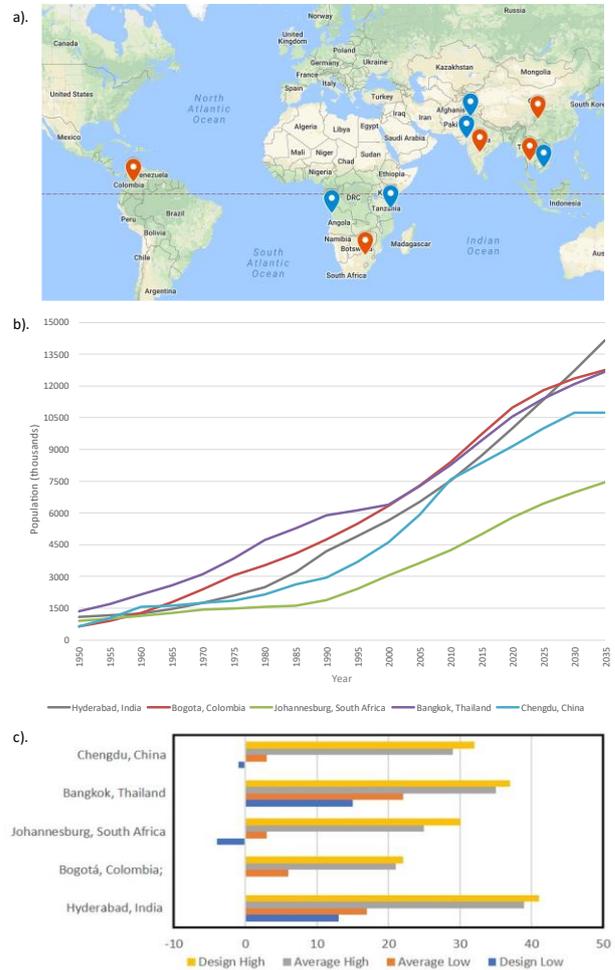
**Fig. 2.** a). 10 Upcoming Megacities between 2016 and 2030 [2]. b). Population within the upcoming top 5 Megacities between 1950 and 2035 [2]. c). Temperature range in the selected 5 megacities [34].

This temperature range determines how the models would vary according to the location. Depending on seasonal requirements, each city would need to have separate annual schedules for heating and cooling. Also, natural ventilation would only provide comfortable indoor conditions if used in the correct temperature range. In order to understand the temperature limits for heating, cooling and natural ventilation, two methods were used. Firstly, the psychrometric chart available on Climate Consultant and secondly, the data available in CIBSE Guide A: Environmental Design [34]. The psychrometric chart was able to provide

comfortable temperature ranges using several passive design strategies.

Although some of the design strategies varied for each city, the following data was similar for all: Comfort zone: 20-24°C; Comfortable with internal gains: >13°C; Comfortable with natural ventilation only: <27°C; Comfortable with fan-forced ventilation: <28°C; Air-conditioning required: >28°C. For heated, cooled and airconditioned spaces, CIBSE Guide A: Environmental Design [34] presents the bands of comfort temperature inside offices related to the running mean outdoor temperature. This recommends winter operating temperatures as 21-23 and summer operating temperatures as 22-25. For free-running buildings, it suggests the indoor temperature range can be between 19-29 (19-23 in winter and 25-29 in summer). Taking both the above data into consideration, for the model with only mechanical ventilation, the heating setpoint can be considered as 20° C and cooling setpoint as 24 °C. For the mixed-mode ventilation model, the WHO's recommendations for minimum safe indoor temperatures were considered, which is 18 °C for healthy sedentary occupants [35]. Thus, considering passive heating and cooling, the mixed-mode ventilation could be modelled with a heating setpoint of 18 °C and a cooling setpoint as high as 28 °C. Natural ventilation could be used between 20-28 °C. These settings were used to create various schedules for different models.
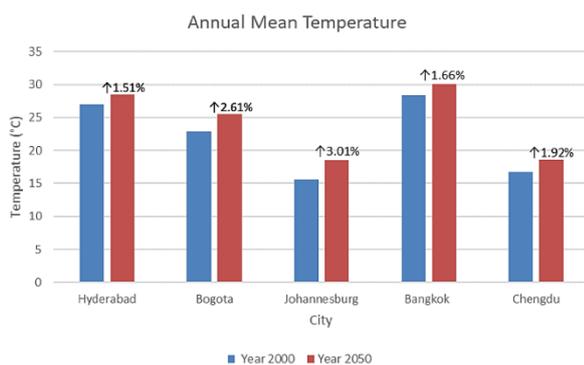


**Fig. 3.** Difference between annual mean temperature in year 2000 with predictions of 2050 [36].

Along with the consideration of the current temperature ranges within the 5 megacities shown in Fig. 2c, the projected annual mean temperature is equally as important. Fig. 3 presents the annual mean temperature for the year 2000 and the projected temperature for 2050. The increase in annual mean temperature for each city is important for consideration into the strategies implemented into building designs for these locations, with attention towards the aspects of annual energy savings, costs, and thermal comfort with occupancy satisfaction.

## 3.3 Building Energy Simulation (BES) Geometry and Setup

The geometry chosen was based on a typical medium-size office building as specified by the U.S. Department of Energy (DOE), which represents fairly realistic building characteristics and construction practices in the US. These models were developed as standard or reference building energy models for the most common commercial buildings in the US. It allows the simulation of new technologies; optimisation of designs, and develop new standards and energy codes. It is not intended to represent the energy use in any specific building. They are rather hypothetical models with ideal operations that meet specific requirements. The selected base model was used for validating our modelling approach and as a starting point for the analysis conducted in this study.It should be noted that the case study building models located in Hyderabad, Bogotá, Johannesburg, Bangkok, Chengdu were modified in terms of the construction materials and orientation. In addition, we didn't have sufficient information to create a building model for each city that can represent the building stock in those cities, in terms of construction properties. Hence, we have classified cities based on the statistical climate classification scheme introduced in ASHRAE 169-2021 and the appropriate U values for each climate zone were then used to conduct the simulation on EnergyPlus based on IECC International Energy Council Code. Future research can develop building models which represent more realistic building characteristics and construction practices in the different case study cities.

This basic geometry is shown in Fig. 4. The building was oriented such that the longer side is aligned along the East-West axis. The selected orientation will prevent overheating from the sun path passing from east to west through the south and exposing a larger surface area of the building to direct solar gain.
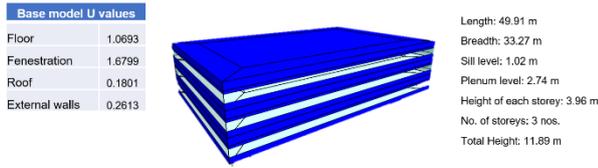
**Fig. 4.** Typical medium-size office building geometry by the U.S. Department of Energy (DOE).

### 3.3.1 Base Model

For all cities, the office hours were assumed to be 8 AM to 6 PM, Monday -Friday. The main HVAC system used was a dual duct VAV system, and the auxiliary system was a Constant Volume System with variable fresh air rate (closest to fan-forced ventilation). The heating setpoint was taken as 20 °C and the cooling setpoint at 24 °C. Separate summer and winter profiles were used for each city.

An initial run without HVAC determined monthly indoor air temperature ranges, which would differ from the outdoor temperature because of the envelope of the building providing resistance to heat gain/loss. Based on this, a comprehensive chart was created for heating/cooling seasons, as shown in Table 1. Modulating profiles were created for the mechanical-only model such that when ta<20, heating would turn on and when ta>24, cooling would turn on (where "$t_a$" is the indoor air temperature). The auxiliary ventilation, providing 10 l/s/person, was assumed to start operating when the temperature went above 26 °C.

**Table 1.** Heating and cooling seasons for each city.

| Sl. No. | City | Outdoor Temperature Range | Indoor Temperature Range |
|---|---|---|---|
| 1 | Hyderabad, India | 11-42°C | 23-46°C |
| 2 | Bogota, Colombia | 0 -24°C | 21-28°C |
| 3 | Johannesburg, South Africa | 2-32°C | 21-35°C |
| 4 | Bangkok, Thailand | 15-39°C | 25-43°C |

| Mechanical ventilation only model | | Mixed-mode ventilation model | | Implication |
|---|---|---|---|---|
| Heating - Active only (<20°C) | Cooling - Active only (>24°C) | Heating - Active only (<18°C) | Cooling - Active only (>28°C) | |
| X | Jan-Dec | X | Jan-Dec | AC reqd. throughout the year |
| X | Jan-Dec | X | X | Only NV and fan forced ventilation reqd. |
| X | Jan-Dec | X | Jan-Dec | AC reqd. throughout the year |
| X | Jan-Dec | X | Jan-Dec | AC reqd. throughout the year |
| Dec, Jan, Feb | Feb-Dec | Jan-Feb | Apr-Oct | Heating not necessary if adequate internal gains achieved. AC reqd. for part of the year |

### 3.3.2 Model 2

Depending on outdoor conditions, natural ventilation alone has the capability to provide comfort/reduce heating and cooling loads between 20-28 °C, and internal gains can cater to comfort between 18-20 °C. For this model with mixed-mode ventilation, new heating and cooling profiles for winter and summer based on Table 1 were created with setpoints of 18 and 28, respectively. Natural ventilation profiles for indoor temperature between 20-28 °C (ta>20 and ta<28) were also created. This strategy was modeled using the MacroFlo tool in IES VE [37] with the following settings:

- **Exposure type:** Sheltered wall (considering it will be a megacity with surrounding buildings of either similar height as this building, or bigger). Also, it is

a low-rise building since the total height is less than 12.5m.

- **Opening category:** custom/sharp edge orifice (as specified in the user guide for a simple, idealised model which is optimum for a basic comparative study)

- **Openable area:** 20% was considered for all 5 cities.

- **Degree of opening:** Annual profile created for natural ventilation.

### 3.3.3   Model 3

In many cases, it is difficult to position windows with appropriate orientation due to aesthetic reasons or interior design constraints [38]. This could lead to a considerable amount of solar heat gain, which in turn increases the indoor air temperature and causes thermal discomfort [39]. Along with providing the building protection from direct solar radiation [40], solar shading devices also provide a healthy working environment by reducing visual discomfort and glare problems [38].

Establishing the best combination of shading devices and their parameters is a complex task involving many parameters (for example, the building, shading device, indoor and outdoor conditions) that can be interconnected and sometimes conflicting. Such evaluation must be carried out for a specific building or case study to obtain an optimum shading design and strategy. Several works [41-44] have already carried out such evaluations and employed approaches such as parametric modelling, energy simulation and genetic algorithms to establish an optimum solution. Hence, we did not carry out a similar optimisation in the present work and instead focused on assessing the impact of shading devices on the energy performance of commercial buildings located in the upcoming megacities. To accomplish such a task, we have used a simple approach and assumed that all glazing were shaded. This initial evaluation will allow us to establish which cities will benefit the most from the addition of shading devices, which can then be investigated later using a more complex optimisation approach that would include daylighting and energy performance and comfort factors such as visual and glare.

In this study, horizontal overhangs were used on all facades with the dimensions: 33.28m width, 1.28 height and 0.9m projection. The shading type chosen was a projection instead of recessing the window. According to [45], recessing windows from the face of the exterior wall decreases the air movement against the window. This air movement can carry away the heat from the window surface, which would be preferred in hot climates.

### 3.3.4   Model 4

Various factors determine the performance of the building envelope, such as thermal mass, insulation, conductivity, etc. The U-value or the thermal transmittance is a principal factor in determining the steady-state heat losses or gains in the envelope and thus determines the heating/cooling system required in the building [34]. Appropriate U-values were used to modify the model according to each city instead of replacing the building materials themselves in each city. Knowing the U-value required, materials could be chosen, which could work together to achieve this value. Chen and Tong [11] classified cities based on the statistical climate classification scheme introduced by [39] in ASHRAE 169-2021. According to [46], the appropriate U values for each climate zone were then used to conduct the simulation on EnergyPlus. These values have been tabulated in Table 2. Table 3 shows the description of each climate zone. Since the thermal criteria data used for this classification was not available for the chosen megacities, the zones were identified by co-relating the Koppen-Geiger classification and the ASHRAE 169-2006 classification in the United States.

**Table 2.** Ideal U values ($W/m^2 \cdot K$) for different building envelope components based on climate type.

| Climate Zone Number | Fenestration | | Roofs | |
|---|---|---|---|---|
| 1 | 0.5 | 2.839 | 0.048 | 0.273 |
| 2 | 0.5 | 2.839 | 0.048 | 0.273 |
| 3 | 0.46 | 2.612 | 0.048 | 0.273 |
| 4 except 4C | 0.38 | 2.158 | 0.039 | 0.221 |
| 5 and 4C | 0.38 | 2.158 | 0.039 | 0.221 |
| 6 | 0.336 | 2.044 | 0.032 | 0.182 |
| 7 and 8 | 0.29 | 1.647 | 0.028 | 0.159 |

| External Wall | | Floor | |
|---|---|---|---|
| 0.142 | 0.806 | 0.322 | 0.806 |
| 0.142 | 0.0806 | 0.107 | 0.0806 |
| 0.11 | 0.625 | 0.076 | 0.625 |
| 0.104 | 0.591 | 0.076 | 0.591 |
| 0.078 | 0.443 | 0.074 | 0.443 |
| 0.078 | 0.443 | 0.064 | 0.443 |
| 0.061 | 0.346 | 0.055 | 0.346 |

**Table 3.** Description of climate zone type based on ASHRAE 169-2021 classification.

| Climate Zone Number | Climate Zone Name |
|---|---|
| 1 | Very Hot-Humid (1A) Dry (1B) |
| 2 | Hot-Humid (2A) Dry (2B) |
| 3 | Warm-Humid(3A) Dry (3B), Warm Marine (3C) |
| 4 expect 4C | Mixed-Humid (4A) Dry (4B) |
| 5 and 4C | Cool-Humid (5A) Dry (5B) Marine (5C), Mixed-Marine (4C) |
| 6 | Cold-Humid (6A) Dry (6B) |
| 7 and 8 | 7 Very Cold, 8 Subartic |

Based on this the cities were categorised into zones as follows: Hyderabad (Zone 1); Bogotá (Zone 4C/3C); Johannesburg (Zone 4C/3C); Bangkok (Zone 1); Chengdu (Zone 4). Since some climate zones couldn't be precisely identified due to ambiguity, the ideal set of U values for each city was confirmed by running multiple simulations with different settings. It is important to note that as demonstrated by the CIBSE Energy Performance Group [34], it is possible that the actual energy consumption could be 2-5 times the simulated values. This is because not all energy uses in the building have been considered (e.g. lighting, small power loads, etc.), and because in-use energy consumption is often much higher than design values.

## 4. RESULTS AND DISCUSSIONS

The following section presents the results based on the different climatic zone categories: Hyderabad (Zone 1); Bogotá (Zone 4C/3C); Chengdu (Zone 4).

## 4.1 City specific study for Zone 1: Hyderabad, India

Hyderabad has very hot weather for most of the year. Cooling would be required for most of the year, and heating may or may not be required. The indoor air temperature for the base model shows that there is no requirement for heating and the building envelope makes it too hot even in the cooler months.

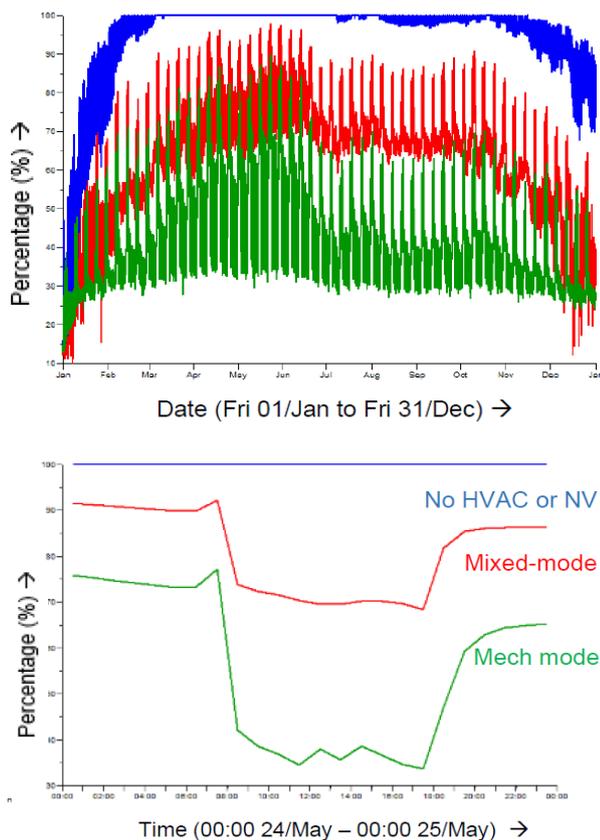### 4.1.1 Mechanical only vs Mixed-mode ventilation

Fig. 5 shows that mechanical cooling with a set point of 24 °C can help keep the indoor temperatures within comfortable ranges for most of the year except March to June because the outdoor temperature is extremely high during these months. With mixed-mode ventilation, the temperature goes above the comfortable range for most of the year except January and December (The higher temperatures shown in the graph are on weekends). Natural ventilation introduces hot outside air which makes the interior conditions worse. There would be no heating load, but the cooling load would be high between February and July, as seen in Table 4. The figure also shows that mixed ventilation reduces the cooling load only slightly in the peak summer months (mostly because of the larger range of setpoint temperatures). In April and May, mixed-mode has higher cooling loads than the mechanical model. Natural ventilation reduces the cooling load in the cooler months since the indoor temperature is closer to the comfortable range. The estimated energy saving ES% is 18.48%.
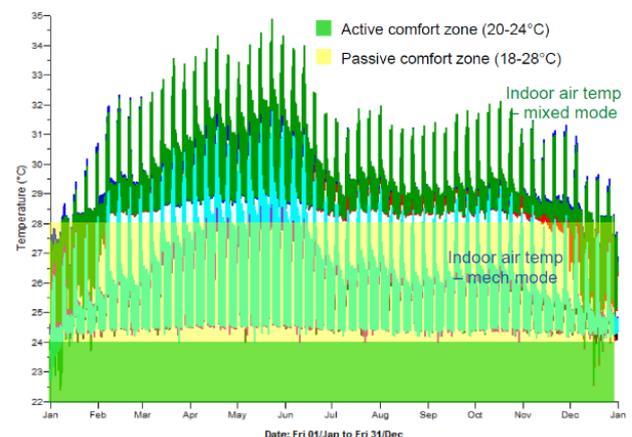


**Fig. 5.** Indoor air temperature range – mechanical vs mixed-mode models.

**Table 4.** Total energy consumption with mixed-mode ventilation and sensible loads.

| Month | Hyderabad, India Total Energy (MWh) | |
|---|---|---|
| | Mixed Mode | Mechanical Only |
| January | 3.915 | 18.099 |
| February | 19.619 | 23.296 |
| March | 29.976 | 30.171 |
| April | 34.527 | 31.682 |
| May | 35.888 | 32.061 |
| June | 27.231 | 29.355 |
| July | 19.546 | 24.702 |
| August | 17.602 | 23.813 |
| September | 18.742 | 23.895 |
| October | 20.049 | 22.968 |
| November | 16.486 | 22.863 |
| December | 4.444 | 20.334 |
| Summed Total | 248.030 | 302.242 |





**Fig. 6.** Percentage of people dissatisfied – base model (no HVAC or NV) vs mechanical vs mixed-mode models.

As expected, without HVAC or natural ventilation, and with outdoor temperatures as high as 40 °C and indoor temperatures being above 28 °C for most of the year in the base model (Fig. 6), the base model would have the highest percentage of dissatisfied people. Fig. 6 shows that 100% people are dissatisfied nearly throughout the year for the base model, the percentage is lesser for mixed-mode (up to 74% on the peak summer day of May 24 as confirmed from range tests for weekdays between 8AM-6PM), and even lesser in the mechanical-only model (up to 43%). These peak values for the hottest day (May 24) is given in Fig. 8. This shows that the climatic condition of Hyderabad is unsuitable for natural ventilation.

The indoor $CO_2$ levels were first compared for the mechanical vs mixed-mode models with the outdoor levels set as the current global level of 408.97 ppm [47] and then to the 2030 level of 445 ppm [48]. Fig. 7 shows the indoor CO2 levels are exorbitantly high in the cooler months of the year for the mechanical model. This is because auxiliary ventilation only switches on above 26 °C, which means that there is zero inflow of fresh air in the cooler months. Even when there is auxiliary ventilation (summer months), there is still a very high concentration of indoor CO2. The recommended level of indoor $CO_2$ is below 1000 ppm.
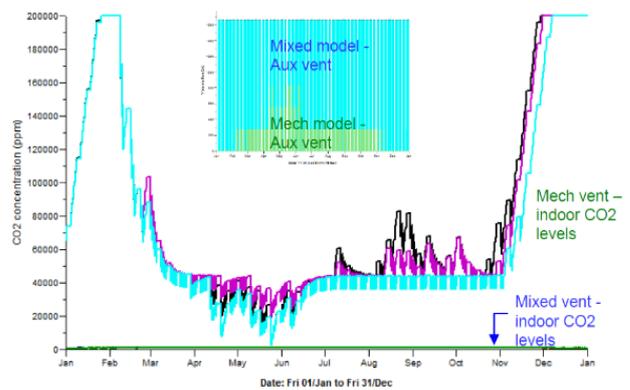


**Fig. 7.** Indoor CO2 levels: current levels for mixed vs mechanical model.

Fig. 8 also shows that the indoor CO2 levels for mixed-mode ventilation are much lower due to the introduction of fresh air through natural ventilation. With the current CO2 levels, the mixed-mode model can keep the levels within the recommended 1000 ppm limit. In 2030, it exceeds the limit to 1050 ppm. The figure also shows clearly that the external ventilation is responsible for keeping the levels much lower in the cooler months.
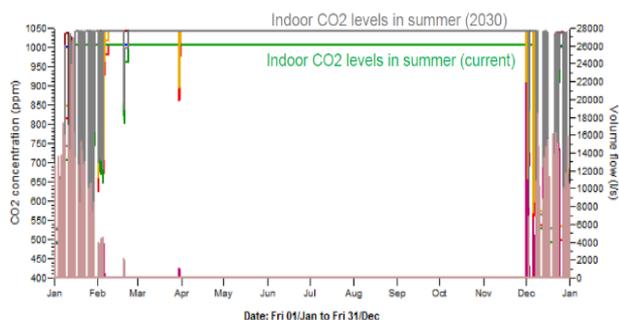
**Fig. 8.** Indoor CO2 levels: Current vs 2030 levels for mixed-mode model.

### 4.1.2 Mechanical ventilation vs Shaded model

Table 5 shows that this creates a reduction in total annual energy consumption. The ES% = 20.08%. This is only slightly higher than that with mixed-mode ventilation because although there is a reduction in energy use in every single month, mixed-mode provided larger reductions in the cooler months as compared to this model.

In terms of comfort, Fig. 9 shows that for the hottest day of the year (May 24), the maximum PPD without shading during working hours was 43% and it went down to 39% with shading.

**Table 5.** Cooling load and total energy consumption with shading (no heating).

| Month | Hyderabad, India Total Energy (MWh) | |
| | Mechanical and Shading | Mechanical Only |
| --- | --- | --- |
| January | 12.520 | 18.099 |
| February | 16.219 | 23.296 |
| March | 24.064 | 30.171 |
| April | 27.461 | 31.682 |
| May | 27.850 | 32.061 |
| June | 24.861 | 29.355 |
| July | 20.610 | 24.702 |
| August | 19.859 | 23.813 |
| September | 19.708 | 23.895 |
| October | 18.874 | 23.968 |
| November | 16.622 | 22.863 |
| December | 14.491 | 20.334 |
| Summed Total | 243.144 | 304.242 |
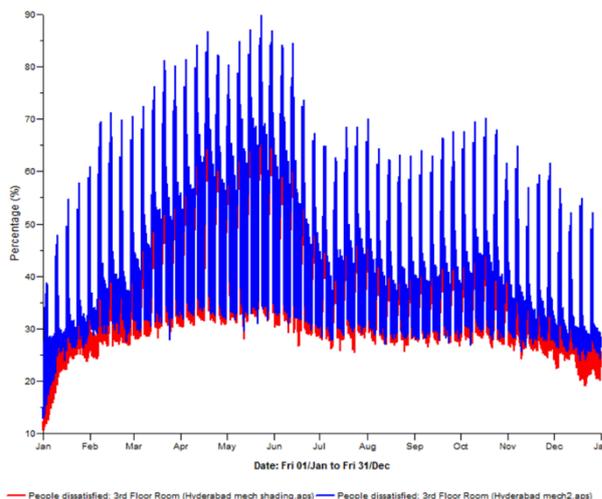


**Fig. 9.** PPD with shading vs without shading.

### 4.1.3 Mechanical only vs model with new construction materials

The new construction materials assigned were based on climate type as detailed in Table 2 and 3, which shows that Hyderabad is expected to be in climate zone 1. However, all the templates were applied to check the change in energy consumption and PPD. These were inter-related to reach to a conclusion of the ideal materials to be used in the city. Table 6 shows the annual energy consumption with different templates.

**Table 6.** Annual energy consumption with different construction templates – Climate zones 1-6 and base mechanical-only model.

| Climate Zones | 1 | 2 | 3 |
| --- | --- | --- | --- |
| Date (Month) | Total energy (MWh) | | |
| January 01-31 | 20.019 | 19.955 | 20.311 |
| February 01-28 | 27.070 | 26.957 | 27.276 |
| March 01-31 | 40.067 | 39.273 | 38.369 |
| April 01-30 | 45.395 | 43.874 | 42.394 |
| May 01-31 | 47.936 | 45.570 | 43.834 |
| June 01-30 | 37.698 | 36.628 | 36.003 |
| July 01-31 | 28.465 | 27.822 | 27.739 |
| August 01-31 | 27.236 | 26.524 | 26.476 |
| September 01-31 | 27.650 | 26.968 | 26.803 |
| October 01-31 | 28.207 | 27.860 | 27.751 |
| November 01-30 | 25.305 | 25.091 | 25.422 |
| December 01-31 | 20.804 | 21.048 | 21.710 |
| Summed total | 375.853 | 367.581 | 364.089 |

| 4 | 5 | 6 | Mech |
|---|---|---|---|
| **Total energy (MWh)** | | | |
| 20.820 | 20.842 | 20.927 | 18.099 |
| 27.585 | 27.483 | 27.602 | 23.297 |
| 37.954 | 37.374 | 37.156 | 30.172 |
| 41.477 | 40.733 | 40.215 | 31.682 |
| 43.016 | 42.245 | 41.789 | 32.062 |
| 35.853 | 35.455 | 35.228 | 29.355 |
| 27.891 | 27.793 | 27.788 | 24.702 |
| 26.720 | 26.624 | 26.615 | 23.813 |
| 26.927 | 26.788 | 26.769 | 23.895 |
| 27.821 | 27.610 | 27.542 | 23.969 |
| 25.946 | 25.983 | 26.101 | 23.863 |
| 22.447 | 22.626 | 22.810 | 20.334 |
| 364.456 | 361.553 | 360.541 | 304.243 |

For a clearer picture, this has been arranged into Table 7 along with the max. PPD in each case (as per range tests). It is seen that all the models have higher energy consumption than the base model.

**Table 7.** Energy consumption and max. PPD.

| | **Base model** | **Climate zone 1** | **Climate zone 2** |
|---|---|---|---|
| Annual Energy Consumption (MWh) | 304.242 | 375.852 | 367.580 |
| max. PPD | 43 | 54 | 53 |

| Climate zone 3 | Climate zone 4 | Climate zone 5 | Climate zone 6 |
|---|---|---|---|
| 364.088 | 364.456 | 361.553 | 360.541 |
| 51 | 49 | 48 | 47 |

If we refer again to the Table of U-values for each climate as shown in Table 8 we see that the base model has very low U-values for all parts except the floor. The floor isn't exposed to direct solar gain, while the other parts are. Also, since the surface area of the external walls and roof is the largest, the resistance to heat gain of these surfaces contributes the most to the total energy consumption. Low U-values for these parts implies high resistance to heat loss/gain.

**Table 8.** U-values for different climate zones.

| Climate Zone Number | Fenestration | Roofs | External Wall | Floor |
|---|---|---|---|---|
| | W/m2.K | W/m2.K | W/m2.K | W/m2.K |
| Base model | 1.680 | 0.180 | 0.261 | 1.069 |
| 1 | 2.839 | 0.273 | 0.806 | 1.828 |
| 2 | 2.839 | 0.273 | 0.806 | 0.608 |
| 3 | 2.612 | 0.273 | 0.625 | 0.432 |
| 4 expect 4C | 2.158 | 0.221 | 0.591 | 0.432 |
| 5 and 4C | 2.158 | 0.221 | 0.443 | 0.420 |
| 6 | 2.044 | 0.182 | 0.443 | 0.363 |
| 7 and 8 | 1.647 | 0.159 | 0.346 | 0.312 |

Comparing the values for the lowest PPD in Table 9, the U-values corresponding to Climate 6 seems optimum for Hyderabad. But Climate 6 corresponds to Cold Dry/Humid climate which does not describe Hyderabad's very hot weather. An interesting observation is that the max. PPD shown is only for the working hours of the office. If we consider the whole day, the max. PPD is as shown in Table 9. It is seen that the U-values for Climate 1 are most suitable for thermal comfort, which more accurately describes Hyderabad's climatic conditions (Very Hot Humid/Dry).

**Table 9.** PPD for entire day on the hottest day in Hyderabad.

| | **Base model** | **Climate zone 1** | **Climate zone 2** | **Climate zone 3** | **Climate zone 4** | **Climate zone 5** | **Climate zone 6** |
|---|---|---|---|---|---|---|---|
| max. PPD | 78 | 92 | 97 | 98 | 97 | 97 | 97 |

This brings us to the conclusion that during the occupied hours, lower U-value, i.e. higher resistance to heat gain is better since the direct solar gain can be very high. During the unoccupied hours (night/early morning), the heat inside the building needs to escape, and without any ventilation, the only way is through low resistance materials (higher U-value). Considering the occupants of the office will not be subject to the heat inside the building during these times, it is safe to assume that the U-values of climate 6 is more suitable for this city. The intricacies involved in timing and envelope heat loss/gain means that the

guidelines in IECC 2009 (based on which Table 2 was populated) might need to be re-evaluated and updated to account for these factors.

Comparing the energy consumption and max. PPD for shading vs. mixed-mode ventilation (Fig. 10), it is seen that even though shading increased the energy savings only by 1.6% (20.08%-18.48%), the percentage of people dissatisfied is significantly lower. Additionally, from utilising the global electricity prices in 2018 given by [49], the cost of electricity in India was 0.08USD/kWh. This provided a total annual running cost of the different methods in Fig. 10. It presents the annual running cost of utilising the shading technique is the lowest ($19842.46 USD). Along, with the annual energy consumption and percentage of people dissatisfied results, this shows that shading works much better in Hyderabad as an energy-saving passive cooling strategy than mixed-mode ventilation.
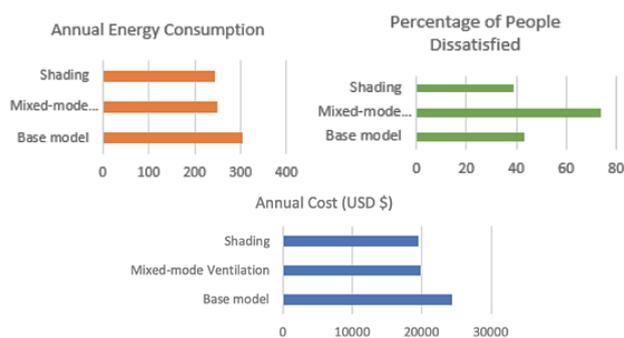


**Fig. 10.** Comparison of energy consumption, PPD and for shading vs mixed-mode and the annual running cost for Hyderabad.

## 4.2 City specific study for Zone 4C/3C: Bogota, Colombia

The dry bulb temperature in Bogota is mostly lower than the comfort zone for most of the year. Heating would be required for most of the year, and cooling would not be required. The indoor air temperature for the base model; however, shows that there is no requirement of heating or cooling since the building envelope makes it comfortable throughout the year (considering all windows are kept closed).

Fig. 11 shows that with mechanical ventilation only, the temperature is a little above the active comfort limits. Considering the setpoint for cooling is 24 °C for the model with only

mechanical ventilation, this means that there will be some cooling load for this model. On introducing the cooler outdoor air through natural ventilation, it is seen that the indoor temperature goes down but remains in the comfortable range of temperatures. Since it is within the limits of passive heating and cooling, the mixed-mode ventilation model will not have any heating or cooling loads.
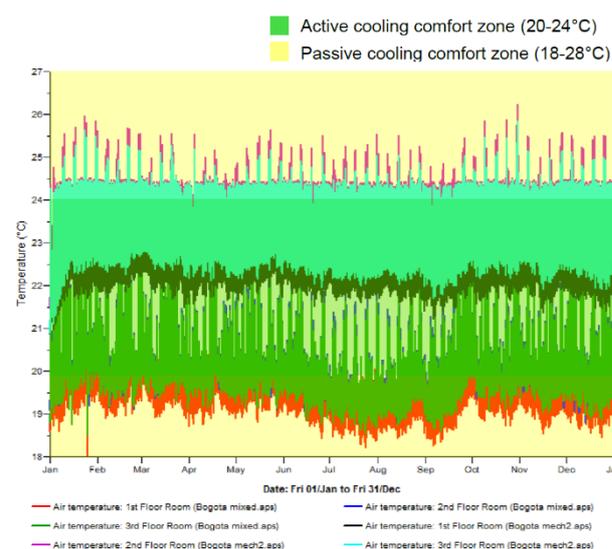


**Fig. 11.** Indoor air temperature range – mechanical vs mixed-mode models.

With low temperatures outside, it is expected that a lower range within the comfortable temperature range would be easier to adjust to as compared to higher ranges. Thus, even though both mechanical and mixed-mode provide indoor air temperatures with a comfortable range, mixed-mode has a much lesser percentage of dissatisfied people. This means that Bogota has the perfect climatic conditions for mixed-mode ventilation as a passive cooling strategy. From a closer look at the PPD values during the hottest day of the year (May 11). the application of the mixed-made suggests an average of 6% of the people would be dissatisfied, with a peak during 13:00-15:30. However, when mechanical ventilation was applied, a minimum percentage of occupancy dissatisfaction would be 12% and during the building operational hours of 08:00-20:00, the percentage of occupancy dissatisfaction would range between 30-35%. Hence, it suggests the maximum PPDmech is 26% and PPDmixed is 10%. Therefore, the PPD decreased by 61.54 % with mixed-mode ventilation.

The previous sections show that mechanical ventilation alone can provide comfort. However, Fig. 12 shows that the lack of fresh air makes the indoor $CO_2$ levels exorbitantly high. Mixed-mode ventilation reduces the levels and brings it down to the safe levels of within 1000 ppm.
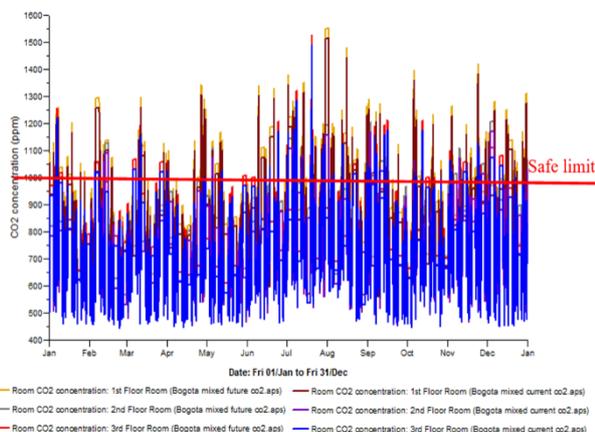


**Fig. 12.** Indoor $CO_2$ levels for mixed-mode model - current and future levels of atmospheric $CO_2$.

Table 10 shows these along with the max. PPD in each case (as per range tests). It is seen that

climate 1 has the least energy consumption and max. PPD which implies that for Bogota, higher U-values and thereby lower resistance to heat gain/loss is preferable during occupied hours since it is generally quite cold in Bogota and solar gain during the day would be preferable.

The ES% with shading is 48.21%, which is quite high but compared to 100% ES% for mixed-mode along with the 61.54% decrease in PPD, mixed-mode proves to be a better strategy in Bogota (Fig. 13). Additionally, the annual running cost reflects upon the annual energy consumption. For Bogota, an electricity price of 0.187USD/kWh was assumed (Statista, 2018). If the base model was implemented; it would have provided an annual running cost of 19004USD. However, if the shading technique was applied, it would provide an annual running cost of 9842USD. This is a high reduction (nearly 50%) towards annual costs. However, through the consideration of the ES% for mixed-mode being 100%, it provides the lowest energy consumption and costs. Hence, mixed-mode would be the best strategy for Bogota.

**Table 10.** Energy consumption and max. PPD.

|  | Base model | Climate zone 1 | Climate zone 2 | Climate zone 3 | Climate zone 4 | Climate zone 5 | Climate zone 6 |
|---|---|---|---|---|---|---|---|
| Annual Energy Consumption (MWh) | 105.577 | 43.480 | 62.216 | 85.722 | 105.034 | 113.870 | 120.654 |
| max. PPD | 26 | 23 | 25 | 26 | 27 | 28 | 28 |
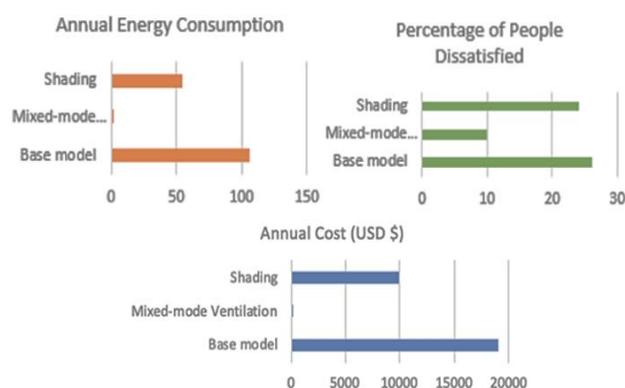


**Fig. 13.** Comparison of energy consumption, PPD and costs for shading vs mixed-mode for Bogota.

### 4.3 City specific study for Zone 4: Chengdu, China

Like Johannesburg, Chengdu also has a wide range of temperatures between summer and

winter. The dry bulb temperature shows hot summers with a peak temperature of around 35 °C and very cold winters with temperatures going down to freezing point. Unlike Johannesburg though, in this case, the building envelope cannot protect the occupants entirely from the peak cold days in winters. Therefore, Chengdu would require both heating and cooling systems. Fig. 14 shows that in the case of mechanical ventilation, the system can't keep the temperature within the active comfort zone, but it is within the passive comfort zone. With mixed-mode ventilation, the temperatures go outside the limits of comfort both in summer and in winter. This proves that mechanical ventilation is better than mixed-mode for Chengdu.
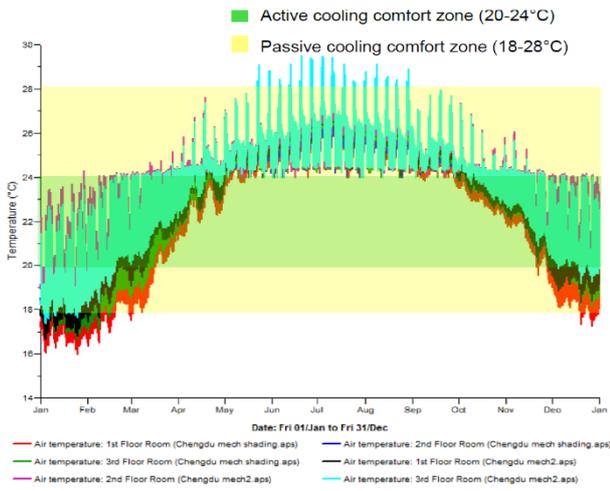
**Fig. 14.** Indoor air temperature range for mech vs mixed-mode models in Chengdu.

**Table 11.** Cooling loads and energy consumption.

| Month | Chengdu, China Total Energy (MWh) | |
|---|---|---|
| | Mixed Mode | Mechanical Only |
| January | 0.000 | 2.461 |
| February | 0.000 | 1.012 |
| March | 0.000 | 5.025 |
| April | 0.149 | 14.387 |
| May | 2.478 | 19.776 |
| June | 12.643 | 23.718 |
| July | 17.896 | 24.876 |
| August | 15.180 | 22.766 |
| September | 3.480 | 18.996 |
| October | 0.000 | 11.442 |
| November | 0.000 | 5.258 |
| December | 0.000 | 0.708 |
| Summed Total | 51.828 | 150.428 |

Table 11 shows that even though mechanical ventilation is better, due to the low setpoints, the loads and the energy consumption are much higher for mechanical ventilation in some months. In fact, there is no heating load for the mixed-mode model making the energy savings quite high (ES% = 65.55%).

Fig. 15 shows that with mixed-mode ventilation PPD is higher in both peak summer and peak winter than the mechanical ventilation only model. This was expected since the previous section shows that the indoor temperature during these periods is not within the comfort zone. The hottest day PPD was checked considering the summer indoor temperatures were high for both models. For the

hottest day (June 16) shows that that mixed-mode model has much higher PPD. Range tests on this day show that: Max. $PPD_{mech}$ is 35% and Max. $PPD_{mixed}$ is 70%. Therefore, the Percentage of People Dissatisfied increased with mixed-mode ventilation by 100%. This is a clear indication that mixed-mode ventilation is not suitable for comfort in Chengdu due to extreme winters and summers.
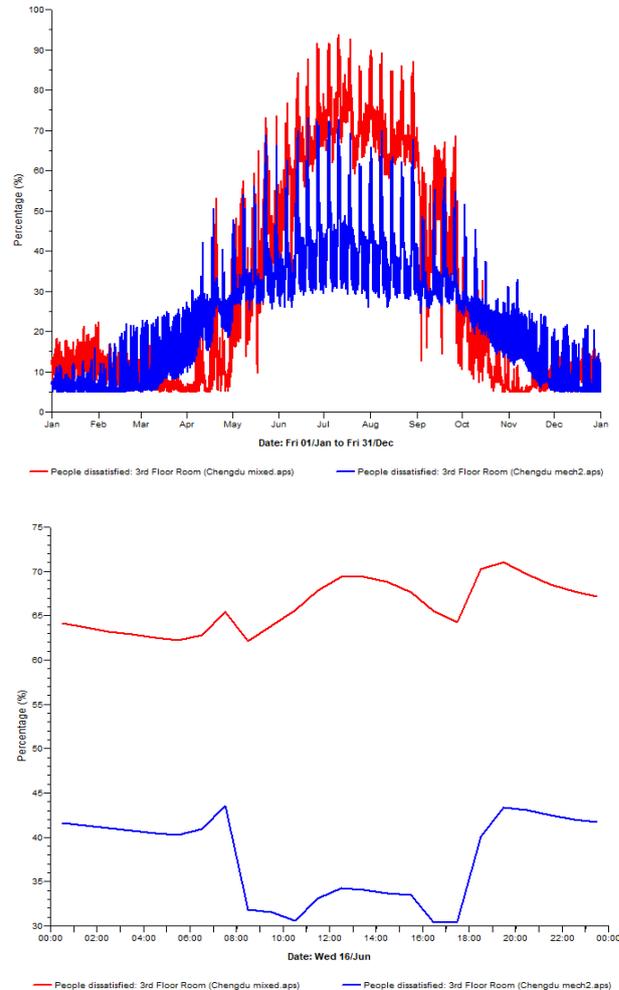


**Fig. 15.** Annual PPD – mech vs mixed-mode and PPD for the hottest day in Chengdu (Jun 16).

Table 12 shows these along with the max. PPD in each case (as per range tests). It is seen that the values for climate 3, 4 and 5 are almost the same, with 4 being the least energy-consuming. Climate 3, 4 and 5 correspond to the Warm, Mixed and Cool variants of Humid/Dry respectively. It makes sense that Chengdu would be classified into these categories, and thus the IECC 2009 recommendations for climate 4 are quite accurate. With Chengdu's mix of hot summers and cold winter, climate 4 is an accurate description of the climate of the city. The mixed climate would need U-values that are not too high and not too low.

**Table 12.** Energy consumption and Max PPD.

| | Base model | Climate zone 1 | Climate zone 2 | Climate zone 3 | Climate zone 4 | Climate zone 5 | Climate zone 6 |
|---|---|---|---|---|---|---|---|
| Annual Energy Consumption (MWh) | 150.428 | 191.321 | 178.025 | 170.738 | 170.329 | 170.386 | 172.347 |
| max. PPD | 35 | 37 | 39 | 39 | 39 | 39 | 39 |
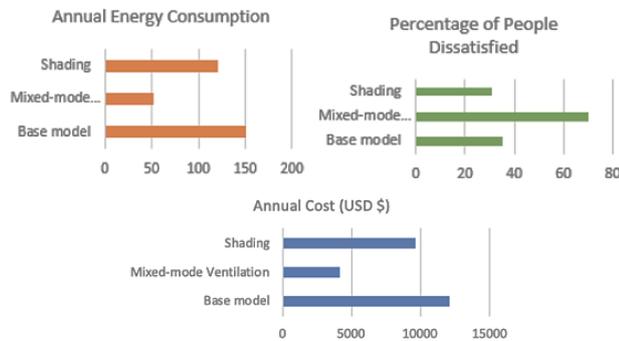


**Fig. 16.** Comparison of energy consumption, PPD and costs for shading vs mixed-mode for Chengdu.

Along with earlier discussions and Fig. 16, it shows that even though the ES% for mixed-mode is much higher, the fact that the PPD increases by such large amounts make it clear that shading is preferable over mixed-mode ventilation as a passive cooling strategy in Chengdu. With the annual cost reflected upon the annual energy consumption; using the electricity price of 0.08USD/kWh based on (Statista, 2018), the shading strategy would provide an average annual cost of 9605USD.

### 4.4 Comparing the Five Megacities

#### 4.4.1 Mixed-mode ventilation

Mixed-mode ventilation is capable of very high reductions in energy consumption by drastically reducing (or even negating) the need for mechanical heating or cooling systems. Bogota benefited most from mixed-mode ventilation since the introduction of outdoor air itself was adequate to keep indoor temperatures within comfortable limits. Based on PPD reduction, mixed-mode ventilation was a valid option only for Bogota, considering the max. PPD increased for all other cities on introducing natural ventilation.

#### 4.4.2 Shading

Shading decreased energy consumption in all cities since the cooling loads would be reduced with lesser solar gain. The scale of reduction,

however, was not as high as that with mixed-mode ventilation. Yet again, Bogota had the most reduction in energy use. This is because Bogota has the least seasonal temperature variation as compared to other cities. In the case of other cities, even if the cooling load was reduced, the heating load was still existent. The lesser variation in temperature, the more one single strategy would be able to change the energy consumption. Based on PPD reduction, shading decreased max. PPD for every city since overheating is an important issue during the day. Chengdu benefits most from shading because the summer indoor temperature is very high and unbearable whilst shading can bring it down within the comfortable range of temperatures.

Based on the above arguments, mixed-mode ventilation is most advantageous in Bogota – both in terms of energy-savings and thermal comfort. Even though the thermal comfort increase is not as high as it is in other cities, taking both ES% and PPD into account, Bogota benefits most from shading as well. It can therefore, be deduced that Bogota has the highest energy-saving potential using these passive cooling strategies.

#### 4.4.3 Use of appropriate materials

The results for optimum U-values for each city are summarised in Table 13 based on the values that provided the best combination of low energy consumption and low PPD.

**Table 13.** Optimum U-values for the five mega cities.

| City | U-values (W/m2.K) | | | |
|---|---|---|---|---|
| | Window | Roof | Ext. Wall | Floor |
| Hyderabad | 2.0441 | 0.182 | 0.442 | 0.363 |
| Bogota | 2.839 | 0.273 | 0.806 | 1.828 |
| Johannesburg | 2.839 | 0.273 | 0.806 | 0.607 |
| Bangkok | 2.0441 | 0.182 | 0.442 | 0.363 |
| Chengdu | 2.158 | 0.221 | 0.590 | 0.431 |

## 4.5 Ranking the Five Cities

The five cities were ranked for each strategy taking both the ES% and the PPD reduction into consideration. The graphs in 17 show the rankings.



(a)



(b)



(c)
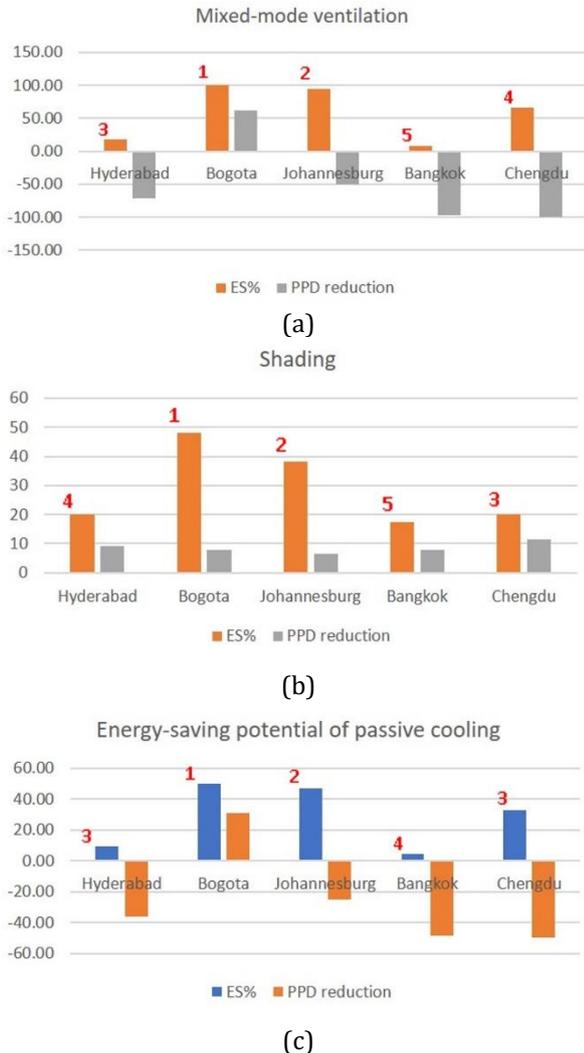
**Fig. 17.** City rankings a). Mixed-mode ventilation. b). Shading. c). Energy-saving potential of passive cooling.

For mixed-mode, even though Chengdu has third highest ES%, it is in 4th place because of the high max PPD. It is important to note here that for Johannesburg and Chengdu, the high seasonal variations in dry-bulb temperature means that during the very cold winters, even though PPD is satisfactory, the indoor CO2 levels are unhealthy due to low ventilation. Thus, for these cities, the potential is lesser than shown here unless there is an auxiliary ventilation system.

Considering both strategies, a final ranking given in Fig. 17c was also made for the 5 cities taking averages of all values for determining the

city with the highest energy-saving potential of passive cooling. Based on this, Bogota has the highest potential, followed by Johannesburg. Chengdu and Hyderabad have similar potential, and Bangkok has the least potential.

With temperatures rising over the years (Fig. 5), mixed-mode ventilation will become lesser of a feasible passive cooling strategy. Shading and appropriate building envelope will become more relevant as a passive cooling strategy for energy-saving. However, for the selection of appropriate strategies, the annual running cost for each megacity should be considered. Fig. 18 presents the annual costs for each strategy; it shows a high dependence on annual energy consumption and the electricity price for each country. Bangkok, Thailand had the highest overall energy consumption with an electricity price of 0.13USD/Wh. In comparison to other cities, it provided a high annual cost for every strategy. Whereas Johannesburg had a lower electricity price of just 0.09USD/KWh along with a lower total annual energy consumption. Therefore, many aspects should be considered before finalising which strategy would be the best application for these upcoming megacities.
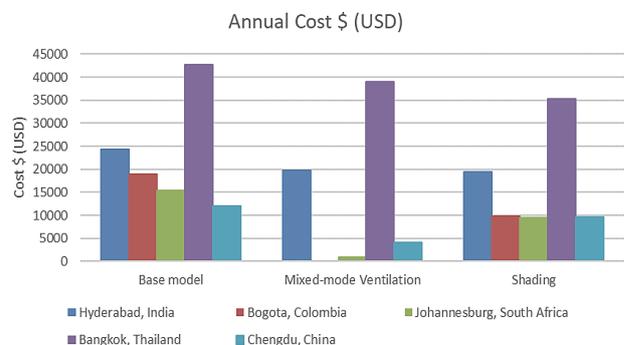


**Fig. 18.** Annual costs for all 5 cities.

## 5. CONCLUSION AND FUTURE WORK

This study was able to provide a glimpse at a few of the many passive cooling strategies that could be used to reduce energy consumption with due attention to thermal comfort and air quality. The study showed that while shading can reduce cooling loads and, subsequently, energy consumption in all cities, mixed-mode ventilation was not able to provide similar results everywhere.

Being tropical regions with high temperature and humidity, Bangkok has the least potential

with an energy saving of 4.27%, and Hyderabad is close behind with 9.24%. Due to the high outdoor air temperatures throughout the year, it results in the use of natural ventilation would only bring in more hot air towards the indoor environments of a building.

Chengdu has a subtropical mixed-humid climate with large seasonal variations making it difficult to provide comfort in the peak summer and winter periods. Evidently, it was projected that an average of 50% of the people would be dissatisfied when passive strategies were used.

Furthermore, Johannesburg also has large seasonal variations. Since it has a temperate milder range of temperatures, it indicated that it would be easier to apply passive modes to buildings. This includes both mixed-mode ventilation and shading to provide an overall energy-saving potential of 47.20%.

Bogota's temperate (mixed) oceanic climate with very less seasonal variations is ideal for passive cooling. It indicated that both shading and mixed-mode ventilation strategies could provide the highest amount of energy saving compared to other cities with 100% from mixed-mode ventilation and 48.21% from shading. Overall, it projected the use of passive cooling could provide up to 50% of the energy savings. Since the outdoor conditions are not extreme and thus subjecting the indoor environment to the outdoor elements through passive methods, it indicated that this location would not be detrimental to comfort.

With temperatures rising over the years, mixed-mode ventilation will become lesser of a feasible passive cooling strategy. Shading and appropriate building envelope will become more relevant as a passive cooling strategy for energy-saving.

The use of appropriate materials was a separate study that involved a comparison of several sets of U-values to find the optimum value for the city. The results showed that the IECC 2009 recommended values might need to be updated, especially for Climate 1, by considering the differences in energy consumption and thermal comfort during occupied hours and unoccupied hours and daytime versus night-time.

This study can be expanded to more cities and using more strategies/combining and trying several permutations and combinations of strategies, leading to results that can make an immense change in the way we view building design and planning. Other strategies such as atria, wind catchers, solar chimneys and double-skin facades could be incorporated into the design to assist natural ventilation. There is also great potential for future work in terms of including residential buildings in the study, assessing the economic feasibility of each strategy in each country, studying the existing policies and predicting the ease of implementation of new guidelines in each city, the availability and feasibility of including renewable technologies as well as analysing the effects of full vs partial user-control of the indoor environment. Furthermore, it should be noted that our results are based on an isolated and single commercial building and cannot be generalised over all different classifications. Future research could expand this study by including residential buildings and assessing the economic feasibility of each passive cooling strategy within different national and local contexts. In addition, the evaluation of relevant building codes, policy frameworks, and the practicality of implementing new design guidelines in each city would enhance the real-world applicability of the findings. Further investigations could also explore the integration of renewable technologies, the degree of occupant control over indoor environmental conditions, and the influence of surrounding urban form and building configurations. Urban heat island effects and local air quality should also be considered, as they significantly impact the effectiveness of passive strategies. Ultimately, future studies should adopt a more holistic performance assessment approach that encompasses not only energy consumption but also thermal comfort, visual comfort, and economic viability to support informed and sustainable design decisions across different urban scales.

## Acknowledgements

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