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Simulation-based evaluation of low carbon design strategies for extreme climates

Argenis Toyo Diaz and Seyed Masoud Sajjadian

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ABSTRACT

Extreme climate conditions present the greatest challenge in achieving thermal comfort in buildings. To address this issue, researchers have evaluated the effectiveness of various low-carbon strategies in extreme climates, assessing their impact on comfort levels and carbon emissions. Among the strategies examined are shading, natural ventilation, dehumidification/humidification, insulation, and green roofs. This research uses dynamic thermal simulations to investigate the efficacy of these strategies on a detached house in extremely dry, humid, and cold climates. Although the study found that insulation is the most effective design strategy, a range of context-specific design combinations can substantially reduce HVAC loads, with reductions of 39%, 32%, and 40% achievable for tropical, dry, and cold climates, respectively. These findings underline the importance of carefully considering design strategies when constructing buildings in extreme climates. By employing a combination of insulation, shading, natural ventilation, and other low-carbon strategies, architects, and builders can create buildings that are more resilient and comfortable to inhabit while minimizing their carbon footprint.

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KEYWORDS

Extreme climates; low carbon design; simulations; thermal comfort; carbon footprint

1. Introduction

As reported by the World Green Building Council, the built environment is responsible for 39% of carbon emissions globally (WGBC 2019) and based on the findings of the International Energy Agency (2018), the energy consumed for electricity and HVAC system across all building typologies reaches approximately 33% of total carbon emissions. These highlight the role of architects and engineers in reducing global emissions, in the era of changing climate, through a reduction in energy demand and improving building performance (Nazi et al. 2017). Climate change mitigation strategies are diverse and complex (BEIS 2021). The WGBC (2021) reported that the built environment sector impacts are up to 53% of the 17 United Nations Sustainable development goals, including industry, innovation and infrastructure, sustainable cities, climate action, and well-being.

Zero to low carbon emission design generally refers to ‘a design with less or no dependency on energy-intensive high-emission cooling and heating technologies to achieve comfort for users’ (Gething et al. 2010). Schrot et al. (2021) warn demanding climate change conditions push architecture to address extreme climate conditions even though Domingos and Rato (2019) stated that severe weather has always existed, and architecture technology should focus on improving techniques in such situations. especially, when the future showcases hotter summers and warmer winters worldwide. The purpose of this research is to

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simulate and analyse the effectiveness of low carbon strategies for achieving thermal comfort in extreme climates.

2. Literature review

Based on the literature, the following design strategies and technologies are found to be most effective in improving thermal comfort and reducing carbon emissions in extreme climates:

- **Shading:** These devices are mainly labelled as louvred shades, overhangs or side fins. These are most predominantly located at outdoor windows but could also be at indoor or other openings. The definition of the shape depends on the capability of sunlight infiltration or visibility. In shading simulation studies, Lavafpour and Sharples (2015), Nematchoua et al. (2020), and Touma and Ouahrani (2017) quantified the positive effect of shadings in extreme climates. Elouadjeri, Boussoualim, and Haddou (2021) reported shading devices impact daylighting, but the most appropriate approach should be based on multicriteria strategies. Furthermore, high-performance devices such as kinetic shading actively mitigates the weather conditions through changing seasonal and daily sun orientation (Wanas et al. 2015).
- **Dehumidification / Humidification:** This process regulates air flow, especially indoor space's relative humidity. Once the Internal Air Quality is affected, it is necessary to use humidity control and moisture buffering to improve thermal comfort while decreasing the HVAC demand (IEA 2013). Spaces below 40% relative humidity tend to be unhealthy for users (Tu, Li, and Hwang 2020). A hot-humid climate with a relative humidity of over 60%, increases the use of cooling devices, as stated in the parametric study with EnergyPlus (version 6.0). Therefore, indoor humidity control and infiltration minimization reduce energy consumption (Fang, Winkler, and Christensen 2010). This highlights the fact that accurate regulator devices could be ideal for high indoor humidity cases. The principle of such regulators is to circulate the saturated water vapour indoors through a dry airflow in a chamber (Veldscholte, Horst, and de Beer 2021). They could also be effective in dry and cold climate Furthermore, Osanyintola and Simonson (2006) state hygroscopic finishes decrease heating demand between 2% and 3%, and 5% to 30% on cooling Energy.
- **Natural Ventilation:** As stated in ASHRAE (2021), this is the 'flow of outdoor caused by wind and thermal pressures through intentional openings in a building's shell'. The relation between local conditions and building for efficient ventilation relays on window sizes, location and most notably, building orientation. Such strategies can reduce the consumption of cooling devices, avoid moisture condensation, and allow fresh air for healthy indoor spaces. According to Brager and Baker (2009), using natural ventilation instead of electro-mechanical ventilation earns health cost savings by nearly 18%.
- **Thermal Insulation:** In the case of 'Thermal Insulation', the aim is to have a high thermal resistance and low thermal conductivity (Livesey, Suttie, and Scovell 2013) Another relevant feature is the 'Thermal transmittance' or U-Value. Allbury and Anderson (2011), classified insulation materials as 'Traditional', 'Organic' and 'Advanced Material'. The most common ones worldwide are the following:
 - (a) **Mineral Fiber:** is a 'Traditional' insulation material. Predominantly, according to Livesey, Suttie, and Scovell (2013), stone wool is used for roof and truss insulation. These are usually found as batts and composite panels.
 - (b) **Expandable polystyrene (EPS):** is an 'Organic Non-Renewable' insulation material. Kon and Caner (2020) stated that the high vapour diffusion resistance coefficient for EPS by 30 μ is suitable for avoiding condensation and optimum thickness depends on the combined performance between temperature and dewpoint gradients of materials in the building envelope.

Table 1. Extreme climate envelope (Domingos and Rato 2019).

1. Climate	Good material performance	Poorly material performance
Low temperature	Polytetrafluoroethylene (PTFE), Polymers, glass, biopolymers, wood and wood derivatives, glass and foams.	Ceramics, concrete, stone and metals
High temperature	Polyethene terephthalate (PET), Polymers, biopolymers, wood, polymers foams and glass	Concrete, stone and metals.

Domingos and Rato (2019) suggest the effectiveness of ‘Multicriteria strategies’ for buildings is dependent on the optimum use of thermal insulation materials for the envelope, they established the following guidelines for extreme climate conditions in Table 1:

- Phase Change Material (PCM): is an ‘Advance material’, not a rigorously thermal insulator. However, this works as a thermal energy storage (Baetens, Jelle, and Gustavsen 2010). This material is encapsulated mostly as a wallboard ideally designed for extreme seasonal temperatures (Feldman et al. 1991). As stated by Pacheco-Torgal et al. (2014) natural resources for PCM are ideal scenarios due to its high embodied carbon. Alternatively, Sajjadian, Lewis, and Sharples (2015) highlighted the benefits of PCM and Air gap integration to improve the PCM effects. Moreover, they reflect on the positive impacts of this thermal energy strategy on residential buildings.
- Green Roof: This roof typology is suitable for energy conservation, reducing the thermal island effect and absorbing greenhouse gases. This roof is an envelope component that requires more rigorous techniques, irrigation systems, and site precipitation studies compared to a conventional roof (Grullón – Penkova, Zimmerman, and González 2020). Velasco and Roth (2010) stated, the passive approach of green roof vegetation processes helps capture CO₂ from the surroundings; therefore, this is ideal for carbon sequestration. In slightly moderate environments, such as the Mediterranean zones (subtropical oceanic), decrease of cooling demand in summer by 11% is reported with green roofs (Ascione et al. 2013).

The selected strategies aim to influence indoor thermal comfort. Thermal comfort is challenging to quantify as it relies on environmental conditions, occupant metabolism and occupant’s perception of feeling cold or hot within an indoor space and is highly dependent on context. Even though there is no universally accepted quantitative metric for thermal comfort. ASHRAE 55 standard has been widely used for thermal comfort assessment due to its clear guidelines, consistent development based on research and industry acceptance. This standard is for quantification in this study.

2.1. Extreme climate conditions

Beck et al. (2020) classified five different types of climates; Tropical, Arid, Temperate, Continental, and Polar. Generally, every Climate and its sub-classification require a specific design. According to CIBSE (2017a), the exponential growth of cities requires climate-based data to achieve a low-carbon built environment.

Despite the demanding conditions of Polar climate, such areas are not considered in this study because they are not populated to the same extent as the rest of the groups. Moreover, a Temperate climate is

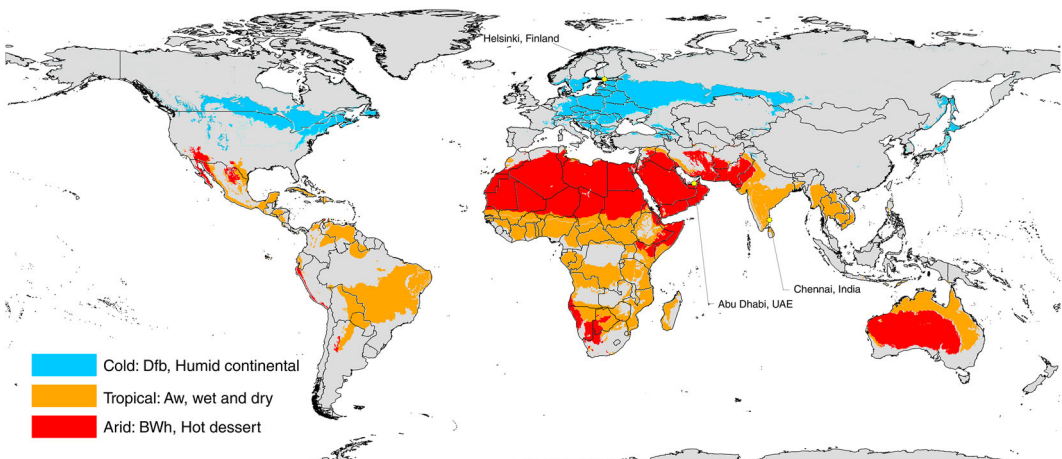


Figure 1. Cold (Dfb), Tropical (Aw, As) and Arid (BWh) climates (1980–2016). Present and future Köppen-Geiger climate classification maps at 1-km resolution (Beck et al. 2020).

generally measured as comfortable with less requirement for HVAC systems to provide comfort (Jamei et al. 2021) large cities in cold, arid and tropical climates are the following (see Figure 1):

- Cold: Montreal (Canada), Chicago (USA) and Helsinki (Finland).
- Arid: Abu Dhabi (UEA), Lima (Peru) and New Delhi (India).
- Tropical: Singapore (Singapore), Chennai (India) and Rio de Janeiro (Brazil).

In the guidance ‘Building for Extreme Environment’, CIBSE (2014; 2017a; 2017b) emphasized the current and future extreme climate conditions in these zones (see Table 2) as well as general strategies for adaptable building design:

3. Methods

The framework of effective design strategies was established based on the literature review as noted in section 1 and results are filtered by climate consultant software. A climate consultant (CC) digests EnergyPlus Weather (EPW) data to understand the local climate precisely. Climate physics such as ambient air temperature, radiation, dew point, sun shading, etc. are the basic information that this software process uses to suggest design strategies regarding determined locations (Murray Milne and Alshaali 2016). CC compiles the following annual data for cities:

- Weather data summary: This includes the monthly average for 17 climate parameters.
- Comfort Models: California Energy Code, ASHRAE Standard 55, ASHRAE 2005, Adaptive Comfort Model in ASHRAE 2010.
- Criteria: Frame of strategies and their fundamental data.
- Monthly graphics about Temperature Range, Diurnal and daylight hours averages, Sky cover range, Ground temperature, Dry bulb, Dew point and Relative Humidity, and Sun shading.
- Psychrometric chart: Set up of local climate conditions.
- Design framework: Set of different design strategies.

A digital 3D model is designed and used as case study for simulations. Simplicity, flexibility and adaptability of the model were the main considerations for comparative study. There is significant architectural and cultural differences in the studied cities but the characteristic of the model allows the focus to remain on effective strategies and technologies on energy, comfort and carbon emissions. Due to high accuracy of DesignBuilder on numerous studies (Martin-Escudero et al. 2022), the software is used for evaluations. This software analyses location and climates and Computational fluid dynamics (CFD) to optimise ventilation, indoor temperature, or airflow. Section 2.1, 2.2 and 2.3 provide details of the model and conditions of simulations including site parameters and how aforementioned design and technologies applied to the model.

Table 2. Cities Climate condition.

City and Category	Climate Condition	Solution
Chennai, India Aw, wet and dry	Minor seasonal differences. During the summer season, it usually rises more than 35°C and nights around 20°C (CIBSE 2017b).	High ceiling and facades. Light thermal mass as a building envelope because it gets cold quickly, but not necessarily as exposed material. On the other hand, shading and reflective building envelope are necessary to reach thermal comfort due to high radiation exposure.
Abu Dhabi BWh, Hot dessert	Minor seasonal differences. During the summer season, it usually arises at more than 40°C and nights around 25°C (CIBSE 2014).	Maximum shading and air movement are ideal for the region as a strategy. Indirect lighting and ventilation catching through wind towers is also effective. Evaporative cooling.
Helsinki, Finland Dfb, Mild summer, long cold winter (humid continental)	Seasonal differences. Winter with variations between -25 °C and 0°C, and Summers between 15 °C and 30°C (CIBSE 2017a).	Insulated envelope, heat recovery systems, skylights facing south and maximising glazing at south façade as well as high thermal mass.

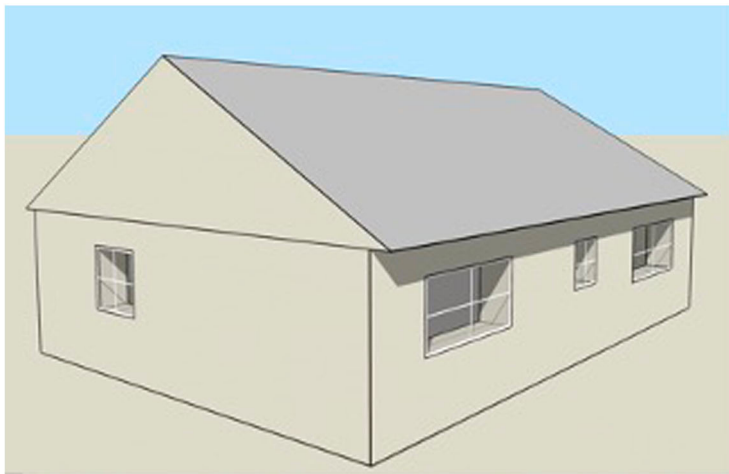
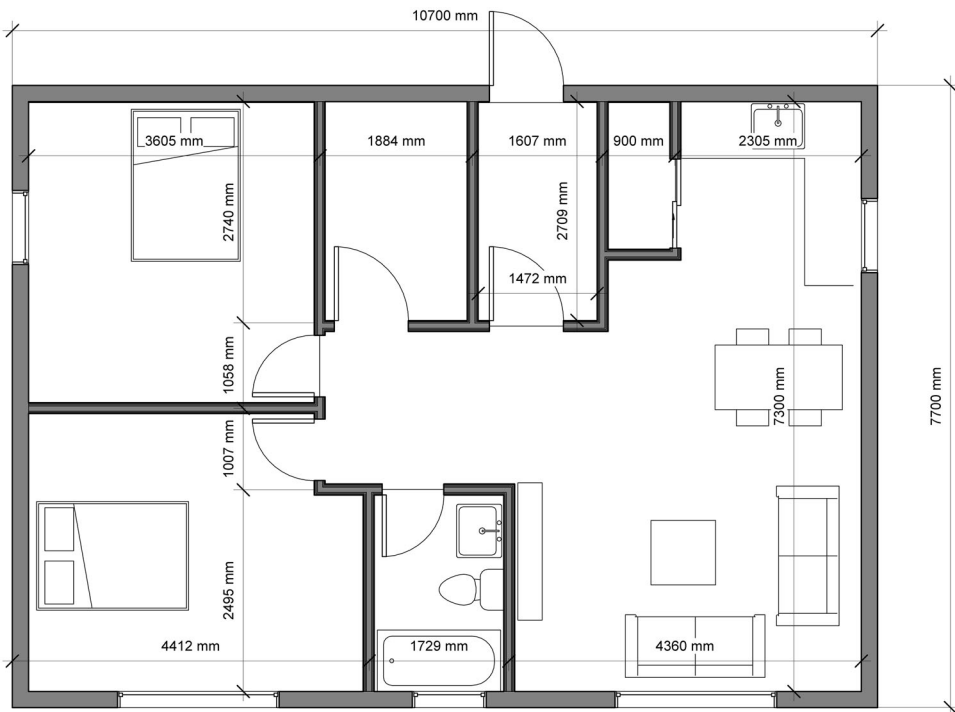


Figure 2. Layout and 3D model used for simulation.

3.1. Description of modelled house

A detached house is rectangular-shaped with a $65m^2$ total building area as shown in [Figure 2](#). The internal ceiling height is 2.5 m, and the pitched roof is a 30° slope facing South – North with 30 cm of overhang. The one-storey building has two bedrooms, one bathroom, one service room, one closet, one entrance hall, a living room, and a kitchen. The entrance faces north, and the building form is East–West orientation. Windows mostly face south; subsequently, individual windows face east and west equally.

Table 3. Basic model envelope's U-Value.

Envelope U-Value	
Envelope component	U-Value (W/m^2-K)
Wall	1.485
Roof	2.93

The model uses precast concrete for slabs and walls. Concrete is globally a popular construction material and in the last decades, has dominated the building industry due to its longevity, quality, and logistics benefits for construction developers (Kim, Kim, and Cho 2020). The U-Values for the wall and roof are shown in Table 3:

3.2. Site parameters

Table 4 provides a detailed summary of the site parameters that were utilized in the simulations conducted for this research.

Double glazed windows are used, and layers are generic clear 3 mm glass with a U-Value of $1.960 W/m^2-K$. No shading is included. The HVAC system is a fan coil unit (4-Piper) air cooler chiller, the heating uses natural gas, and the cooling system uses electricity from the grid.

3.3. Setting of strategies

Table 5 displays the various low-carbon strategies that were simulated for each extreme climate condition, including dry, humid, and cold. The strategies were carefully selected based on their potential effectiveness in achieving thermal comfort and reducing carbon emissions.

Two types of shadings are used as shown in Figure 3. SD1 is a 1-meter overhang over the windows and SD2 has additional sidefins and louvers for bedroom one and living/kitchen. Circulation, service, or closet places were not considered for daylighting studies. The material applied for the shading options was steel.

Depending on context humidification and dehumidification are activated. The Air Change rate per Hour is 5.00 ac/h.

4. Results and discussion

Figure 4 shows the extent of extreme climate in the selected cities, it shows the percentage of comfortability without energy loads in the model per year and the remaining percentage that needs multicriteria design strategies to achieve thermal comfort.

Table 4. Cities site parameters (EnergyPlus and World Meteorological Organization 2022).

Cities	Latitude	Longitude	Altitude (m)	ASHRAE Climate zone	Temp. ($^{\circ}C$)	RH (%)		
Abu Dhabi	24.43	54.65	27	1B Arid	35.3	19.4	63.83	49.4
Chennai (Nellore)	14.45	79.98	20	1B Tropical	31.3	24.3	80.23	61.7
Helsinki	60.32	24.97	56	6A Cold	18.3	-4.9	87.21	67.8

Table 5. Strategies and coding.

Carbon emission	Design strategy	Sub-Category	Code
Low	Dehumidification/humidification		DHum
Neutral	Shading	Shading 1	SD1
		Shading 2	SD2
	Natural ventilation		NVen
	Insulation	Expandable polystyrene	EPS
		Insulated Pitched roof	InPR
		Insulated Flat roof	InFR
		Phase Change Material	PCM
	Energy Storage	Flat roof	GFR
		Pitched roof	GPR
	Green Roof		

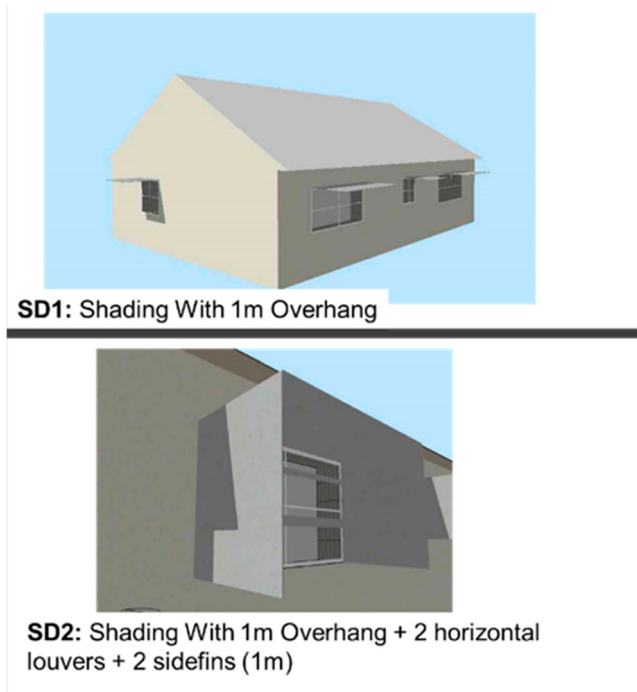


Figure 3. 3D model with shading options in DB.

As shown in [Figure 4](#), the more challenging Climate is Chennai, India, where the comfortability hours are 0.6% per year. The climate conditions for design options based on the literature review and CC framework stated the following order ([Figure 5](#)) of design priorities for the case study.

The focus of the analysis on this software was the energy consumption per square meter. For each scenario, energy distribution was divided between ‘Lighting and equipment’ and ‘Cooling and Heating’. Since ‘Lighting and equipment’ is a constant user consumption, the exact value of 1507 kWh is observed in different climates. The ‘HVAC Template’ used in this study is the ‘Fan Coil Unit (4-Pipe), Air cooled Chiller’ with

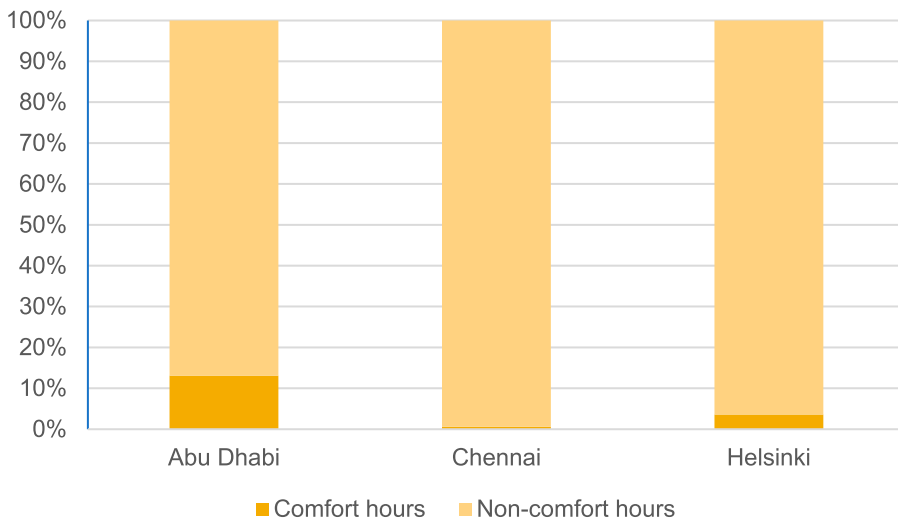


Figure 4. Comfort zone annually (8760 h) by ASHRAE 55 Methodology – Cities. Climate consultant.

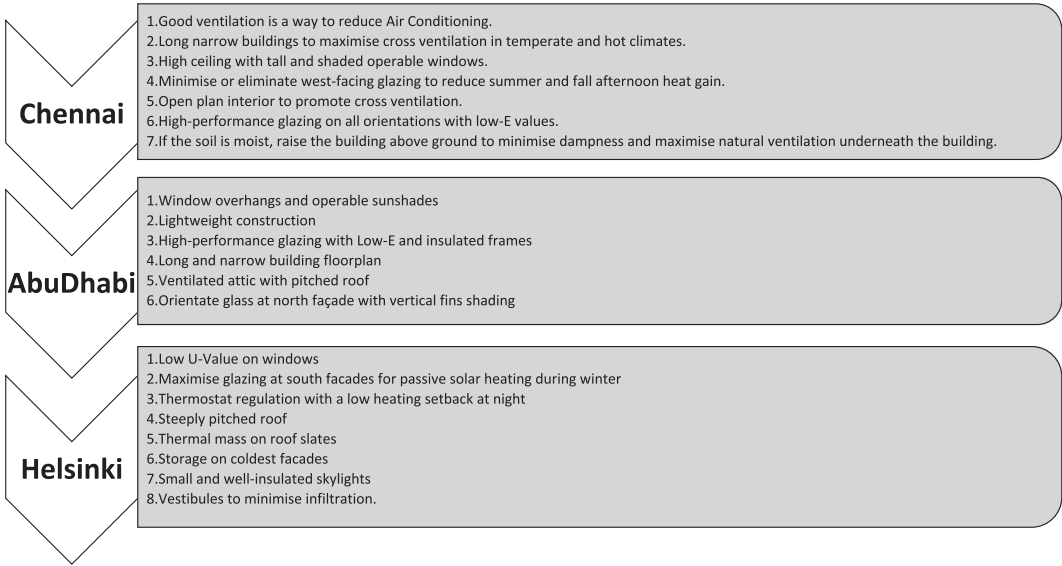


Figure 5. Strategies per city.

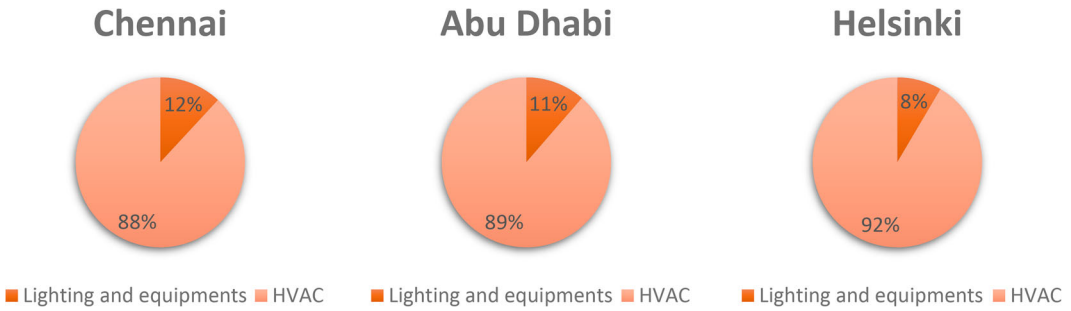


Figure 6. Energy consumption distribution.

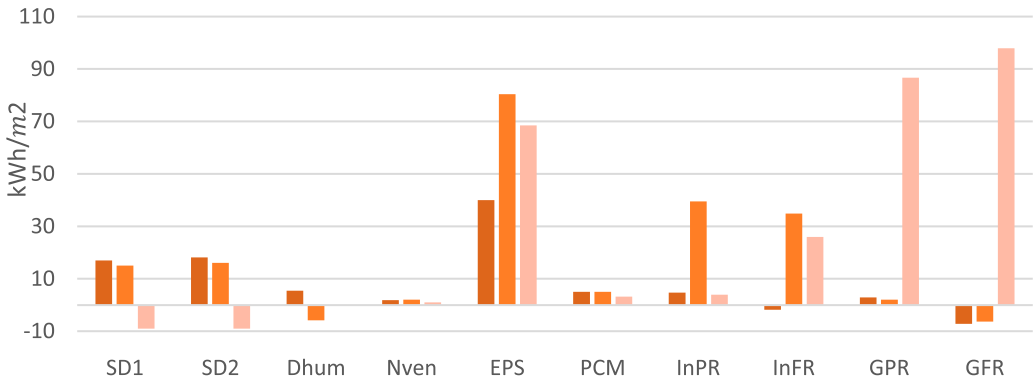


Figure 7. Effectiveness of operable energy decrease per strategies in different climates based on Table 5 (kWh/m²).

Table 6. Energy per total building area improvement from base model (kWh/m²).

City/Climate	Energy per total building area improvement from base model (kWh/m ²)									
	SD1	SD2	Dhum	Nven	EPS	PCM	InPR	InFR	GPR	GFR
Chennai/Tropical	17	18.15	5.44	1.85	40	5	4.68	-1.85	2.86	-7.17
Abu Dhabi/Arid	15.03	16.08	-5.87	2.05	80.39	5	39.5	34.83	2	-6.32
Helsinki/Cold	-9	-9	0	0.96	68.5	3.16	3.93	25.96	86.66	97.89

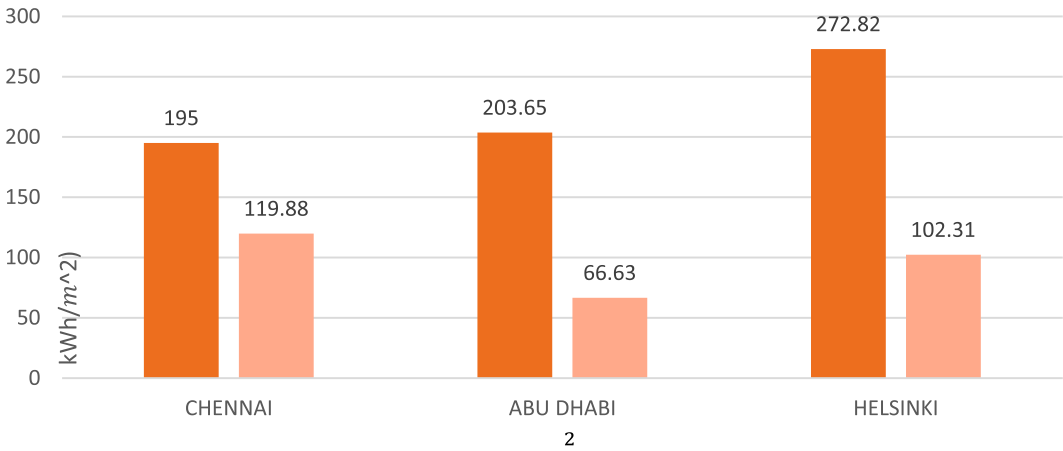


Figure 8. Comparison between the base model (kWh/m²) and most effective design strategies (kWh/m²).

Table 7. Design Strategies' Effectiveness in Chennai.

Chennai's energy per total building area improvement from base model (kWh/m ²)										
DS	SD1	SD2	Dhum	Nven	EPS	PCM	InPR	InFR	GPR	GFR
Impact	17	18.15	5.44	1.85	40	5	4.68	-1.85	2.86	-7.17
Base model =	Best design combination decrease = 119.88 kWh/m²									
	195 kWh/m ²									

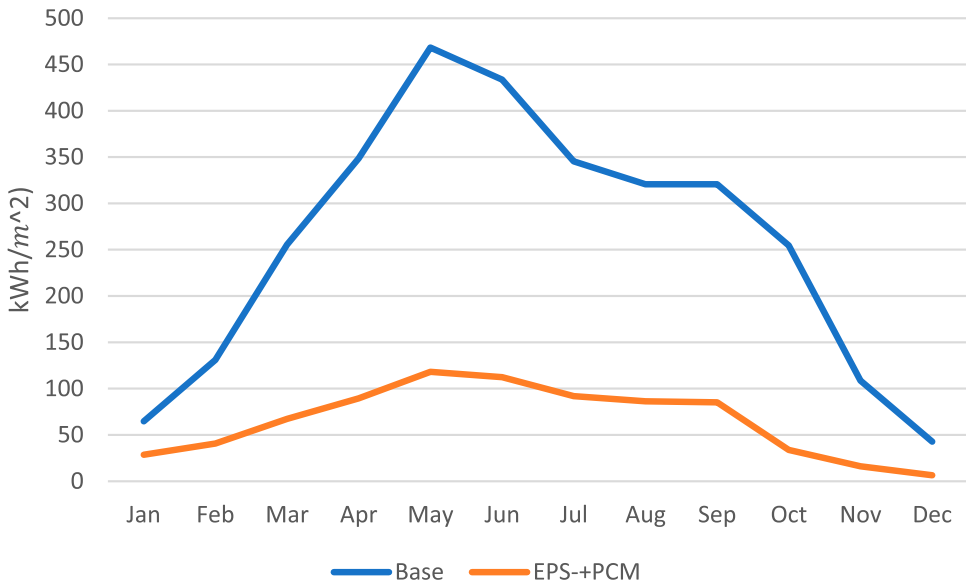


Figure 9. Base model vs EPS + PCM for Chennai.

Table 8. Abu Dhabi's design strategies' effectiveness.

Abu Dhabi's energy per total building area improvement from base model (kWh/m ²)										
DS	SD1	SD2	Dhum	Nven	EPS	PCM	InPR	InFR	GPR	GFR
Impact	15.03	16.08	-5.87	2.05	80.39	5	39.5	34.83	2	-6.32
Base model =	Best design combination decrease = 66.63 kWh/m²									
	203.65 kWh/m ²									

Table 9. Comparison between base fabrics wall and EPS + PCM wall (kWh).

	Comparison between base fabrics wall and EPS + PCM wall (kWh)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Base	-219.8	-122.9	-25.73	227.51	581.9	739.53	892.66	918.48	709.39	396.34	81.66	-176.5
EPS + PCM	-25.56	-7.36	4.63	44.33	95.33	119.73	141.73	145.73	115.43	75.2	32.56	-8.84

Table 10. Helsinki's design strategies.

DS	Helsinki's energy per total building area improvement from base model (kWh/m ²)										
	SD1	SD2	Dhum	Nven	EPS	PCM	InPR	InFR	GPR	GFR	
Impact	-9	-9	0	0.96	70.92	3.16	3.93	25.96	86	97.89	
Base model = 272.82 kWh/m ²	Best design combination decrease = 102.31 kWh/m ²										

Table 11. Helsinki's Comparison between base roof and GFR (kWh).

	Helsinki's Comparison between base roof and GFR (kWh)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Base	-1919	-1741	-1453	-800	-395	-223.2	-179.6	-219.3	-432.7	-894.1	-1570	-1894
SD2	-255	-315	-487	-728	-969	-535	-729	-398	-303	-185	-223	-251

seasonal CoP of 1.8 (for all climates). The HVAC energy consumption represents 88% to 92% overall energy load as shown in Figure 6. The most severe case was Helsinki, where the rate is 92%.

Figure 7 shows the effectiveness of each strategy as outlined in Table 5. Figure 8 shows overall energy savings where a combination of strategies is applied to the base case model and Table 6 shows the energy per total building area improvement from the base model.

The multicriteria in Table 6 established the influence of the strategies. The best performance strategies are combined and compared with the base model energy performance in Figure 7, which shows the effectiveness of the design improvement. Table 7 shows the breakdown of each strategy's effectiveness in Chennai.

Furthermore, this location is the most affected by overheating in the summer months; therefore, the SD2 achieves a desirable internal solar gain from windows to reduce energy consumption by 24%. Even though the daylight at SD2 implementation affects the annual hours of solar gain, there are no significant changes in lighting energy consumption because indirect natural lighting keeps spaces illuminated.

Figure 9 illustrates the effect of PCM in combination with EPS insulation. Therefore, the heat balance (kWh) stabilizes from 16kWh to 118 throughout the year, compared to the base model with the highest peak of 469.3 kWh in May.

Table 8 shows design Strategies' Effectiveness in Abu Dhabi. It shows a similar trend to Chennai's but with more negative impact from DHum and roof options. Like the tropical Climate, the insulation in the envelope shows significant impact. However, as expected overheating through solar gain at exterior windows in the base model created an excess energy consumption as shown in Figure 9.

The best strategy in Abu Dhabi was the wall insulation (EPS) combined with PCM as shown in Table 9. The highest energy savings were in July and August.

Table 10 shows the results for Helsinki. Among the strategies, this was a climate in which insulation, as expected was the most effective strategy. Besides, Helsinki was the only one in the cases that GR has significant impact. Table 11 shows the GR impact on energy loads throughout the year. Compared to the other cities, shadings have negative impact on the case study in Helsinki. This is due to the fact that Lighting level in Helsinki is significantly lower than the other two cities and use of shading devices is not improving comfort conditions, Figure 10 compares the daylight level in the three studies cities.

The annual simulation of the model in different climates achieves specific strategies and combinations ideal for reducing HVAC devices' use. Dehumidification was notably efficient on Chennai's Climate. Humidification had a neutral effect on Abu Dhabi as relative humidity normally fluctuates between 41% and 52%. Helsinki had months that humidity dropped below the recommended 40% from October to mid-March.

The Shading was effective in reducing overheating in Chennai and Abu Dhabi. Chennai has heavy seasonal rainfall with annual precipitation of 1400 mm (World Meteorological Organization 2022). This condition benefits irrigation for GR from June to December. However, the added thermal mass by the GR did not improve the performance in our model.

GR strategies are ideal for carbon sequestration too as it contributes to reducing the 'urban heat island' effect. DB currently does not include the projection of the carbon sequestration effect for GR. Furthermore, specific parameter settings for plant species do not create significant changes when simulated on DB. Wong et al. (2003) highlight Climate's sub-division, coordinates, microclimate and cities' elevation from sea level are crucial for providing ideal conditions for the green roof in tropical weather.

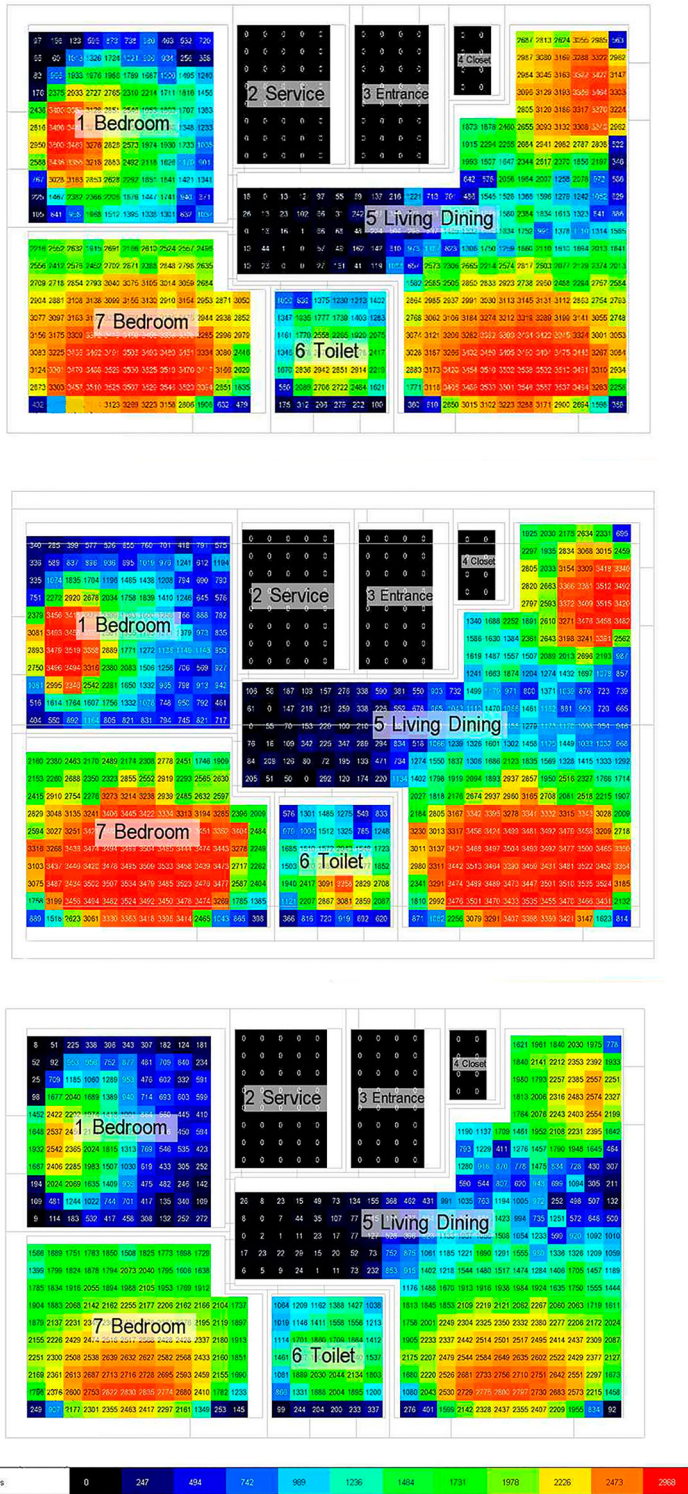


Figure 10. Daylight comparison in three cities, from top to bottom: Chennai, Abu Dhabi and Helsinki.

5. Conclusion

In this research, a framework to evaluate the most used design strategies in extreme climates is created. By comparing each design strategy, the overall best performance was achieved when insulation was applied to the case study. The green roof was most effective for extremely cold climates and shading efficiency is evident in arid and tropical climates, however, a comprehensive research about how the air flows in different scenarios is required to further find optimum solutions for this strategy and its impact on ventilation. As proven by simulation, the low U-Values and phase change materials are essential to achieve the best performance in all scenarios. Other key qualitative findings of this research are:

- There is no one size fit all for extreme climates, the most effective method is multicriteria strategies, due to the complexity of the building's adaptability to local weather.
- Simulation-based evaluation offers guidance for new or retrofitted projects in the extreme climates, but further research on real-scale monitoring is key for expanding the comprehension and accuracy of the model's simulation.
- Roof shape (flat or pitched) is a key factor for heat gain throughout the year. Flat roofs are ideal in cold climates, but pitched roof showed better performance in warmer climates.

Further research on dehumidification and humidification devices or materials (as hygroscopic) is also required to better understand the effectiveness of specific climates and building occupancy.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Notes on contributors

Argenis Toyo Diaz is an Architectural Innovator, Technologist, and Designer with six years of experience in diverse-scale projects. He is a recent graduate of Architectural Technology and Building Performance from Edinburgh Napier University and has a research focus on net-zero carbon buildings.

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