



Residential Comfort and Energy Efficiency in a Csb Mediterranean Climate: An Adaptive Comfort Study

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Abstract

Indoor thermal comfort safeguards occupant health and wellbeing and is a driver of energy consumption in buildings and greenhouse gas emissions. This paper assesses the indoor thermal conditions in a naturally ventilated middle-class residence in the Mediterranean climate of Cape Town.

Data logged in two separate rooms was imputed into Ladybug, a building environmental design software, to execute a full-year adaptive comfort simulation for each room.

It was found that indoor thermal comfort can be maintained by passive, psychological and behavioural adaptive measures only without the need for artificial space conditioning.

The upper indoor adaptive comfort limit for Cape Town was found to be 29°C. Indoor temperatures rarely exceeded this upper limit. Therefore, overheating is not a problem in the naturally ventilated residence.

The lower adaptive comfort limit for Cape Town was found to be 19°C. In both rooms, a significant number of hours had temperatures below this threshold. The northwest-facing room was found to be excessively cold for 45% of the year. The southeast-facing room was found to be excessively cold for 75% of the year.

At 55 percent, the hours of the year for which the logged indoor operative temperatures are within the bounds of comfort in the northwest-orientated room were found to be more than double those in southeast-orientated at 25 percent. Orientation has a significant impact on thermal comfort.

In a sensitivity analysis, the above results proved to be robust for other cities in Csb Mediterranean regions in the southern and northern hemispheres.

The above results signify that in Cape Town and similar Mediterranean climates, policies should drive practice to use orientation, indoor heat preservation and passive heating to improve comfort, safeguard health and save energy for both new and existing housing stock.

Further research in Cape Town and other Csb climates is needed using larger sample sizes to generate more evidence, increase generalisability, and advance Energy Modelling for Policy Support (EMoPS).

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Keywords

Residential Thermal Comfort; Natural Ventilation; Adaptive Comfort; Environmental Simulation; Passive Design

1. Introduction

1.1. Contextual Background

This paper studies the thermal conditions of indoor spaces in a naturally ventilated middle-class residence in a Mediterranean climate and proposes suitable energy-efficient measures for improving comfort. Attainment of indoor

thermal comfort is a key performance parameter of good housing. This includes protection from both excessive heat and excessive cold. ASHRAE (the American Society for Heating Refrigeration and Airconditioning Engineers) defines thermal comfort as “that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation” (ASHRAE, 2004: 4). Although thermal comfort is a subjective notion, it has significant implications for occupant health and wellbeing. The World Health Organization (WHO) guidelines for health and housing highlight excessive heat and excessive cold as predisposing factors for poor health outcomes (WHO, 2018). The WHO guidelines target both existing housing stock and new housing (WHO, 2018). Excessive indoor cold increases the risk of respiratory and cardiovascular conditions and hypothermia, particularly in temperatures below 18°C (Jevons et al., 2016; Ryti et al., 2016). Excessive indoor heat impacts mortality and morbidity (WHO, 2018). This risk is exacerbated in summer and during heat waves, especially for the elderly and other vulnerable individuals (Ormandy and Ezratty, 2016; Ormandy and Ezratty, 2012).

On the other hand, thermal comfort is a key driver of energy consumption and greenhouse gas emissions (Kaptan, 2019). Buildings consume more than 30 percent of global energy, 90 percent of which is for space heating and cooling. Buildings are also responsible for 40 percent of carbon dioxide emissions (International Energy Agency [IEA], 2020). Buildings provide a significant opportunity to save energy through low-energy design for new buildings and refurbishment to improve the performance of existing housing stock (Global Alliance for Buildings and Construction, the International Energy Agency, and the United Nations, 2019). Hence, buildings are pivotal to attaining the Paris Agreement target of keeping global temperatures to 1.5°C below pre-industrial levels.

The range for indoor thermal comfort is generally taken to be between 20°C and 25°C (Lechner, 2014). However, with an adaptive approach, 90% of people will find indoor conditions ranging from 18.4°C to 32.9°C acceptable (see the theoretical background below). Changing the indoor thermostat temperature settings can yield huge energy savings (Zhou et al. 2018 and Stefanović 2016). For instance, lowering the thermostat setpoint by 1°C can result in 10% heating energy savings (Holt et al., 2009).

An empirical study was undertaken in Cape Town, a city in a temperate climate. Regions with temperate climates, according to Cohen and Small (1998), have most of the world's population. Such regions arguably offer great potential for saving building operational energy and mitigating climate change. Specifically, Cape Town has a Mediterranean climate. The Mediterranean climate occurs between latitudes 30° North and 45° South on the western coasts of Africa, Australia, Europe, South America and North America (World Weather Information Service, 2010). The mild Mediterranean climate type offers great potential to save energy for space heating and cooling (Sánchez-García et al. 2018). But it is concerning that even in these temperate conditions, energy-wasteful approaches to thermal comfort are widespread. For example, in the mild Mediterranean region of Andalusia in Spain, 57.4% to 84% of existing homes have air-conditioning (Sánchez-García et al., 2018), a situation which must be avoided by Middle-income countries as they build new houses.

On the Koppen Geiger classification system, Mediterranean climates can be designated as either Csa or Csb. These climates have hot-dry summers. The letter “C” means that this is a Temperate climate type with an average temperature above 0°C but below 18°C in the coolest months. The letter “s” represents dry summers with less than 30mm of precipitation per summer month (summer being April to September in the case of the Northern Hemisphere and October to March in the case of the Southern Hemisphere). The third letter, “b”, indicates the average temperature in the warmest month is below 22°C. Cape Town has a Csb climate (Beck, 2018; Conradie, 2012), which is the cooler Mediterranean climate type.

Examples of other cities in the world with Csb climate type include: Concepción (Chile), Pasto (Colombia), San Carlos de Bariloche (Argentina), Nakuru (Kenya), San Cristóbal de la Laguna (Spain), Salamanca (Spain), Porto (Portugal), Guarda (Portugal), Rieti (Italy), Ohrid (North Macedonia), Bilecik (Turkey), Kütahya, (Turkey), San Francisco (United States), Santa Barbara ((United States), Seattle, (United States), Victoria, (Canada), Albany (Australia), Devonport (Australia) and Mount Gambier (Australia) (Kudacity, 2019).

Globally, the total building area is growing by 2.5% (IEA) per annum and building stock is set to double by 2050 (IEA, 2020). Like Cape Town, many of the cities with Csb climates are located in Upper Middle-Income Countries

(such as Colombia, North Macedonia and Turkey). These are emerging economies with a high demand for new building stock, which presents an immense opportunity for climate-smart housing design (IEA, 2020).

1.2. Research Problem and Knowledge Gap

In Cape Town, the highest mean monthly temperature is 20.9°C in January/February, and the lowest mean monthly temperature is 14.1°C in July/August (see 3.2 below). Surprisingly, in this mild Cape Town climate, buildings consume 78 percent of mostly coal-generated electricity and contribute 50 percent to carbon emissions (City of Cape Town, 2015). This is higher than the global average. In one study, 47 percent of Cape Town residents indicated that they use an electric heater for keeping warm in cold weather (Sustainable Energy Africa, 2015). Space heating accounts for 9 percent of residential energy consumption (City of Cape Town, 2015). Over 80 percent of mid-income respondents identified electric heaters as the most frequently used heat source (Sustainable Energy Africa, 2015). Air conditioning accounts for 6 percent of residential electricity use and 36 percent of commercial electricity use (City of Cape Town, 2015). The high levels of space heating and air-conditioning are indicative of poor indoor thermal conditions. Indigent households are subject to worse indoor conditions because they live in substandard formal and informal housing (Naicker et al., 2017).

In 2011, the South African Bureau of Standards (SABS) enacted new national building regulations for energy efficiency in buildings. The regulations, SANS 10400-XA:2011 (South African National Standard 10400 Part XA), made it obligatory to use low energy methods for thermal comfort for all new buildings in South Africa (SABS, 2011). The deemed-to-satisfy design methods of the regulations specify envelope and passive design measures for attaining indoor comfort for various climatic regions in the country. However, literature review does not reveal any systematic climatic-data-based studies of thermal conditions in South African middle-class buildings constructed prior to enactment of the regulations. Klunne (2003) aimed to identify baseline thermal comfort conditions in low-cost housing, but the research based its findings on qualitative interview data only. Ebhojie (2019) also used interviews to study the energy efficiency of low-cost housing. Some thermal comfort studies have been undertaken using measured temperatures in low-cost housing in Johannesburg and its surrounds (Mabuya and Scholes, 2020; Naicker et al., 2017). What is common about all these studies is that they focus on low-cost housing and are in South African locations with climates other than the Csb Mediterranean type. This leaves a gap in studying pre-regulation indoor thermal conditions of relatively better constructed middle-class buildings in South Africa, in Cape Town specifically and other Csb climate locations more generally.

Internationally, many adaptive comfort studies have been done for naturally ventilated buildings in climates different from the cool Csb Mediterranean type. For example, Pathirana et al. (2019) studied adaptive comfort for naturally ventilated buildings in the tropics, while Soflaei et al (2020) used an adaptive approach to investigate optimal layouts for courtyards in subtropical desert climate settings. Some adaptive comfort studies have also been undertaken in Csb climates. In the Mediterranean climate city of Seville, Sánchez-García et al. (2018) observed that building energy efficiency regulations do not yet address existing housing stock and argued that this is a missed opportunity to save energy and reduce carbon emissions in mild climates. Rubio-Bellido et al. (2017) undertook adaptive comfort studies in a Csb climate using empirically measured temperatures, but this was for only 10% of the year. Pérez-Fargallo et al. (2018) measured outdoor and indoor temperatures over 9 months in their adaptive study on low-income housing in Chile. But they came up with the surprising recommendation that, to save energy, lowest temperature setpoints should be legislated downwards to 13°C because, in their findings, poorer people could tolerate significantly low temperatures. This proposed setpoint is a whole 5°C below the WHO-recommended lower limit for healthy housing, and yet the authors do not explain why they ignore the WHO recommendation. In their study, Sánchez-García et al. (2018) and Sánchez-García et al. (2019) measured temperatures in a northwest-facing and a southwest-facing room in the Mediterranean climate of Seville in Spain. However, their study was limited to 21 days in winter, 30 days in summer and 31 days in spring (a total 81 days) instead of the full year. Furthermore, their objective was to validate a model for long-term future carbon-emission scenario forecasting in the context of climate change.

To the author's knowledge, the current paper reports results of the first systematic adaptive comfort study of indoor thermal comfort of naturally ventilated spaces in a middle-class residence in a Csb Mediterranean climate using

empirically measured temperatures over an entire year at one-hour time steps. Hence, this study makes an important contribution to a growing body of evidence for energy-efficient housing in mild Csb Mediterranean climates.

The study focuses on middle-class housing stock in Cape Town constructed before 2011. An adaptive comfort approach (see 1.1 below) is used to address the research question: For a selected middle-class house in Cape Town, constructed prior to the enactment of the national regulations for energy efficiency and operating without artificial space heating and cooling, what do actual measured temperatures reveal about indoor thermal conditions? Answering this question provides insights into the thermal conditions of a representative building type in Cape Town. The results are important for several reasons. First, by understanding thermal conditions, inferences can be made about potential implications for comfort and health in such housing. Second, they will provide a basis for decisions around suitable energy-efficient and passive solutions for thermal comfort in Cape Town and in similar Csb climates internationally. Finally, they will provide a baseline against which the efficacy of the national building regulations may be gauged in future thermal comfort studies. The results, therefore, contribute to an evidence basis for academia, policy and practice around existing housing stock in Cape Town and other cities in the world with Csb Mediterranean climate.

2. Theoretical Background and Methods

2.1. Theoretical Background: Adaptive Comfort

The following definitions are important in discussing the adaptive comfort approach:

- MET: is a measure of the energy emitted by a person corresponding to the person's activity level. A seated person emits 1 MET while a person standing doing light activity emits about 1.3 MET (see ASHRAE, 2004).
- CLO: According to ASHRAE (2004), CLO is the insulation provided by clothing. There is a range of CLO values depending on what a person is wearing. A person wearing long pants and an open-neck shirt attains an equivalent of 0.5 CLO. A typical business suit is equivalent to 1 CLO (see Haggard et al., 2016). According to Humphreys (1994b) and Sykes et al. (1994), as much as one-half of the seasonal changes in acceptable indoor comfort temperature are attributable to clothing flexibility (a behavioural factor)
- Effective temperature (ET): ET is defined as either the mean monthly temperature or mean daily outdoor temperature (de Dear and Brager, 1998 pp 12 – 13)
- Operative temperature: is an index that combines the effects of indoor dry bulb temperature and radiative gains. It can be calculated as the average of the dry-bulb and mean radiant temperatures (Schiavon et al., 2014).
- Neutral temperature: for a given ET, the neutral temperature is “the indoor thermal index value corresponding with a mean vote of neutral on the thermal sensation scale by a sample of building occupants”. In naturally ventilated buildings, this temperature corresponds with the optimum operative temperature, which satisfies the greatest possible number of people at a given clothing and activity level (de Dear and Brager, 1998 pp 12 – 13).

Thermal comfort, as originally defined by ASHRAE, was based on the Predicted Mean Vote / Predicted Percentage of Dissatisfied (PMV/PPD) for artificially conditioned buildings only (Schiavon et al., 2014). Developed by Fanger et al. (1972), the PMV model became the basis for ASHRAE comfort standard 55-92. The adaptive comfort hypothesis arises from dissatisfaction with the static PMV model in accounting for thermal comfort in naturally ventilated buildings. Humphreys (1975) argued that building occupants were comfortable in indoor thermal conditions covering a range of up to 13K. He attributed this to adaptive factors. These findings were corroborated by Humphreys (1978) and Auliciems (1981), especially for naturally ventilated buildings. The studies also revealed a strong correlation between indoor thermal neutralities in naturally ventilated buildings and outdoor climate. In a meta-analysis of field studies, Brager and de Dear (1998) surmised that adaptive factors were behind the observed differences in thermal comfort between air-conditioned and naturally ventilated buildings. Arguing that the PMV approach is not suitable for naturally ventilated buildings, de Dear and Brager (1998) developed the Adaptive Comfort model for naturally ventilated buildings for when outdoor temperatures are between 10°C and 33.5°C. They found that, as outdoor temperatures fluctuated, occupants of naturally ventilated buildings stayed comfortable within a wider range of indoor thermal conditions. They discovered that neutral thermal conditions in buildings that utilise heating,

ventilation and air conditioning (HVAC) technologies are confined to between 21°C and 25°C compared to between 20°C and 27°C in naturally ventilated buildings. Behavioural adjustments (removing/adding clothing, opening/closing windows, switching on a fan, and cultural ones such as a siesta), physiological adjustments (both within an individual’s lifetime and intergenerationally), and psychological adjustments (real/perceived control over indoor thermal conditions, habituation, and future expectations) enable people in naturally ventilated buildings to adjust to a wide range of indoor thermal conditions. They highlighted behavioural and psychological factors as the most significant for adaptive comfort. The more building occupants perceive the availability of options to personally adjust the indoor environment in response to changes in ambient outdoor conditions, the greater the band of adaptive comfort.

Adaptive comfort is dynamically responsive to outdoor temperature variations. It is a function of the effective temperature (ET) (see definition below). For instance, in summer, people will be comfortable in indoor conditions they would consider too warm in winter. And inhabitants of cold climates would accept indoor temperatures that people in warm climates may find too cold.

In ASHRAE Standard 55 (ASHRAE, 2004), the Adaptive Comfort model was incorporated as valid for naturally conditioned buildings under the following conditions:

- No mechanical cooling and heating systems
- Outdoor temperatures are between 10°C and 33.5°C.
- Building occupants engaged in sedentary activities (MET between 1.0 and 1.3)
- Occupants have the freedom to adapt their clothing within the range 0.5 to 1.0 CLO

For any outdoor condition, it should be noted that there is a range of acceptable temperatures below and above the neutral temperatures within which people can adapt to stay thermally comfortable. Adaptive comfort-neutral temperatures and operative temperature ranges for any given location can be presented on the chart with ET as the abscissa and operative temperature as the ordinate (see Schiavon et al., 2014). Adaptive comfort is defined for 90% and 80% acceptability. In Table 1 below, the upper and lower limits for the adaptive comfort standard are identified using a web-based adaptive comfort visualisation tool developed by Tartarini (2020).

Table 1: Parameters for Adaptive Comfort

Outdoor effective temperature (ET) limits for adaptive standard		Indoor optimum/ neutral temperature limits	Operative Temperature Ranges			
			80% acceptability limits		90% acceptability limits	
Highest	35.5	27	24.7	33.9 °C	25.7	32.9 °C
Lowest	10	20	17.4	26.6 °C	18.4	25.6 °C

* This table is generated from the web-based thermal comfort visualisation tool CBE (see Tartarini, 2020).

Table 1 above shows the range of outdoor effective temperatures (ET) for which the adaptive comfort approach to thermal comfort is valid. The table also shows the minimum and maximum possible neutral temperatures in the adaptive standard. Furthermore, the table shows the limits of adaptive comfort for 80% and 90% acceptability that correspond to the respective lower and upper ET limits.

Givoni (1992) proposed passive design methods for naturally ventilated buildings. Many of these methods, such as comfort ventilation, night purge (opening and closing windows) and adjustable solar shading, extend the behavioural and psychological capacity for occupants to adapt to a range of indoor thermal conditions.

By far, the most important scholars on adaptive comfort are de Dear and Brager. Having originally introduced the model in 1998, they set the theoretical premises of adaptive comfort and have authored prolifically on adaptive comfort and indoor climate. Starting by limiting adaptive comfort to natural ventilation, they have lately also extended the approach to air-conditioned spaces (de Dear and Brager 1998; Brager and de Dear 2001; de Dear 2011; de Dear and Brager 2001; de Dear and Brager 2020).

Compared to steady state approaches to thermal comfort, adaptive comfort as originally conceived by de Dear and Brager (1998), extends the range of acceptable thermal conditions by increasing the maximum temperature and reducing the minimum temperature for human indoor comfort (see Table 1). Significantly, recent localised empirical studies suggest that the adaptive comfort range can extend the thermal comfort range more than originally proposed. For instance, in Lima, income housing residents experienced low temperatures of 13°C as comfortable (Oraopoulos, 2023). While residents in India were found to still be comfortable at a temperature of 35°C (Rawal et al., 2022). The key conclusion is that focused adaptive comfort studies can potentially result in increases in localised comfort ranges, energy and cost savings and climate change mitigation.

Only introduced in 1998, adaptive comfort as a topic has become so widely published that papers solely focusing on literature reviews of publications on the topic have now come to the fore (Yao et al. 2022; de Dear 2013 and Karyono 2020).

2.2. Method

A thermal comfort study was undertaken in a two-storey free-standing middle-class residence in Muizenberg, a Cape Town coastal location. Zizzamia et al. (2019) define a middle-class household in South Africa as having a mean monthly per capita expenditure of 4536.20 ZAR (about 298 USD). Only about 20 percent of South Africans are stable in the middle-class while 60 percent are in transient or chronic poverty (ibid). The per capita household expenditure in the particular house is more than 50 percent higher than the above per capita expenditure. The middle-class residence used in this study is therefore taken to be a representative of mainstream acceptable construction practice in Cape Town. Hence, the residence is considered better in terms of construction and thermal quality than the formal and informal housing for the urban poor (see Naicker et al., 2017). However, because the middle-class residence was constructed in 2006 and therefore predates the SANS10400XA regulations, no specific passive design measures were applied. There are also no active heating and cooling interventions in the building. The building thus provides a suitable setting to study indoor thermal conditions in a house representative of pre-regulation mainstream residential construction practice in Cape Town.

Within the house, two adjacent bedrooms on the upper floor were chosen (see Table 2 below). The two bedrooms are similar, and each has two external walls. They share the length of a southwest-oriented external wall. But the wall containing the window is oriented differently for each room. In the one room, this wall is oriented northwest (Room A), while in the other, it is oriented southeast (Room B). The main characteristics of the chosen bedrooms are described in Table 2 below.

Table 2: Room A and Room B Descriptors (Source: Author)

		Room A	Room B	
Orientation	<i>External wall 1</i>	Northwest	Southeast	
	<i>External wall 2</i>	South west	South west	
Use		Bedroom	Bedroom	
Measurements (m)	<i>length</i>	3	3	
	<i>Width</i>	3	3	
	<i>Height</i>	2.5	2.5	
Envelope Materials Insulated	<i>External walls</i>	Double cavity concrete blocks plastered in and out	Double cavity concrete blocks plastered in and out	
	<i>Internal walls</i>	Single cavity	Concrete block single cavity	
	<i>roof</i>	Cement tiles on wooden structure		
	<i>Ceiling</i>	Flat “chipboard”		
	<i>floor</i>	Concrete structural + PVC planks		
	<i>Extra insulation</i>	None	None	
Window	<i>Orientation</i>	North west	South east	
	<i>Frames</i>	PVC	PVC	
	<i>Glazing</i>	Single pane clear	Single pane clear	
	<i>Openable</i>	50%	50%	
	<i>Area</i>	3.24m ²	3.24m ²	
	<i>Roof overhang</i>	<i>Length</i>	0.5m	0.5m
		<i>Height above window</i>	0.25m	0.25m
	<i>Extra sun shading</i>	Adjustable internal blinds	Adjustable internal blinds	
	<i>Ratio window area to net floor area</i>	36%	36%	
	<i>Height from floor</i>	0.8m	0.8m	
	<i>Orientation</i>	North west	South west	
<i>Vent</i>	None	None		

* The main difference between the two rooms is the orientation of the windowed wall

2.2.1. Measuring indoor thermal conditions

In each room, a wireless SSN-22 USB Temperature & Humidity Data logger (see Smith, 2020) was used to measure and record the indoor thermal conditions. The instrument takes fractionated measurements of indoor air temperature, relative humidity, and dew point. It comes with a USB interface to connect with a computer and software for specifying the measurement start time and end time as well as the logging interval.

In this study, the loggers were set to log at half-hourly intervals starting July 2019 to record a full year's readings for temperature, relative humidity, and dew point. Once set up, one instrument was placed in each room on an internal wall at a height of 1.8m above floor level away from direct sunlight as recommended by the manufacturer. After the logging period, each instrument was connected to a computer to download the data. The logger's software generated data and graphs with the option to export data to Microsoft-Excel (Ms-Excel) file format. The two data sets were exported to MS Excel file format. To bring synchrony between the logged data and the EnergyPlus weather files used in Adaptive comfort simulation (see 2.2 below), each Ms-Excel dataset was reorganised in three ways (i) each alternate reading of half-hourly data was deleted to give only hourly data readings by numbering each data row alternately with 1 or 0 using the $=(\text{MOD})$ function in Ms-Excel, then sorting and deleting odd number rows] (ii) Data start time was reorganised to start at midnight on the first of January (1,1,1) [i.e. the first hour of the first day of the first month of the year] and to end in December (12,31,24) [the last hour of the last day of month of the year] (iii) Because 2020 was a leap year, the data for the 24 readings for 29th February were removed to leave 365 days and 8760 hours. The data is available as supplementary data (*Room_A_Data*.xlsx* and *Room_B*.xlsx*) (see Sanya, 2024a)

2.2.2. Adaptive Comfort Simulation Using Ladybug Software

This study used Ladybug (LB). LB is an open-source plugin for Grasshopper for building energy and thermal comfort simulation (Roudsari, 2020). Grasshopper is a visual programming interface for Python coding that is integrated with the CAD (Computer Aided Design) programme Rhino3d (Mode Lab, 2015). Numerical results from LB coding are visualised on the Rhino3D interface in different formats, such as charts. The LB default analysis period is one full year split into 8760 hourly periods (24 hours for 365 days). The default start hour is midnight on the 1st of January, while the default last hour is 11 pm on the 31st of December.

The LB interface offers numerous components (tools) for energy-conscious building design. Each component requires inputs and produces outputs. Some outputs may be used for subsequent input to other components. LB works with real climatic data in the form of EnergyPlus weather (EPW) files. The climate data is available on a website (see Lawrie and Crawley, 2019). Using the LB *EPW+STAT* component, climate data for Cape Town International Airport was directly imported from the website. The LB import EPW component was used to read the climate data.

Of the sixteen outputs from the *importEPW* component, the adaptive comfort study requires only the outdoor *dryBulb* temperature (see *outdoorTemperature* in Table 3 above).

Indoor thermal studies for the entire year were undertaken using two LB components: *AdaptiveChart* (an adaptive comfort chart simulator) and *AdaptiveComfortCalculator* (an adaptive comfort calculator). Anchored in research by Tartarini et al. (2020), these two LB adaptive comfort components are inherently coded to fulfil ASHRAE Standard 55-2010 and 2013. Each LB adaptive comfort component may take up to 16 inputs, of which only seven are strictly necessary to undertake the simulations. The seven inputs for the adaptive study in this paper are: dry bulb temperature, mean radiant temperature, outdoor temperature, comfort parameters, wind speed, analysis period and a Boolean toggle to run the simulation. Some of these inputs must be imputed by the user (required), and in the other cases, LB uses default values unless the user opts to use different ones. In reference to Roudsari (2020), these inputs are described in Table 3 below. The last column of the table describes the sources for the required inputs for this study as well as, where applicable, the LB default values used.

Table 3: Description of Simulation Input Parameters (adapted from Roudsari, 2020)

Input Parameter	Description	User Input	Source for this simulation
<i>dryBulbTemperature</i>	A list of numbers representing the dry bulb temperature of air (°C)	Required	Hourly room temperature readings as measured with a data logger for Rooms A and B, respectively. For each room, a *.txt file with the data was imported from a local computer drive to LB using the LB <i>Read File</i> component.
<i>meanRadiantTemperature</i>	A list of numbers representing mean radiant temperature of surrounding surfaces (°C)	Optional	Default (the mean radiant temperature is assumed to equal the dry bulb temperature).
<i>outdoorTemperature</i>	A list of numbers representing prevailing outdoor temperature (°C)	Required	Ladybug EPW file for Cape Town from Lawrie and Crawley (2019) (see 2.2 above)
<i>ComfortPar</i>	Various parameters, including the percentage of people satisfied	Optional	Used the default of 90% of occupants satisfied
<i>windSpeed</i>	A number representing indoor wind speed (m/s)	Optional	The Ladybug default of 0.2m/s is substituted with 1m/s (see note*)
<i>analysisPeriod</i>	Period of time over which the simulation is run	Optional	Default Ladybug period of one full year (8760 hours) used. Start: midnight 1 st January (1,1,1) End: 11 pm 31 st December (12,31,24).
<i>Runit</i>	Boolean toggle (false/true)	Required	Set to true to run the simulation and generate an adaptive comfort chart and other results

Important to note here is that indoor wind speed for this study was, compared to the LB default of 0.2m/s, set at a relatively high value of 1m/s. 0.2m/s is also the comfortable indoor speed recommended by ASHRAE. The reason for choosing a relatively high wind speed for this study is because Cape Town in general, and the coastal location of the empirical residence specifically, experiences very windy conditions at an average of 5m/s (18Km/hr) in the NW and SE prevailing directions. The coastal location also experiences frequent wind gusts of 8m/s (30km/h) and more. The building where this study was undertaken is oriented perpendicular to prevailing wind directions and experiences high levels of air leakage throughout the year.

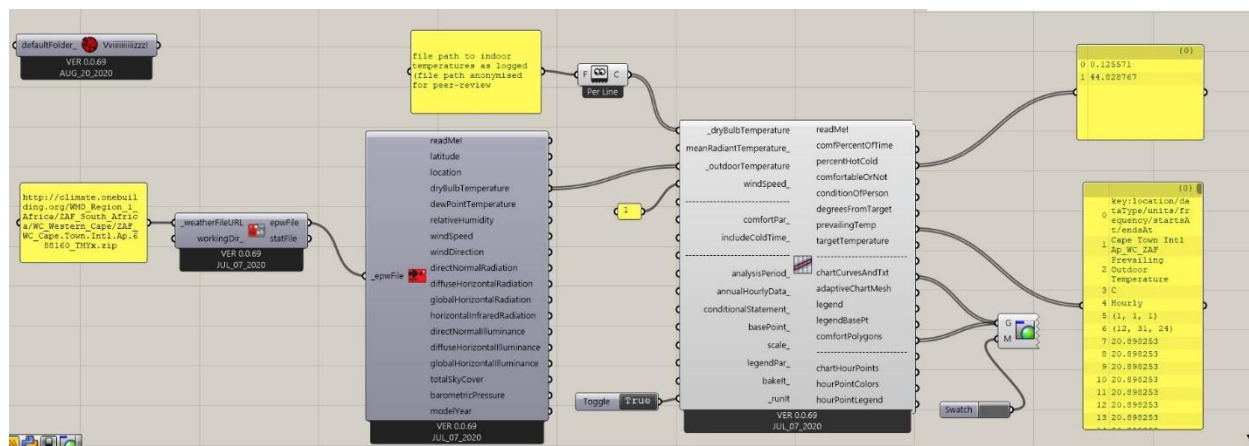


Figure 1: Adaptive Comfort Simulation Setup (for each of the rooms A and B, one such simulation was set up) [see Sanya, 2024b]

Using the inputs described in Table 3 above, the full-year LB adaptive comfort simulations were set up (see Figure 1 above). For each room, an *AdaptiveChart* and *AdaptiveCalculator* were executed. The full simulation setup steps are shown in Figure 1 above. The scripts for all of the above simulations are available (see Sanya, 2024b)

2.2.3. Validity and Replicability

Current scholarly publications evidence the widespread use of adaptive comfort as a valid method for indoor thermal comfort studies. The adaptive comfort approach has been used for indoor thermal studies of different building typologies in varied contexts: homes in Australia (Jeong 2024); office buildings in San Luis Potosí (Mexico) (Caro, 2024); vernacular dwellings in Portugal (Costa-Carrapiço et al 2022); old people care homes (Yoon Yi et al, 2022); low cost housing in Mumbai India (Malik 2023); low cost housing office buildings in Lima Peru (Oraopoulos, 2023); classrooms in Australia (de Dear et al 2015); and rural dwellings in China (Tang, 2024). Adaptive comfort is considered a suitable approach for understanding the thermal conditions of varied building types in different locations.

Cape Town's effective outdoor temperature (ET) ranges from 20.9°C to 12.4°C (see 3.2 below). This is well within the Adaptive Comfort method range of applicability (10°C to 33.5°C) highlighted in the theoretical background above.

The outcomes of this paper are replicable because the LB simulation scripts are accessible on an open-source repository (Sanya, 2024b). The raw data files used in the simulations are also (Sanya, 2024a) on the open-source repository. Therefore, anyone with the software and requisite skills can rerun the simulation to replicate the results. Alternatively, the raw data can be imputed into a different simulation programme to replicate the results.

3. Results

Table 4 below defines and describes the main outcomes of the full-year adaptive comfort simulations and summarises the main results from this study. The results are presented and discussed further in five parts: (i) hourly logged data, (ii) hourly temperatures, (iii) adaptive comfort charts, (iv) percentage thermal conditions, and (v) thermal conditions visualisation.

Table 4: Outcomes of Adaptive Comfort Study

Output Parameter	Description	Study outcomes	
		Room A	Room B
<i>comfPercentOfTime</i>	Percentage of time for which the occupants are comfortable	55%	25%
<i>percentHotCold</i>	The percent of time for which the occupants are too hot	0.1%	0%
	The percent of time for which the occupants are too cold	44.9%	75%
<i>conditionOfPerson</i>	Hourly indoor thermal conditions for occupants: -1 = The input conditions are too cold 0 = The input conditions are comfortable +1 = The input conditions are too hot	Imputed into the LB <i>3DChart</i> and <i>Preview</i> components to generate full-year hourly thermal condition visualisations in Rhino-3D (See Figure 3a)	Imputed into the LB <i>3DChart</i> and <i>Preview</i> components to generate full-year hourly thermal condition visualisations in Rhino-3D (See Figure 3b)
<i>prevailingTemp</i>	A stream of temperature values in degrees Celsius indicating the prevailing outdoor temperature. This is the same as ET (see definition in 1.1 above).	The full set of results is captured in a combined spreadsheet in the <i>Room_A+B_Results*.xlsx</i> file. The results are sortable by each column. Highest ET: 20.9°C Lowest ET: 12.4 °C	
<i>targetTemperature</i>	A stream of temperature values in degrees Celsius indicating the mean target temperature (neutral temperature) (°C). Varies as outdoor temperatures change (see definition in 1.1 above).	The full set of results is captured in a combined spreadsheet in the <i>Room_A+B_Results*.xlsx</i> file. The results are sortable by each column. Highest target temperature: 24.3 °C Lowest target temperature: 21.6 °C	
<i>chartCurvesAndTxt</i>	Curves and text labels of the adaptive chart.	Imputed into LB <i>Preview</i> to generate an adaptive chart visualization in Rhino3D (see Figure 2a)	Imputed into LB <i>Preview</i> to generate an adaptive chart visualization in Rhino3D (see Figure 2b)
<i>adaptiveChartMesh</i>	Colors representing the number of hours on the adaptive chart		
<i>legend</i>	A legend showing the number of hours that correspond to each color.		
<i>comfortPolygons</i>	Lines representing the range lower and upper boundaries.		
<i>upperTemperatureBound</i>	Temperature values in degrees Celcius indicating the highest possible temperature in the comfort range for each hour.	Results for upper temperature boundaries for each hour of the year captured in formatted a spreadsheet <i>Room_A+B_Results*.xlsx</i> file. The results are sortable by each column. LB gives the maximum upper temperature boundary as 29.0°C	
<i>lowerTemperatureBound</i>	Temperature values in degrees Celcius indicating the lowest possible temperature in the comfort range for each hour	Results for lower temperature boundaries for each hour of the year captured in formatted a spreadsheet <i>Room_A+B_Results*.xlsx</i> file. The results are sortable by each column. LB gives the minimum lower temperature boundary as 19.1°C	

3.1. Hourly Logged Data

Empirical full-year hourly data logger readings for indoor dry bulb temperature, relative humidity and dew point are captured as supplementary data for each room in the files (*Room_A_Data*.xlsx* and *Room_B_data*.xlsx*) [see (see Sanya, 2024a)]. The data is a valuable research outcome as, to the author's knowledge, it is the only set of publicly available full-year indoor thermal data loggings for residential (envelope-dominated rooms) in Cape Town and probably in any Csb climate type. The data may be used by any researcher in future studies. From this data, the hourly indoor dry bulb temperature loggings for each room are extracted for the adaptive comfort study and discussed further in the results below.

3.2. Cape Town is Within the Range of Adaptive Comfort

From the LB adaptive comfort simulations, as prevailing outdoor temperature changes, hourly values (totalling 8760 hours for the entire year) are generated for indoor target temperature and upper and lower adaptive comfort temperature limits. The target temperature values are the same for both Room A and Room B. However, the actual hourly indoor temperatures as logged in each room show some differences. The Ms-Excel file *Room_A+B_Results*.xlsx* (see Sanya, 2024a) presents the above information in a spreadsheet with seven columns headed respectively as

- Hourly Timestamp running consecutively from 1 to 8760
- Prevailing Temperature (ET) (°C)
- Upper Temperature Bound (°C)
- Target Temperature (°C)
- Lower Temperature Bound (°C)
- Room A Dry Bulb Temperature (°C)
- Room B Dry Bulb Temperature (°C)

For any given hour, when the logged dry bulb temperature in the room falls within the lower and upper bounds of adaptive comfort, indoor thermal conditions for that hour are acceptable. If the logged dry bulb temperature falls below the lower bound of adaptive comfort in that hour, indoor conditions are too cold. Where the logged bulb temperature falls above the upper limit in a particular hour, indoor conditions are too warm.

The seven-column results spreadsheet is formatted in MS Excel to allow the results to be sorted (in ascending/descending order) and/or filtered (greater/ below any chosen value).

Sorting the results by prevailing temperature reveals that the highest effective outdoor temperature (ET) occurs in January and February (Cape Town summer) at 20.9°C. The lowest ET is 12.4°C, occurring in June and July (winter). Therefore, the temperature range of the prevailing outdoor conditions in Cape Town is within the Adaptive Comfort range of applicability (10°C to 33.5°C) highlighted in the theoretical background above. It follows that for such buildings, passive design and behavioural and psychological measures ought to be sufficient to maintain indoor comfort throughout the year without the need for artificial space conditioning.

The upper and lower limits of adaptive comfort are also captured in the spreadsheet. Sorting by the upper temperature bound shows temperatures ranging from 24.1°C to 29°C. While sorting by the lower temperature bound gives a range from 19.1°C to 21.8°C. Hence, the entire adaptive comfort zone for the rooms ranges from 19.1°C to 29°C. This study's results indicate that in Cape Town and similar Mediterranean locations, the upper comfort range can be extended by 4°C above the 25°C used in steady methods. Considering that a 1°C change can result in 10% heating energy savings (Holt et al., 2009), the energy, cost and climate mitigation implications of this potential adjustment are very significant.

3.3. Orientation Impacts Thermal Comfort Significantly

For each room, the LB simulation generated an adaptive chart for 90% acceptability (see Figures 2a and 2b below). On the adaptive chart, the prevailing outdoor temperature is on the X-axis while the indoor operative temperature is on the Y-axis (see definitions in Table 4 above).

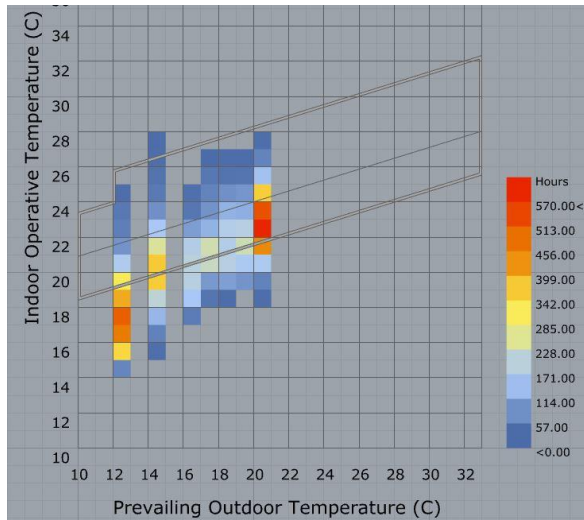


Figure 2a: Adaptive Chart for Room A

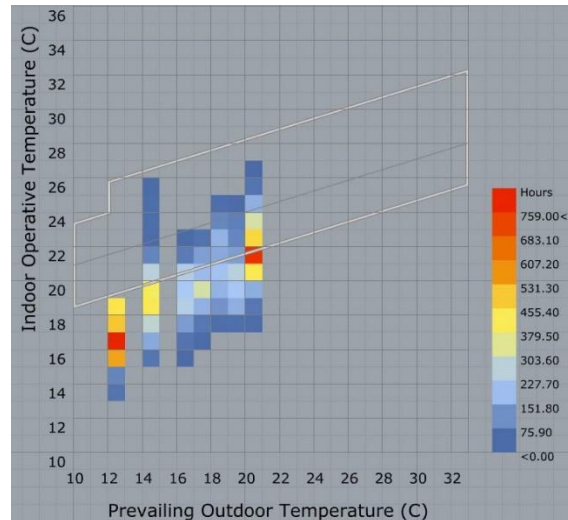


Figure 2b: Adaptive Chart for Room B

Source: visualisations from the simulation by the author (see Sanya, 2024b)

The lower diagonal line defines hourly lower temperature bounds of comfort. The upper diagonal line temperatures define hourly upper bounds of comfort. Between these two is a diagonal line connecting the hourly target temperatures. On the chart, each hourly indoor dry bulb temperatures as logged on the data logger is also plotted against the respective prevailing outdoor temperature – with a collection of plots represented in a colour gradation (blue – fewer hours in this region of the chart; red – most hours in this region of the chart; and others in the colours in between).

Examining Figure 2a shows that when prevailing outdoor conditions approach the maximum of 20.9°C, indoor dry bulb temperatures as measured in Room A are between 23°C – 25°C for most hours of the year and hence are within the comfortable thermal range. This also corresponds to the most frequent condition of adaptive comfort in Room A. However, the chart also indicates that when prevailing outdoor temperatures fall to 13°C and lower, Room A becomes excessively cold for a significant number of hours. Very few hours in Room have thermal conditions above the upper the bound of comfort.

On the other hand, the adaptive chart in Figure 2b reveals that most temperatures measured in Room B are below the lower comfort bound for most of the year. Even when the prevailing outdoor temperatures approach the 20.9°C maximum mean monthly, about half the hourly indoor temperatures in the room remain below the lower bounds of adaptive comfort. Only a few summer temperatures in Room B are within the band of adaptive comfort. When the prevailing outdoor temperature falls to 13°C and below, all hourly indoor temperatures (covering a substantial number of hours in the year) are below the lower adaptive comfort boundary. The chart shows that indoor conditions in Room B fall below the lower comfort bound for most hours of the year. And none of the hourly temperatures measured in Room B exceed the adaptive comfort upper boundary at any time in the year.

Another important outcome of the simulation is the “percentage comfortable” – hours of the year when the room is within bounds of adaptive comfort. At 55 percent, the hours of the year for which the logged indoor operative temperatures are within the bounds of comfort in Room A (northwest orientation – towards the Equator) are more than double those of Room B (southeast orientation – away from the Equator) at 25 percent. The implication is that in Cape Town, orientation has a very significant impact on indoor thermal comfort. It can be expected that a room oriented ideally to true north (towards the Equator) would perform even better than a room oriented to the south

(opposite the Equator). Therefore, in Cape Town and similar Mediterranean climates, the main living spaces and rooms should, where possible, be orientated towards the Equator side (anywhere from 45° west of true north to 45° east of true north) while south-facing spaces should be largely be limited to auxillary functions like storerooms, bathrooms and garages.

Considering that the upper bound of comfort in Room A is only exceeded for a few hours and not at all in Room B, it is concluded that, ignoring the influence of direct solar radiation into an indoor space, overheating is not a comfort concern for an envelope dominated naturally ventilated building in Cape Town and similar Mediterranean regions. The design implication here is that sun shading of the openings is sufficient to eliminate indoor space overheating in naturally ventilated envelope-dominated buildings in Cape Town. Such shading (whether fixed or movable) needs to be designed in such a way as to allow for sun radiation penetration to warm spaces when needed for passive heating.

3.4. Excessive Indoor Cold Occurs Throughout the Year

Many of the recorded operative temperatures in Room A and Room B fall below the adaptive comfort boundary during both the cold and warm parts of the year (i.e. temperatures are too cold). The LB simulation results show that the measured operative temperatures in Room B are too cold for 75 percent (6570 hours) of the year. For Room A, the comparable figure of 45 percent (3942 hours) is lower but still significant. This again underscores the importance of good orientation in maintaining thermal comfort in Cape Town. But the most important conclusion here is that because of predominance of excessive indoor cold throughout the year, design measures for conserving internal heat gains (e.g. insulation, elimination of excessive air leakage, low envelope/volume ratio, reduction of glazed fenestration area, use of special glazing) and passive solar heating are recommended. Such measures are necessary regardless of room orientation.

3.5. The Coldest Period is Between 6 am and 12 noon

Another outcome from LB is hourly visualisation of the thermal conditions (blue – too cold, yellow comfortable, red - too hot) for each hour of each month of the year (see Figures 3a and 3b below). The visualisations allow a more granular analysis of the above results.

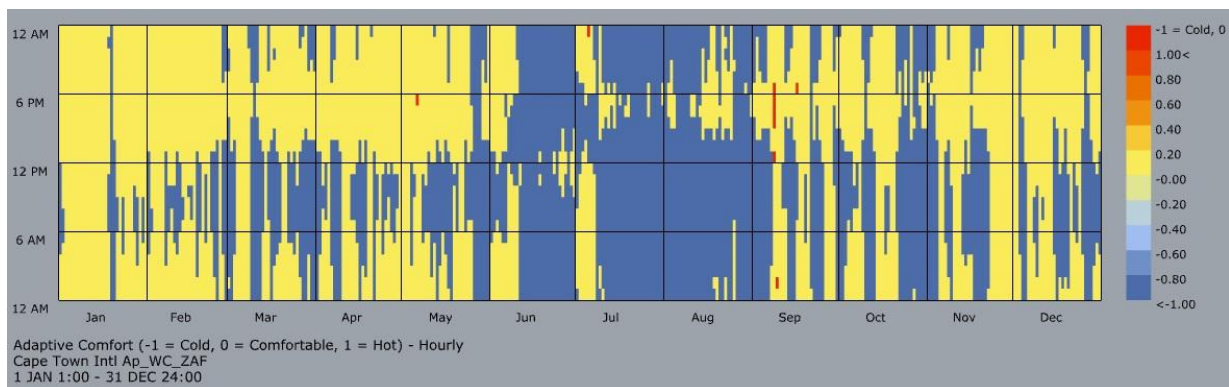


Figure 3a: Hourly Thermal Conditions in Room A [Source: visualisations from the simulation by the author (see Sanya, 2024b)]

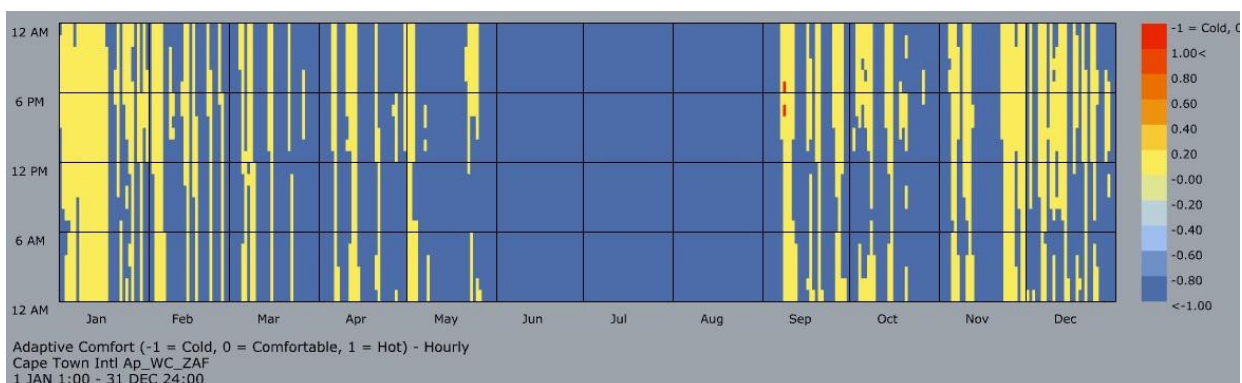


Figure 3b: Hourly Thermal Conditions in Room B [Source: visualisations from the simulation by the author (see Sanya, 2024b)]

Figure 3a (see above) shows that indoor thermal conditions in Room A are comfortable for most of the year. From January to February, Room A is comfortable for 24 hours on most days. Indoor cold conditions are limited during this period. From March to the end of May, indoor conditions are still predominantly comfortable, but excessive cold creeps in, especially between 6 am and 12 noon on most days. The first few weeks of June are also mostly comfortable, but the later weeks of the month become predominantly cold. Excessive cold is the predominant condition throughout July and up to the first week of September. It is noteworthy that the graph shows swathes of comfortable hours occurring indoors, even in this winter period. From the second week of September, indoor conditions in Room A are mostly comfortable till the end of the year. But the latter half of October and some parts of November still show significant periods with cold indoor conditions especially between 6 pm and 12 noon (this can be attributed to the north-west orientation of the room receiving the sun later in the day and generally higher position of the sun as the December summer solstice approaches). There is indoor overheating for only a few hours in the entire year in Room A. Figure 3b (see above) shows that the most comfortable month in Room B is January. But by the second week of February and throughout the autumn, conditions in Room B are mostly too cold.

Starting in the last week of May and lasting throughout the winter and up to the first week of September, all temperatures in Room B are too cold. In the spring, starting in the second week of September and up to December, Room B attains some indoor thermal comfort, but, even then, conditions remain thermally cold for most of the hours, especially from 6 am to 12 noon. Long periods in October and November are also too cold in the room. January has the highest number of hourly temperatures within the comfort band. Significantly, Room B indoor temperatures are too cold even for large parts of the mild Cape Town summer.

In both Rooms A and Room B, the period 6 am and 12 noon stands out as having the most frequent occurrence of cold for most parts of the year. This period should receive focus in the design process through a responsive approach to the circadian occupancy schedule of the house (for example whether most residents at work during this time) and looking into solutions like designing for rapid morning response for passive solar heating – specifically by utilising the easterly and north-easterly sun in Cape Town (also see Sanya, 2017)

3.6. Sensitivity Analysis

Figure 4: Sensitivity Analysis in Southern and Northern Hemispheres (Source: Author)

1. Output Parameter		compPercentOfTime	percentHotCold	conditionOfPerson	prevailingTemp	targetTemperature	chartCurvesAndTxt	adaptiveChartMesh	legend	comfortPolygons	upperTemperatureBound	lowerTemperatureBound
2. Description (adapted from Roudsari, 2020)		Percentage of time for which the occupants are comfortable	The percent of time for which the occupants are too hot	The percent of time for which the occupants are too cold -1 = The input conditions are too cold 0 = The input conditions are comfortable +1 = The input conditions are too hot	A stream of temperature values in degrees Celsius (°C) indicating the prevailing outdoor temperature. This is the same as ET (see definition in 1.1 above).	A stream of temperature values in degrees Celsius (°C) indicating the mean target temperature (neutral temperature) (°C). Varies as outdoor temperatures change (see definition in 1.1 above).	Curves and text labels of the adaptive chart.	Colours representing the number of hours on the adaptive chart	A legend showing the number of hours that correspond to each colour.	Lines representing the range lower and upper boundaries.	Temperature values in degrees Celsius (°C) indicating the highest possible temperature in the comfort range for each hour.	Temperature values in degrees Celsius (°C) indicating the lowest possible temperature in the comfort range for each hour.
3. Main Adaptive Comfort Simulations Results *	Cape Town											
	Room A [Facing Equator]	55%	0.1%	44.9%	Full set of results captured in a combined spreadsheet in the Room_A+R_Results*.xlsx file. The results are sortable by each column.	Full set of results captured in a combined spreadsheet in the Room_A+R_Results*.xlsx file. The results are sortable by each column.	Imputed into LB Preview to generate an adaptive chart visualization in Rhino3D (see Figure 2a)	Imputed into LB Preview to generate an adaptive chart visualization in Rhino3D (see Figure 2a)	Imputed into LB Preview to generate an adaptive chart visualization in Rhino3D (see Figure 2b)	Imputed into LB Preview to generate an adaptive chart visualization in Rhino3D (see Figure 2b)	Results for upper temperature boundaries for each hour of the year captured in a formatted spread-sheet Room_A+R_Results*.xlsx file. The results are sortable by each column.	Results for lower temperature boundaries for each hour of the year captured in a formatted spread-sheet Room_A+R_Results*.xlsx file. The results are sortable by each column.
	Room B [Facing away from Equator]	25%	0%	75%	Highest ET: 20.9°C Lowest ET: 12.4°C	Highest target temperature: 24.3°C Lowest target temperature: 21.6°C					LB gives the maximum upper temperature boundary for Cape Town as 29.0°C	LB gives the minimum lower temperature boundary for Cape Town as 19.1°C
4. Sensitivity Analysis**	Southern Hemisphere	Augusta, Australia	Room A	52%	0.1%	47.9%						
		Room B	27%	0%	73%							
	Santiago, Chile	Room A	66%	0.06%	33.2%							
		Room B	37%	0%	63%							
	Porto, Portugal	Room A	53%	10%	37%							
		Room B	44%	4%	52%							
Northern Hemisphere	San Francisco, USA	Room A	56%	8%	36%							
	Room B	44%	3%	53%								

* The Cape Town results are from comprehensive adaptive comfort simulation undertaken by the author using field measured indoor temperatures.
 ** The focus of the sensitivity analysis is general trends – not absolute values.

To test this paper’s findings in relation to other Csb climate locations around the world, a sensitivity analysis was undertaken using the adaptive comfort simulation model developed in the study. Four cities are chosen for the sensitivity analysis based on two criteria. First, each city must have full-year hourly EPW climate data available for use in running the simulation. Second, for each city, the daily outdoor average temperatures must be within the range

of 10°C to 33.5°C for which adaptive comfort is a valid method. In the southern hemisphere, Augusta (Australia) and Santiago (Chile) are chosen for the sensitivity analysis. In the northern hemisphere, Porto (Portugal) and San Francisco (United States of America) are chosen.

Replacing Cape Town outdoor temperature values with the respective daily means for the above cities gives the sensitivity analysis. Because of the inversion of seasons in the opposite hemispheres, an LB component is used to synchronise LB outdoor temperature with this study's measured indoor temperatures where necessary. A corollary of this is that, for both hemispheres, it becomes more appropriate to describe Room A as Equator-facing and Room B as facing away from the Equator. The sensitivity analysis results are captured at the end of Figure 4 and should only be referenced as indicative but not absolute.

The sensitivity analysis reveals that Csb climate locations elsewhere give similar results to the Cape Town findings. Orientation remains a major factor for indoor comfort. That is, in all locations, the Equator-facing room is comfortable most of the time; there is no trend of overheating, but excessive cold remains a key issue. The room facing away from the Equator has a significant reduction in comfort, more especially so in the southern hemisphere compared to the northern hemisphere; excessive cold remains as the most significant indoor thermal condition in the year; overheating is the least of concerns. Therefore, the sensitivity analysis suggests that for Csb climate locations the world over, orientation towards the Equator, conservation of internal heat gains and passive heating are a sine quo non for energy efficiency.

4. Discussion

There have been just a few studies of adaptive comfort in Mediterranean climates. This paper, therefore, contributes adaptive comfort findings to an understudied climatic type. Moreover, this is the first adaptive comfort study on Middle-Income residential houses in a Csb Mediterranean climate. Unlike the other Mediterranean climate adaptive comfort studies that use thermal data logged for only part of the year (Sánchez-García et al., 2019; Sánchez-García et al., 2018 and Perez-Fargallo et al., 2018), this study uses a full year's data set. Therefore, this paper's finding that adaptive comfort is applicable throughout the year in the Mediterranean Csb climate of Cape Town is a significant finding. Moreover, a sensitivity analysis indicates that trends in this paper are similar to those in other cities with a Csb Mediterranean climate type.

The 75% thermal discomfort for non-Equator rooms and 45% thermal discomfort (both excessive cold) in the Equator-facing room is concerning, particularly considering that this paper focused on an upper-middle-class residences. In South Africa, poor people's housing is generally of poorer quality (Amoah et al., 2022; Kang'ethe and Manomano, 2015; Nokulunga, 2018). It can, therefore, be expected that poor people would be subject to even worse thermal conditions than identified in this paper. Considering the health risks of excessive indoor cold (WHO, 2018), it is necessary to undertake adaptive comfort studies of middle-class and low-income housing in Mediterranean climates to provide an evidence basis for shifting practice and policy to improve thermal conditions, safeguard health, save energy and mitigate greenhouse gases.

The finding that orientation towards the Equator improves comfort in by up to 30% for Cape Town and potentially in other Mediterranean Csb climates without the need for space conditioning is significant because, if applied in practice, it would result in improved wellbeing, healthier indoor condition simultaneous with energy savings and reduction in greenhouse gas emissions.

Another key finding is that excessive indoor cold is more of a concern than overheating in Csb Mediterranean locations. Thermal comfort improvement can, therefore be attained by orientation towards the Equator (the sunny side), preservation of internal heat gains via building envelope insulation, using building form with low envelope to internal volume ratio, airtightening, limiting the amount of fenestration, and using specialised glazing (Lechner 2014 and Sanya 2017).

The South African SANS10400XA regulations do not address existing housing stock. Results from this paper indicate that the above measures for preservation of internal heat gains should be incentivised, or even mandated, for existing housing stock in Cape Town and similar climates.

It is evident that orientation has a significant impact on thermal comfort and design in Mediterranean climates. The impact of orientation on indoor space thermal comfort and energy consumption can further be investigated using building energy simulation software such as *Energyplus* (Gerber, 2014 and Crawley and Pederson, 2001) to test the validity of this important finding.

There is an opportunity to simulate the requirements of deemed-to-regulation in the residential building under consideration to evaluate if these are sufficient to guarantee indoor thermal comfort or if they could direct interventions on existing building stock.

This paper recommended a passive design for heat conservation and heating for Csb climates. These measures include orientation, envelope insulation, airtightening, low window-to-wall ratio, specialised glazing and passive solar heating. The measures maintain indoor thermal comfort while saving energy (Fernandez-Antolin et al., 2019). Considering the costs and benefits over the entire building lifecycle (Shrestha et al 2014), it has been found that, on the balance, passive measures yield positive economic, social and environmental impacts on the balance (Adamczyk and Dylewski, 2017): improved wellbeing and health of users; mitigation of greenhouse gas emissions; lower energy bills and hence reduced operation costs; and increasing the economic value of the building asset. A comparative simulation for a two-story house in different climate types (Falegari and Shirzadi Javid, 2024) found that buildings in Csb climates get significant benefits from applying passive design measures for thermal comfort over the residential building cycle.

The validity of this paper's results is underpinned by empirical quantitative data and the use of the well-tested study method of adaptive comfort. However, the dataset used is from only one middle-class building. This limits the ability to generalise the outcomes of this research for middle-class residents in Csb Mediterranean climate cities. Cross-sectional research is therefore required to extend the generalisability of this paper's findings by increasing the number of buildings sampled in an urban survey. Moreover, longitudinal adaptive comfort studies are also required to test the efficacy of the proposed passive design for residences in cities facing temperature variations due to climate change. Furthermore, the formulaic approach of the paper does not capture how residents actually experience the indoor thermal comforts. Future research that includes insights from qualitative responses of how building inhabitants experience the thermal conditions is required to extend the paper's finding. This is necessary because existing research (Oraiopoulos et al., 2023) suggests that acclimatised residents' perception of comfort may extend the usual range of adaptive comfort. Such future research is required so that a contextually responsive adaptive standard can be defined for Cape Town and other Csb Mediterranean locations.

5. Conclusion

This paper used an adaptive comfort approach to simulate the indoor thermal conditions in a naturally ventilated Middle-Income residence in Cape Town's Csb Mediterranean climate.

Using climatic data, the study found that Cape Town's outdoor effective temperatures range from 20.9°C to 12.4°C and hence fall well within the Adaptive Comfort range of applicability (10°C to 33.5°C) for the entire year. The conclusion from this is that in Cape Town and similar Csb locations, preventative and passive measures are sufficient for maintaining temperatures within a comfortable range without the use of artificial heating or cooling.

The study provides a full set of annual logged indoor climatic data fractionated at 1-hourly intervals. The data is available as open source to be used by any other researcher in a future study.

For Cape Town and similar Mediterranean locations, it was found that the comfort range can be extended by 4°C above the 25°C normally given in literature.

Overcooling (excessive indoor cold) was found to be a more significant problem than overheating, regardless of orientation. In Cape Town and similar Csb climates, policy should drive practice towards preventative and passive measures for internal heat preservation and augmentation.

Orientation was found to have a significant impact on adaptive thermal comfort in Cape Town's Csb Mediterranean climate. The room oriented towards the sunny Equator side (NW) was found to be 30 percent more thermally comfortable compared to the room oriented away from the sun (SE) on an annual basis. At 55 percent, the hours of

the year for which the logged indoor operative temperatures are within the bounds of comfort in Room A (northwest orientation – towards the Equator) are more than double those of Room B (southeast orientation – away from the equator) at only 25 percent. Policy should drive practise orientate living spaces to the sunnyside in Cape Town’s Csb climate and similar Mediterranean climate regions.

Winters were found to be excessively cold in both rooms, with the coldest indoor temperatures being recorded in July. Similarly, for both rooms, the period 6 am to 12 noon stood out for being generally too cold in winter, spring, summer (exception January), and autumn. This is a period, therefore, deserving special attention in design in Cape Town and similar contexts in terms of passive heating and responsiveness to living habits.

More adaptive comfort studies and energy simulation studies are required in Cape Town and similar Csb Mediterranean climate contexts. These should include individual case studies, cross-sectional studies and longitudinal studies to build a large Modelling for Policy Support (EMoPS) evidence base. The ultimate aim should be to improve design and planning decisions, to increase comfortable and healthy housing stock and to promote energy justice in the context of climate change.

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Ethics Approval

Not applicable.

Conflict of interest

The authors declare there is no conflict.

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