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Evaluating Thermal Comfort and the Influence of Passive Design Strategies in Free-Running Local Dwellings of Wadi Hadramout, Yemen

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Abstract: In least developed countries such as Yemen, severe power shortages limit the use of air conditioning for maintaining indoor thermal comfort. In Hadramout province, located in the east of Yemen, climate-responsive adobe dwellings are gradually being replaced by modern buildings that disregard local climate conditions and rely entirely on mechanical ventilation to achieve thermal comfort, particularly during the summer. This paper compares the thermal performance of adobe, concrete, and stone dwellings in Wadi Hadramout during summer using on-site measurements and computer simulations. Additionally, the paper explores the potential impact of passive design strategies on improving indoor thermal comfort in the aforementioned houses. The results indicate that the internal operative temperature is lower and more stable throughout the day in the adobe house compared to the concrete and stone houses. Furthermore, it was found that certain passive design strategies significantly enhance the thermal performance of the tested houses.

Keywords: Thermal Comfort, Passive Design Strategies, Simulation, Local Houses.

1. Introduction

The rapid growth of modern life and technological advancements have led to an increasing demand for energy. Energy demand rose significantly over the 20-year period from 1984 to 2004, increasing by 43%, with an average annual growth rate of 2% (Pérez-Lombard, Ortiz, & Pout, 2008). Buildings account for over 60% of global energy consumption, with 20-40% of this energy used by residential buildings (Cuce & Riffat, 2016). Moreover, according to the U.S. Energy Information Administration, energy consumption in buildings is projected to continue growing at an average rate of 1.5% per year until 2030 (IEA, 2006).

In Yemen, the electricity network is outdated and unable to provide adequate power supplies to the population. Despite having one of the largest populations in the region, Yemen is among the lowest energy producers in the Middle East. According to the World Bank, only 40% of Yemen's population has access to electricity ("International - U.S. Energy Information Administration (EIA)," 2020). However, even those with access to electricity experience frequent power blackouts. The electricity deficit worsened after the onset of the Arab Spring in 2011, with blackout hours increasing significantly due to ongoing vandalism attacks on energy infrastructure and a severe shortage of fuel supplies for power plants (Al-Shabi Mohammed & Rami, 2014). Most people living in rural areas lack access to the electricity network and rely on private generators, which are often powered by diesel fuel (Rawea & Urooj, 2018). However, fuel prices have surged by more than 300% on average since the start of the conflict, as of March 2021, according to the World Relief Organization (OCHA, 2021). This could leave millions of people in rural areas unable to afford fuel, thus depriving them of any reliable source of energy.

Many studies have indicated that the most effective way to reduce energy consumption in the built environment is to design energy-efficient buildings. Energy-efficient buildings respond to climatic conditions by employing passive design strategies that reduce energy demand and promote a sustainable environment. However, the effectiveness of passive design strategies largely depends on the climatic conditions. Therefore, understanding the local climate is crucial for determining the potential for adopting passive design strategies. To this end, several analytical tools, such as Climate Consultant and ECOTECT Weather Tool, are used to evaluate climatic conditions and assess the potential effectiveness of passive design strategies (Nguyen & Reiter, 2014). Various passive design strategies can be employed to enhance thermal comfort in buildings, including thermal mass, natural ventilation, shading techniques, and others. To evaluate thermal comfort, several international standards are used, including ISO EN 7730, ASHRAE-55, ASHRAE-62.1, and EN15251 (Olesen, 2012).

The impact of passive design strategies on indoor thermal comfort has been widely discussed in the literature. For example, studies have shown that traditional houses in Vietnam have successfully adapted to varying climatic conditions by incorporating several passive design strategies (Nguyen, Tran, Tran, & Reiter, 2011). The same research also indicated that under extreme climatic conditions, relying solely on traditional design measures is insufficient to achieve thermal comfort. Vissilia (Anna-Maria, 2009) evaluated specific types of vernacular Greek dwellings and their climatic responses based on various passive design principles related to form, orientation, and building materials. She found that vernacular dwellings effectively adapted to the climatic conditions and provided thermal comfort using low-energy design principles without excessive consumption of building resources. Manioglu and Yılmaz (Anna-Maria, 2009) studied climate-responsive design measures in traditional dwellings in Mardin, a town located in the hot-dry zone of Turkey. They evaluated and compared the thermal performance of a traditional house and a modern house by conducting on-site measurements and administering questionnaires to 100 buildings. Their findings concluded that vernacular houses outperform modern houses in terms of indoor thermal comfort and energy demand. Hiroshi Yoshino et al. (Yoshino, Hasegawa, & Matsumoto, 2007) investigated the cooling effects of traditional techniques in four vernacular farmhouses in northern Japan using on-site measurements and computer simulations. The study revealed that certain traditional cooling techniques, such as thatched roofs for solar shading, natural ventilation, and earthen floors, are effective in enhancing indoor cooling efficiency. Mohamed Ameur et al. (Ameur, Kharbouch, & Mimet, 2020) evaluated the thermal performance of a naturally ventilated residential building in northern Morocco under a selected set of passive design strategies using simulation. The study results indicated that increasing thermal mass and applying external thermal insulation provide the most significant improvement in thermal performance. Mady et al. (Mohamed, Klingmann, & Samir, 2019) compared the thermal performance of a traditional adobe house and a contemporary concrete house in Asir, Saudi Arabia. The results demonstrated the superiority of the traditional mud house over the modern concrete house in terms of internal thermal comfort and emphasized the importance of incorporating passive design measures in modern architecture. Additionally, the reviewed literature highlighted numerous research efforts investigating the impact of climate-responsive design strategies on the thermal performance of traditional houses in China (Sun, Qi, & Long, 2021), Iran (Mohammadi, Saghafi, Tahbaz, & Nasrollahi, 2018), Portugal (Fernandes, Mateus, Gervásio, Silva, & Bragança, 2019), South Africa (Widera, 2021), Nepal (Bodach, Lang, & Hamhaber, 2014), and India (Dili, Naseer, & Varghese, 2010). The reviewed studies concluded that traditional dwellings in various countries effectively adapt to different climatic conditions, providing comfortable indoor thermal environments.

Thermal insulation plays a crucial role in enhancing energy efficiency and improving thermal comfort in buildings. Insulated buildings consume 20–40% less energy compared to non-insulated buildings (Balaras, Droutsa, Argiriou, & Asimakopoulos, 2000; Fang, Li, Li, Luo, & Huang, 2014; Farhanieh & Sattari, 2006). Kolaitis et al. (Kolaitis et al., 2013) compared the impact of internal and external insulation systems on the energy efficiency of residential buildings using numerical simulation. Their findings revealed a significant reduction in energy demand with both insulation systems. Additionally, they indicated that external insulation outperforms internal insulation by 8% in terms of energy efficiency.

The literature review indicates that there are limited studies related to the energy efficiency of local domestic buildings in Hadramout. Baeissa (Baeissa, 2014) A study examined the thermal properties of different building materials in Hadramout Valley and concluded that adobe buildings possess better thermal attributes compared to concrete buildings. Baangood and Hassan (Baangood & Sanusi, 2017) A study examined the impact of courtyards and narrow streets on thermal comfort in traditional buildings in Al-Mukalla city, Hadramout. The findings indicated that courtyards and narrow streets can help reduce air temperature and improve natural ventilation, particularly when the building is oriented in the North-South direction. Al-Shibami et al. (Al-Shibami & Ward, 2002) investigated thermal comfort in traditional adobe houses, modern adobe houses, and modern concrete houses in Seiyun and confirmed the advantages of traditional adobe buildings in terms of thermal comfort. Abdallah et al. (Reda Abdallah, Hassan, & Al-Olofi, 2020) analyzed the types of buildings in different regions and environments of Yemen by examining building methods, techniques, elements, and their influence on energy consumption. The study confirmed the efficiency of various techniques and elements in achieving comfort for the occupants of traditional buildings in Sana'a city.

The aforementioned studies focused on comparing the thermal comfort of traditional and modern houses in various regions of Yemen and examined the impact of a few passive design measures on internal thermal comfort. However, no studies have specifically investigated the potential impact of applying passive design strategies on the indoor thermal comfort of common local residential buildings in the Wadi Hadramout climate. The aim of this research is to identify the most suitable local house types in terms of internal thermal environment and explore the potential influence of passive design strategies in enhancing indoor thermal comfort within the most common local house types of Wadi Hadramout.

2. Research Problem

The power deficit worsens during the summer as energy demand for cooling purposes increases. This ongoing power crisis causes significant inconvenience for inhabitants, particularly those living in hot regions such as Wadi Hadramout. This is primarily because the majority of modern houses were designed without considering local climatic conditions and rely entirely on mechanical ventilation for cooling during the summer. This situation underscores the importance of incorporating passive and climate-responsive design strategies in residential building development.

In the past, vernacular adobe buildings in Wadi Hadramout were adapted to the local climatic conditions in a way that met the comfort needs of their inhabitants without the use of mechanical means. Modern adobe dwellings evolved through trial-and-error processes conducted by our ancestors over hundreds of years to provide comfortable shelters. As a result, these houses incorporated a variety of passive cooling methods, such as shading devices, high thermal mass, and natural ventilation. However, with the emergence of new building materials, traditional materials, including adobe, began to be neglected despite their numerous environmental and economic advantages (Arooz & Halwatura, 2018).

3. Research Aim and Objectives

The aim of this research is to evaluate the thermal performance of local adobe houses in Hadramout in terms of internal thermal comfort during the summer, without the use of mechanical ventilation. To achieve this aim, the following objectives must be fulfilled:

1. Comparing the thermal performance of local adobe, concrete, and stone houses.
2. Evaluating the potential influence of applying selected passive design strategies on the internal thermal comfort of adobe, concrete, and stone houses.

4. Methodology

The research methodology of this study includes climatic analysis, on-site measurements, simulation, and parametric analysis. The aim of the climatic analysis is to understand the impact of climate on the internal environment and to determine the most appropriate passive design strategies to be implemented under the existing climatic conditions. On-site measurements were conducted to assess and compare the internal temperatures of three selected local houses. These measurement results were then used to validate the simulation models. This study uses simulation to evaluate thermal comfort in three types of local houses in Seiyun. Parametric analysis was conducted to investigate the impact of various passive design strategies on thermal comfort during the summer. Finally, the tested dwellings and passive design measures were ranked based on their influence on the thermal environment of the local houses. Figure 1 demonstrates the framework of this study.

Seiyun City was selected as the area for this study for two main reasons:

1. Being the capital of Wadi Hadramout for a long time, Seiyun has become the center of the building revolution in the valley, where both modern and traditional building materials and techniques coexist.
2. The availability of climatic data for Seiyun, as the only weather station in Wadi Hadramout, is located at Seiyun International Airport.

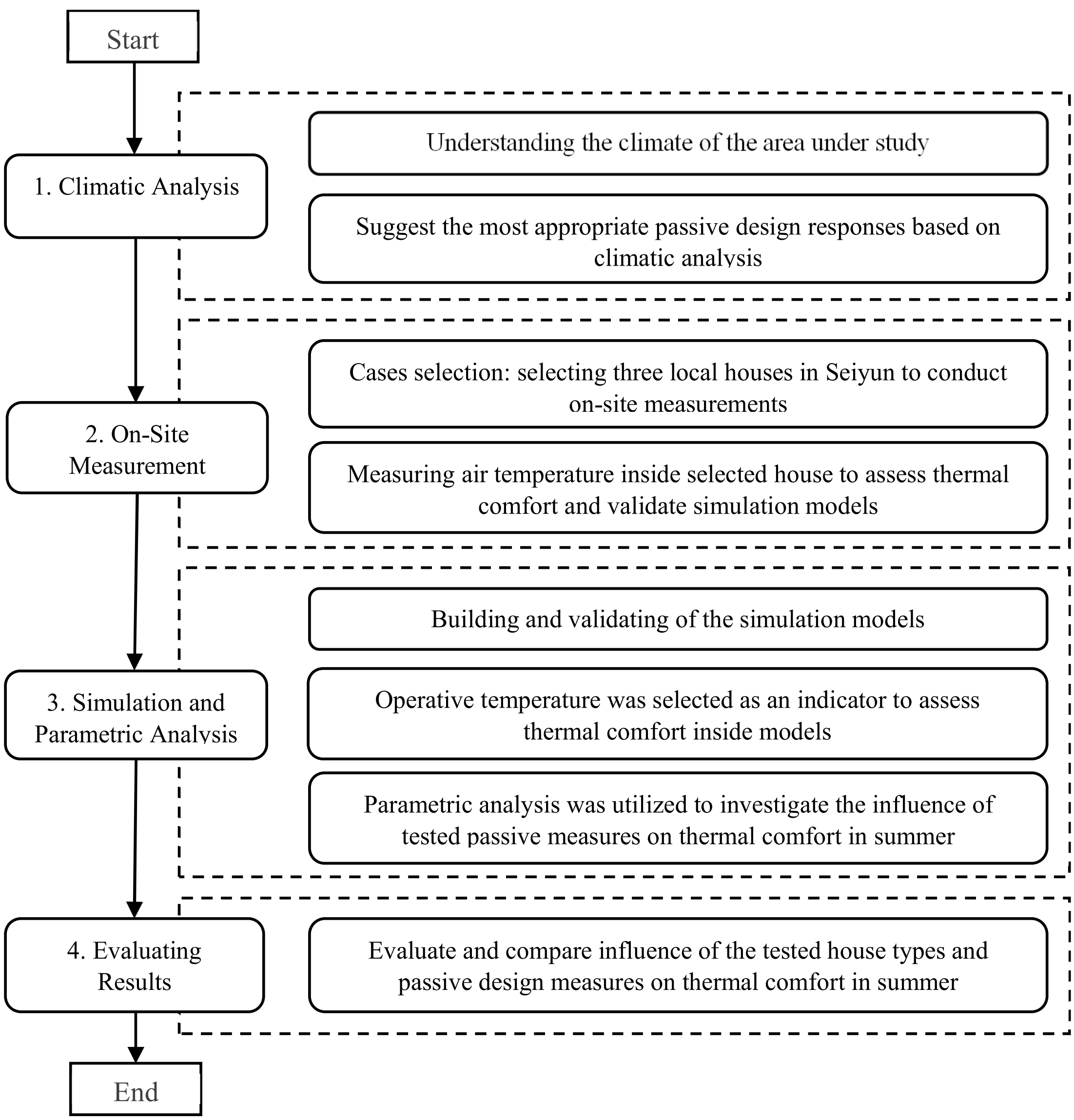

Figure (1). Methodology of the study

4.1 Climatic Features and Traditional Houses in Seiyun

Seiyun city features a tropical climate with hot summers and moderate to cold winters. Temperatures range from 6°C to 28°C in winter and from 26°C to 42°C in summer, with a low precipitation rate, primarily occurring in July and August. Furthermore, there are significant differences in air temperature between day and night, as demonstrated in Figure 2, which represents 30 years of historical weather data for the city of Seiyun.

A psychrometric chart is a highly valuable design tool for creating a comfortable indoor environment, as it helps recommend a set of design strategies specifically tailored to a particular climate. Figure 3 illustrates the effect of applying the design guidelines recommended by Climate Consultant 6.0 on the comfort zone of a residential-scale building situated within Seiyun's climatic

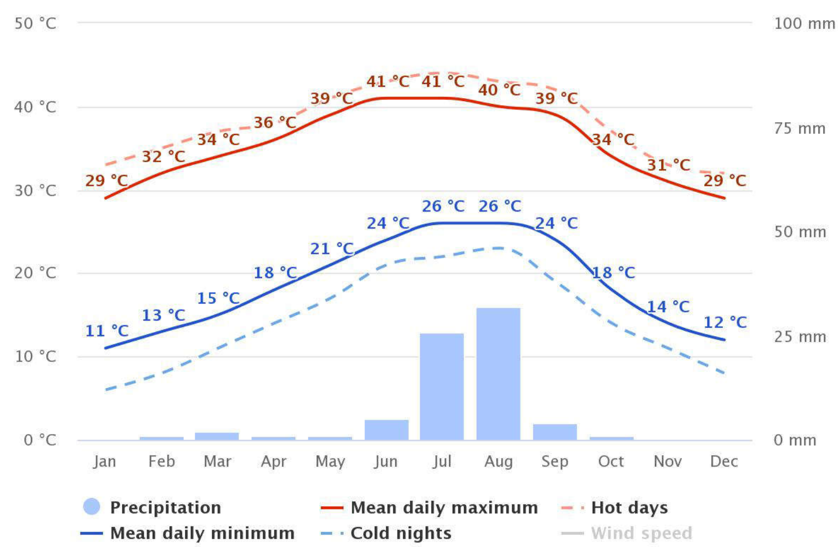

Figure (2). Historical weather data for Seiyun during the past 30 years. Source: ("Climate Seiyun - meteoblue," n.d.)

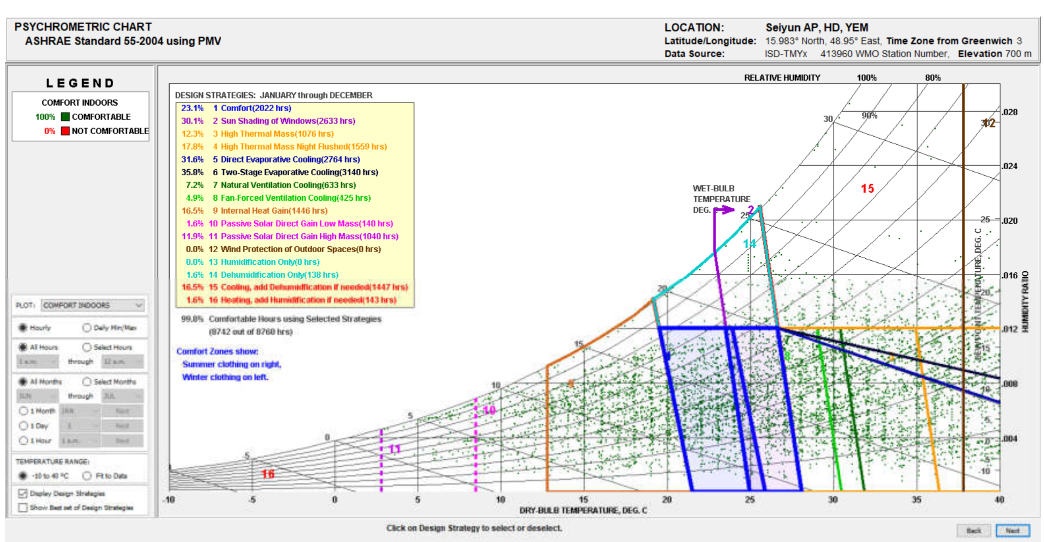

Figure (3). Psychrometric chart and comfort ratio for Seiyun after applying the recommended design strategies, by the author using climate consultant software

region. The chart indicates that occupants will experience comfort in 99.8% of the displayed hours after implementing the recommended design strategies. The figure highlights that evaporative cooling, shading of windows, and high thermal mass are the most effective passive design strategies in improving thermal comfort, in that order.

Vernacular houses in Wadi Hadramout are constructed using mud brick, locally known as "madar." The "madar" is made by mixing mud with water and chopped straw, which is then poured into wooden frames of varying sizes and dried in the sun. The thickness of the walls varies from the lower to the upper levels. At the ground level, the wall thickness can reach up to one meter, gradually decreasing as the building rises, with the upper levels having walls that are about 20-30 cm thick (Ai-shibami, 2004).

The roof of traditional houses in Wadi Hadramout is constructed to mitigate the impact of direct sunlight on the internal temperature of the house. The roof construction incorporates multiple layers as follows:

- Timber joists made of trunks of trees.
- Layer crushed mud brick covering the joists.
- Layer of soil covering the crushed bricks.
- 2 layers of mud plaster.
- 2 layers of lime plaster which known locally as (norah).

The roof requires approximately three months to dry after construction is completed, during which it is refined and coated with lime.

4.2 On-Site Measurements

The thermal environments of three local dwellings were assessed. Adobe, concrete, and stone houses in the same area of Seiyun were selected for the field measurements. Figure 4 shows the layouts of the selected houses, along with the ground floor plans and locations of the measurement points within those plans. Data was collected over three consecutive days (May 2nd, 3rd, and 4th, 2021) for the adobe, concrete, and stone houses, respectively. Air temperature was recorded in selected zones within each house. The architectural features of the rooms where measurements were taken are presented in Table 1.

The HOBO U12-012 data logger, shown in Figure 5 was used to conduct the measurement process. The range, accuracy, and resolution of the data logger are presented in Table 2. The logger was placed 1.5 meters above the ground at the center of each room and set to record data at 5-minute intervals.

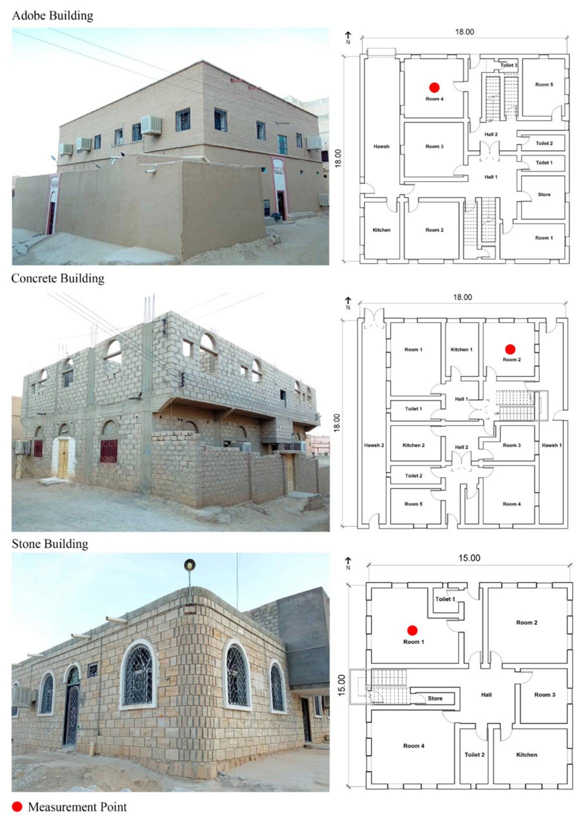

Figure (4). footages of the local houses in which the field measurements were conducted in addition to ground floor plans and locations of the measurement points within the plans

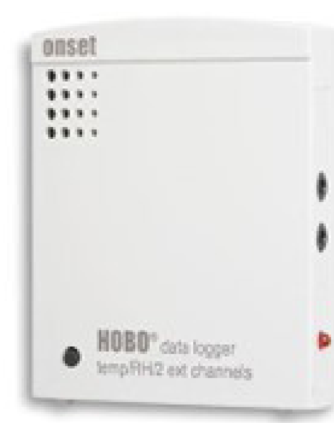

Figure (5). HOBO U12-012 data logger

Table (1). Architectural attributes of the rooms where on-site measurements were conducted within the three selected local houses

Adobe House			Concrete House			Stone House		
Length		5.2 m	Length		6 m	Length		6.2 m
Width		5.2 m	Width		5 m	Width		5.5 m
Height		4 m	Height		3.2 m	Height		2.9 m
Floor Height		0.45 m	Floor Height		0.75 m	Floor Height		0.45 m
Windows	Number	4	Windows	Number	4	Windows	Number	4
	Material	Wood		Material	Glass + Aluminum		Material	Glass + Aluminum
	Width	0.8 m		Width	1 m		Width	0.9 m
	Height	0.9 m		Height	1 m		Height	0.9 m
Door	Width	0.9 m	Door	Width	0.9 m	Door	Width	0.9
	Height	2.3 m		Height	1.8		Height	1.8
	Material	Wood		Material	Wood		Material	Wood
Wall	Material	Adobe	Wall	Material	Concrete Brick	Wall	Material	Limestone
	Thickness	0.45 m		Thickness	0.2 m		Thickness	0.2 m

Table (2). Range, accuracy, and resolution of the HOBO U12-012 data logger

Measurement Range	Temperature: -20°C - 70°C RH: 5% - 95% RH
Accuracy	Temperature: ± 0.35°C in range of 0°C - 50°C RH: ± 2.5% in the range of 10% - 90% below 10% and above 90% ±5%
Resolution	Temperature: 0.03°C at 25°C RH: 0.05%

4.3 Thermal Modeling

4.3.1 Building the Simulation Models

The proposed base model for the simulation was divided into several separate zones as shown in Figure 6. Only seven of these zones are continuously occupied, with one occupant per zone. These occupied zones include the kitchen, living room, bedroom 1, bedroom 2, bedroom 3, reception room, and hall. The model was designed so that all occupied zones have the same area and are arranged around a central zone. This layout enables the implementation of various passive design strategies, such as a central courtyard, while also maximizing connectivity between indoor and outdoor spaces.

Based on the base model, three simulation models using different building materials were developed. These models include the Adobe House (M1), Concrete House (M2), and Stone House (M3), representing the most common building types in Wadi Hadramout. All three models were constructed using IDA ICE, maintaining the same layout as the base model shown in Figure 6. However, different thermophysical parameters were used for each envelope. Tables 3, 4, and 5 present the thermophysical properties of models M1, M2, and M3, respectively. The Typical Meteorological Year (TMY) weather data for Seiyun, representing 8,760 hours annually, was used as the reference climate file in IDA-ICE.

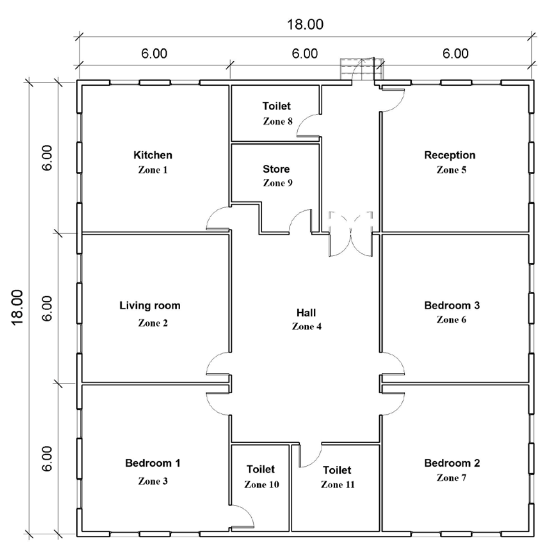

Figure (6). Layout and zones of the base model

Table (3). Thermophysical parameters of the simulated house (M1)

Building element	Material	Thickness (mm)	Thermal conductivity (W/mk)	Density (kg/m^3)	Specific heat (J/kg K)	U-value (W/m^2K)
External Walls	Adobe	450	0.44	1403	1450	1.513
	Gypsum Plaster	12	0.22	970	1090	
Internal Walls	Gypsum Plaster	12	0.22	970	1090	1.33
	Adobe	450	1200	1381	1000	
	Gypsum Plaster	12	0.22	970	1090	
Ground Floor	Cement Plaster	12	1.7	2300	880	2.619
	Soil	200	1.0	1500	800	
First Floor/Roof	Cement Plaster	12	1.7	2300	880	0.677
	Clay or Silt	250	1.5	1600	1875	
	Branches over a Steel Joists	150	0.14	500	2300	
	Gypsum Plaster	12	0.22	970	1090	
Doors	Wood	30	0.14	500	2300	2.602
Windows	Wood	23	0.14	500	2300	2.990

Table (4). Thermophysical parameters of the simulated house (M2)

Building element	Material	Thickness (mm)	Thermal conductivity (W/mk)	Density (kg/m^3)	Specific heat (J/kg K)	U-value (W/m^2K)
External Walls	Dense Concrete Brick	200	1.31	1762	840	2.84
	Gypsum Plaster	12	0.22	970	1090	
Internal Walls	Gypsum Plaster	12	0.22	970	1090	2.63
	Dense Concrete Brick	200	1.31	1762	840	
	Gypsum Plaster	12	0.22	970	1090	
Ground Floor	Ceramic Tiles	12	1.2	2000	900	1.33
	Cement Mortar	20	1.73	2160	950	
	Sand	70	0.33	1500	800	
	Aggregate	340	1	1500	800	
First Floor/Roof	Cement Plaster	12	1.7	2300	880	2.94
	Concrete	120	1.60	2100	880	
	Gypsum Plaster	12	0.22	970	1090	
Doors	Wood	30	0.14	500	2300	2.602
Windows	Wood	23	0.14	500	2300	2.990

Table (5). Thermophysical parameters of the simulated house (M3)

Building element	Material	Thickness (mm)	Thermal conductivity (W/mk)	Density (kg/m^3)	Specific heat (J/kg K)	U-value (W/m^2K)
External Walls	Limestone	200	1.29	2700	909	2.82
	Gypsum Plaster	12	0.22	970	1090	
Internal Walls	Gypsum Plaster	12	0.22	970	1090	2.61
	Limestone	200	1.29	2700	909	
	Gypsum Plaster	12	0.22	970	1090	
Ground Floor	Ceramic Tiles	12	1.2	2000	900	1.33
	Cement Mortar	20	1.73	2160	950	
	Sand	70	0.33	1500	800	
	Aggregate	340	1	1500	800	
First Floor/Roof	Cement Plaster	12	1.7	2300	880	2.94
	Concrete	120	1.60	2100	880	
	Gypsum Plaster	12	0.22	970	1090	
Doors	Wood	30	0.14	500	2300	2.602
Windows	Wood	23	0.14	500	2300	2.990

4.3.2 Simulation Tool

All simulation processes in this study were conducted using IDA ICE (Indoor Climate and Energy). IDA ICE is an advanced energy modeling software developed by Equa, designed to assess the indoor climate and energy efficiency of buildings. This assessment can be performed for individual zones within a building as well as for the entire structure.

IDA-ICE features a user-friendly 3D design environment, enabling the easy import, display, and processing of CAD and geometric objects within the software. Additionally, IDA-ICE affect a building's energy efficiency. For instance, adjusting the building materials of walls or roofs allows for the evaluation of their impact on energy consumption. This feature is particularly crucial for this study, as it examines the use, specifically the impact of various building materials on thermal comfort and energy consumption in local buildings. Furthermore, IDA-ICE presents simulation results in tables, charts, or 3D diagrams, making them easy to interpret, even for non-professionals.

4.3.3 Validation of the Simulation Tool

The accuracy of IDA-ICE was validated for the three models by comparing the measured and simulated results. Air temperature, being a key factor influencing the thermal comfort of occupants, was selected as the experimental variable. The three models shown in Figure 4 were reconstructed in IDA-ICE using the corresponding thermophysical parameters presented in the tables 3, 4 and 5. Indoor air temperature data obtained from field measurements were used to calibrate the models. To assess the consistency between the measured and simulated air temperature readings, the Normalized Mean Bias Error (NMBE) and the Coefficient of Variation of the Root Mean Square Error CV(RMSE) (ASHRAE, 2009) were calculated using the following equations:

$$NMBE(\%) = \frac{\sum_i^n (t_{ip} - t_{im})}{n-1} \times \frac{1}{\bar{t}_m} \times 100 \qquad \textbf{Equation 1}$$

$$CV\ (RMSE)(\%) = \sqrt{\frac{\sum_{i=1}^n (t_{ip} - t_{im})^2}{n-1}} \times \frac{1}{\bar{t}_m} \times 100 \qquad \textbf{Equation 2}$$

Where tip is the simulated air temperature, tim is the measured air temperature, t¯_m is the mean of measured air temperature values and n is the number of samples obtained from field measurement.

In the adobe house, the measured and simulated air temperature values are presented in Figure 7. The average measured air temperature is 30.81 °C, while the average simulated air temperature is 28.69 °C, resulting in a percentage difference of 7.13%. The calculated NMBE and CV(RMSE) values are -7.15 and 2.02, respectively.

In the concrete house, the measured and simulated air temperature values are presented in Figure 8. The average measured air temperature is 31.86 °C, while the average simulated air temperature is 34.30 °C, resulting in a percentage difference of 7.37%. The calculated NMBE and CV(RMSE) values are 7.98 and 8.16, respectively.

In the stone house, the measured and simulated air temperature values are presented in Figure 9. The average measured air temperature is 31.60 °C, while the average simulated air temperature is 33.51 °C, resulting in a percentage difference of 5.86%. The calculated NMBE and CV(RMSE) values are 6.31 and 6.33, respectively.

According to ASHRAE Guideline 14-2014 (ASHRAE, 2014), a model is considered calibrated if the NMBE value falls between ±10% and the CV(RMSE) is within ±30% when using hourly data. The NMBE and CV(RMSE) values obtained from the validation process are well within these acceptable limits, confirming the reliability of IDA-ICE in accurately predicting thermal comfort within the three models.

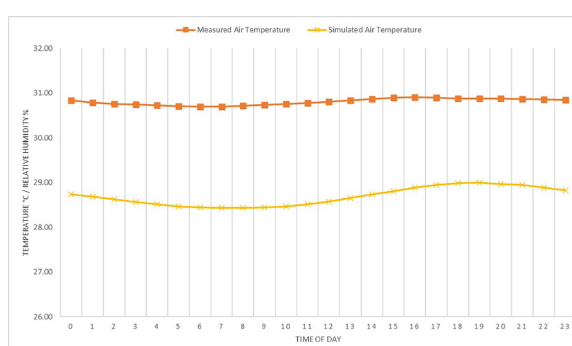

Figure (7). Comparison of air temperature and relative humidity from field measurement and simulation in the adobe house.

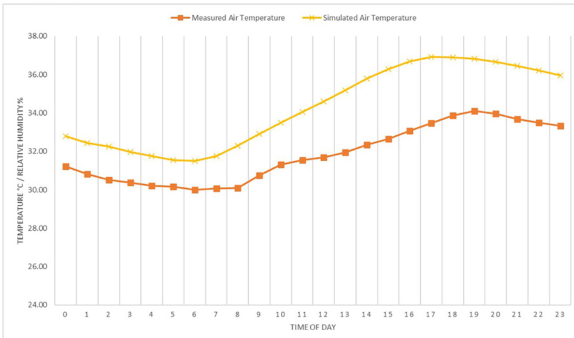

Figure (8). Comparison of air temperature from field measurements and simulation in the concrete house

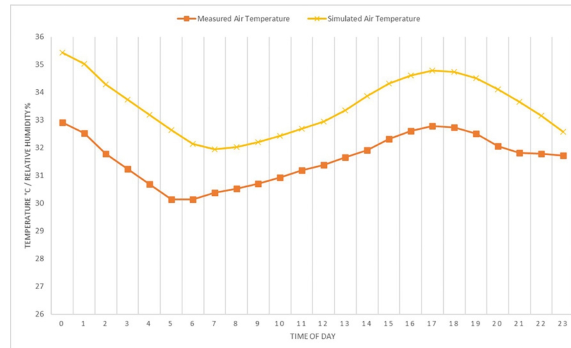

Figure (9). Comparison of air temperature from field measurements and simulation in the stone house.

4.3.4 Tested Passive Strategies

The passive strategies employed in this study were selected based on recommendations provided by the Climate Consultant and the Ecotect weather tool. These recommendations were derived from an extensive analysis of the climatic data for Seiyun. The passive design measures identified as having the most significant impact on thermal comfort were chosen for implementation in this study, as detailed in Table 6.

4.3.5 Modeling Approach

To evaluate the impact of building materials and passive design strategies on thermal comfort during summer, the summer solstice (June 21st) was selected as the reference day for simulation. Each passive design strategy was applied individually to the three base models to assess its effect. Operative temperature was used as the key parameter for analyzing the thermal environment of each case. Operative temperature (t_o) is calculated from air temperature (t_(a)), mean radiant temperature (t_r)

Table (6). Tested passive design strategies

Strategy No.	Strategy Description	Details
S1	Window overhangs and fins	Based on sun chart as demonstrated in **Error! Reference source not found.**.
S2	Optimum orientation	Rotate 177.5° clockwise from north.
S3	Opening windows	When indoor air temperature exceeds 27°C
S4	Convert zone 4 to a shaded courtyard	All doors around the courtyard were kept opened (**Error! Reference source not found.**).
S5	50% Smaller windows	
S6	Use double-glazed windows	
S7	Insulating the roof and external walls	Using 50 mm thick rockwool Insulation Slabs with Thermal conductivity of 0.036 W/mK as shown in **Error! Reference source not found.**.
S8	Increasing roof height by 1.5 m	
S9	25 % thicker outer walls	
S10	External window shading	Using drop arm awning as shading devices for windows (**Error! Reference source not found.**). Awnings open when the incident solar radiation exceeds 100 W/m^2 on the external surface of windows.
S11	Combining S1, S3 and S5	
S12	Combining S3, S5 and S10	

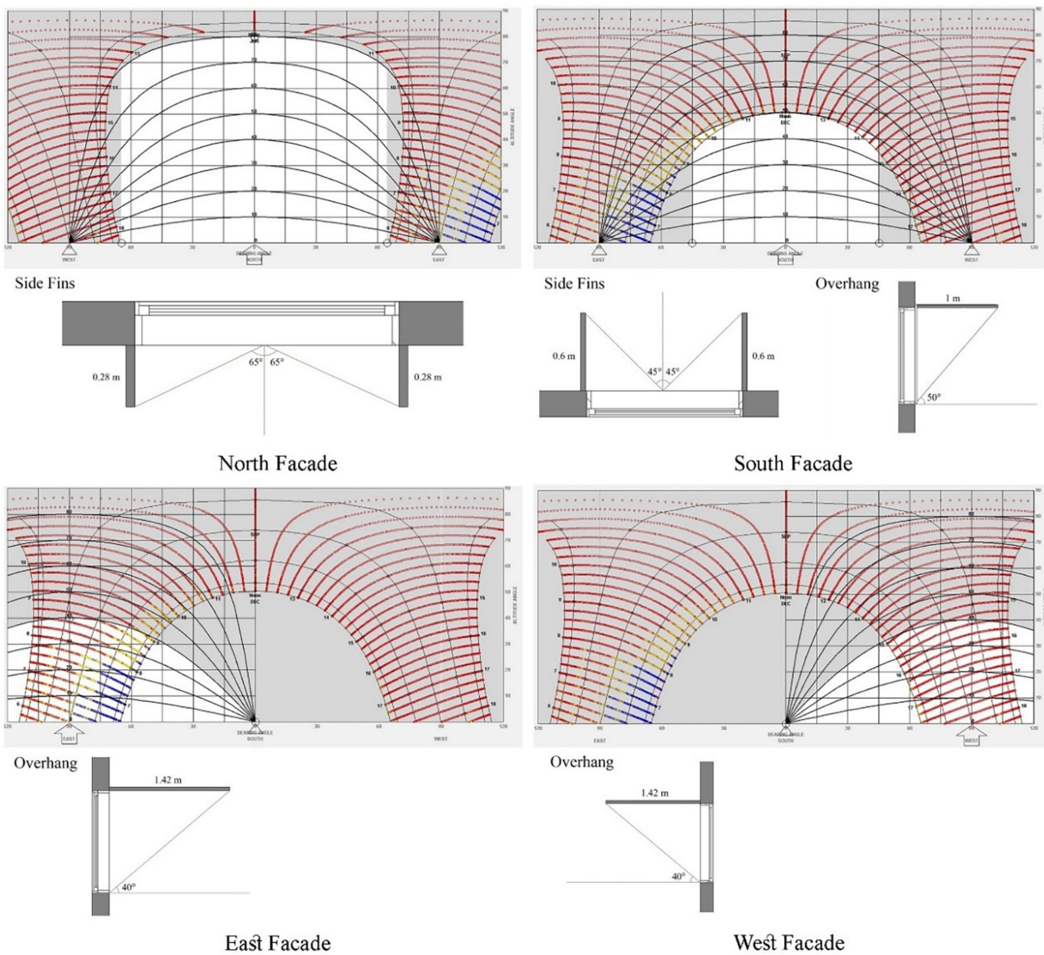

Figure (10). Design of overhangs and fins for windows on the four facades

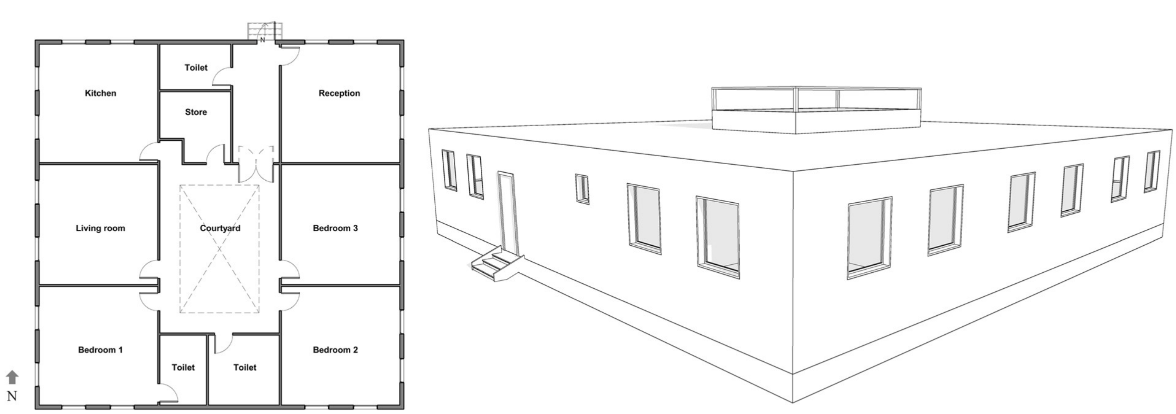

Figure (11). Location of the central courtyard

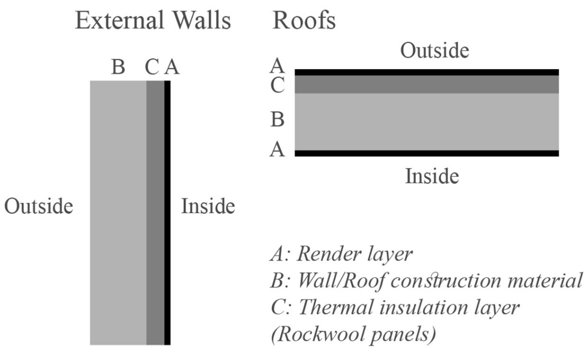

Figure (12). Thermal insulation layers in external walls and roof

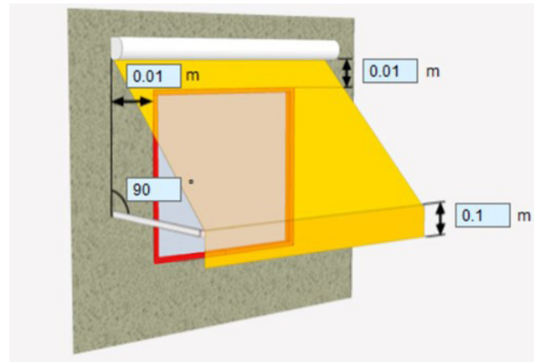

Figure (13). Used a model of a drop arm awning to shade windows. Source: IDA ICE 4.8 SP1

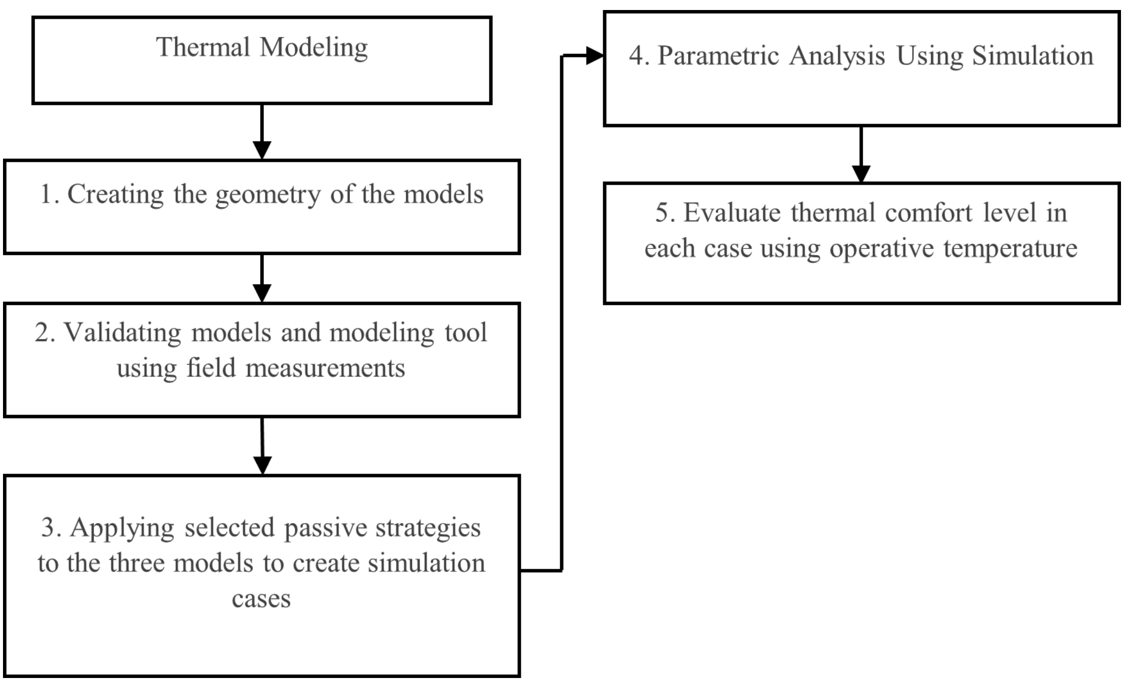

Figure (14). Flowchart of the modeling process

and air velocity (v) (Equation 3) (ISO, 1998). This makes it a more comprehensive measure of thermal comfort compared to air temperature alone.

$$t_o = \frac{t_r + \left(t_a \times \sqrt{10v}\right)}{1 + \sqrt{10v}} \qquad \text{Equation 3}$$

The south-facing bedroom 1 (Zone 3) was selected for thermal modeling, as shown in Figure 6. The modeling process involves creating the geometry of the models, validating them, applying passive design strategies, conducting the simulation, and evaluating thermal comfort in the results, as demonstrated in Figure 14.

5. Results and Discussion

In this section, graphical and numerical analyses were employed to demonstrate the effectiveness of a combination of passive design strategies in three types of local residential buildings. Each graph illustrates the operative temperature inside the simulated zone (Zone 3) under two conditions: (1) the base model without any passive strategies, and (2) the model with each strategy applied individually. Thermal comfort levels in the graphs were defined based on the ranges established by the European Standard EN 15251:2007 (CEN, 2007). This analysis was conducted for all three models on the summer solstice (June 21st). The average and standard deviation (SD) of the operative temperature were calculated for each case. Standard deviation was used as an indicator of the stability of the operative temperature throughout the simulation period. To assess and compare the significance of operative temperature differences between the cases, a One-way ANOVA test and LSD Post Hoc analysis were performed with a significance level of 0.05.

5.1 Model 1 (M1)

Figure 15 illustrates the operative temperature in zone 3 of the adobe house on the summer solstice. Although most simulated cases remain outside the comfort zone, the majority are closer to the upper comfort band than the base model, indicating a reduction in indoor temperature due to the implementation of passive measures. Notably, cases S3, S11, and S12 fall within the acceptable comfort zone between 4:00 AM and 10:00 AM. Among these, S3 achieves good comfort conditions between 6:00 AM and 9:00 AM. However, cases S11 and S12 exhibit the most stable operative temperatures and remain closest to the comfort zone throughout the day, making them the most effective passive strategies for improving thermal comfort.

Table 7 presents the mean and standard deviation of the operative temperature in model 1 for each case. The results indicate that cases S11 and S12 achieved the lowest internal operative temperatures, making them the most effective in reducing heat indoors. Conversely, case S5 exhibited the highest temperature stability throughout the day, suggesting that it provides the most consistent thermal conditions.

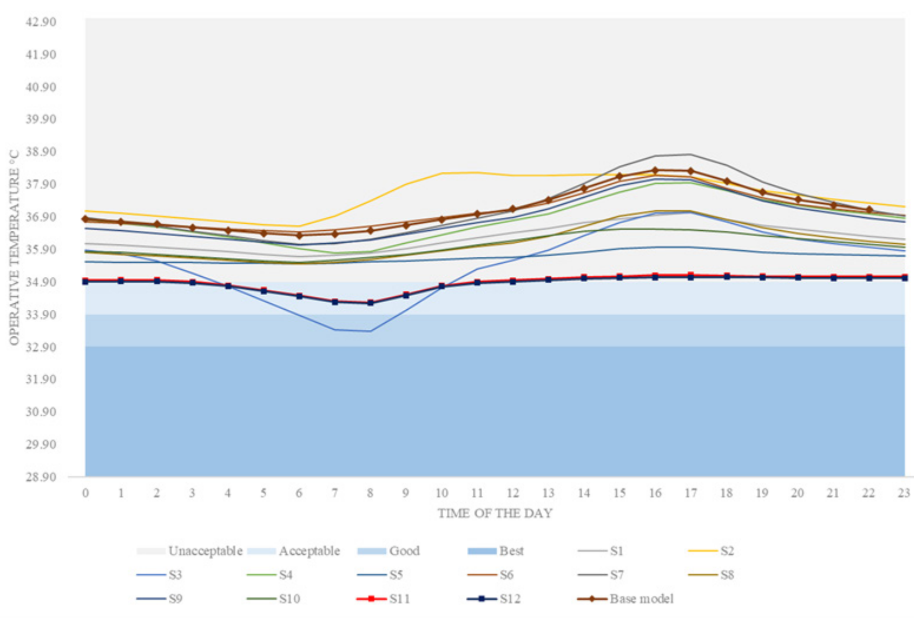

Figure (15). Operative temperature inside zone 3 (Bedroom 1) of model 1 in summer solstice

Table (7). Mean and standard deviation of the operative temperature inside zone 3 (Bedroom 1) of model 1 in summer solstice

Model	Base Model	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
Mean (°C)	37.12	36.26	37.53	35.49	36.81	35.66	37.08	37.14	36.09	36.85	36.01	34.88	34.84
SD	0.63	0.42	0.59	1.09	0.65	0.17	0.54	0.87	0.52	0.64	0.34	0.25	0.24

The ANOVA test results ($F = 54.17$, $P < 0.0005$) confirm that operative temperature differences among the tested cases are statistically significant. The LSD Post Hoc analysis further indicates that cases S3, S11, and S12 show significant improvements in thermal performance compared to the base model ($P < 0.05$). However, the difference between S11 and S12 is not statistically significant ($P > 0.05$). Based on these findings, implementing passive design strategies S11 and S12 is strongly recommended for adobe houses during summer, as they effectively lower operative temperature while maintaining stability throughout the day.

5.2 Model 2 (M2)

Figure 16 demonstrates that passive design strategies have a noticeable impact on reducing the internal operative temperature in the concrete house. Although the base model remains outside the comfort zone throughout the day, case S3 achieves comfort from 6:00 to 10:00 AM. The application of passive strategies delays the rise in temperature and moderates peak temperatures. While the base model reaches a maximum temperature of 41.1°C, cases S3, S11, and S12 show improved performance with lower peak temperatures of 40.3°C, 39.4°C, and 39.4°C, respectively. The stability and proximity to the upper comfort limit in cases S11 and S12 make them the most effective strategies for improving thermal comfort in concrete houses.

Table 8 highlights that case S3 resulted in the lowest internal operative temperature among the tested cases, while case S7 exhibited the most stable temperature throughout the day.

The ANOVA test confirms significant differences in operative temperature across all cases ($F = 5.32$, $P < 0.0005$). However, LSD Post Hoc analysis suggests no significant differences between cases S1, S2, S4-S10, and the base model ($P > 0.05$). On the other hand, cases S3, S11, and S12 demonstrated significantly lower operative

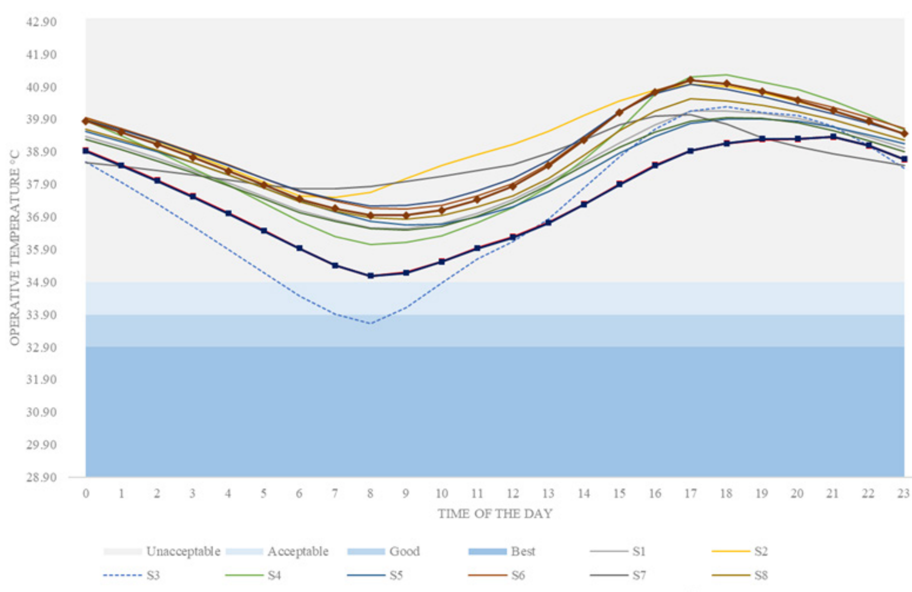

Figure (16). Operative temperature inside zone 3 (Bedroom 1) of model 2 in summer solstice

Table (8). Mean and standard deviation of the operative temperature inside zone 3 (Bedroom 1) of model 2 in summer solstice

Model	Base Model	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
Mean (°C)	38.99	38.46	39.35	37.29	38.68	38.44	39.10	38.66	38.71	39.07	38.34	37.51	37.50
SD	1.40	1.25	1.11	2.21	1.79	1.17	1.34	0.71	1.27	1.24	1.20	1.48	1.49

temperatures compared to the other cases (P < 0.05), but no notable difference was found among these three cases themselves (P > 0.05). As a result, passive design strategies S11 and S12 are recommended for concrete houses in summer due to their effectiveness in maintaining a lower and more stable indoor operative temperature.

5.3 Model 3 (M3)

Figure 17 illustrates that while none of the tested cases fully achieve thermal comfort, case S3 maintains an operative temperature within the comfort zone between 6 and 10 am. Additionally, cases S3, S11, and S12 show improved thermal conditions compared to the base model, indicating the effectiveness of passive design strategies. All cases experience an increase in operative temperature after sunrise. However, at the peak temperature recorded by the base model (40.8°C), cases S3, S11, and S12 exhibit lower maximum temperatures of 39.7°C, 39.1°C, and 38.9°C, respectively. The lowest temperature among all cases occurs in S3 at 8 am.

Table 9 shows that while case S3 resulted in the coolest internal operative temperature, case S7 provided the most stable temperature throughout the day. This suggests that S3 is more effective in reducing peak temperatures, whereas S7 helps maintain a more consistent indoor thermal environment.

The results from the ANOVA test indicate that there are significant differences in the operative temperature between the first ten cases (S1 to S10) and the last three cases (S3, S11, and S12). This suggests that applying the passive design strategies in cases S3, S11, and S12 had a more pronounced effect on reducing the operative temperature compared to the other strategies. Further analysis through the LSD Post Hoc test reveals that there are no significant differences between cases S3, S11, and S12 in terms of operative temperature.

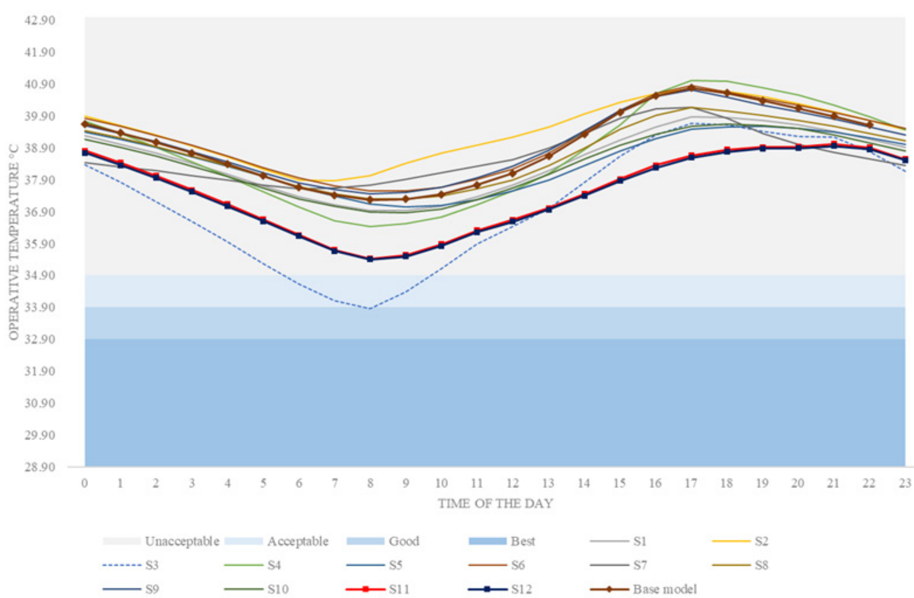

Figure (17). Operative temperature inside zone 3 (Bedroom 1) of model 3 in the summer solstice

Table (9). Mean and standard deviation of the operative temperature inside zone 3 (Bedroom 1) of model 3 in the summer solstice

Model	Base Model	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
Mean (°C)	38.98	38.50	39.41	37.19	38.76	38.48	39.15	38.61	38.74	39.04	38.38	37.54	37.48
SD	1.16	1.01	0.92	1.92	1.56	0.90	1.09	0.80	0.97	1.05	0.96	1.24	1.23

Table (10). The best selected passive design strategies for the summer solstice

	Simulated Cases												
Simulation Models	Base Model	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
M1												X	X
M2												X	X
M3												X	X
Decision												**X**	**X**

This suggests that these strategies are equally effective in providing lower operative temperatures and maintaining better stability throughout the day, making them ideal recommendations for enhancing thermal comfort in the stone house during the summer months. Therefore, it is recommended to use passive design strategies S11 and S12 for the stone house as they not only result in lower operative temperatures but also ensure a higher level of stability throughout the day, leading to a more comfortable indoor environment.

Table 10 presents the best passive design strategies for each building model based on the results from the summer solstice simulation. According to the thermal comfort and statistical analysis, the strategies S11 and S12 consistently performed well across all three models (adobe, concrete, and stone houses). These strategies not only brought the internal operative temperatures closer to the comfort zone but also exhibited the least temperature variation throughout the day, ensuring a stable indoor environment.

6. Conclusion

This study is among the few research efforts that examine the impact of building materials and passive design strategies on the thermal comfort of local residential buildings in the Hadramout region, Yemen. The primary objective of this research is to identify the local housing typology that offers a higher level of thermal comfort without relying on mechanical ventilation. Furthermore, this study investigates the influence of implementing passive design strategies on the thermal comfort of various types of local dwellings. To achieve the study's objectives, climatic data from Seiyun were analyzed to assess the area's thermal conditions and determine the most effective sustainable responses and passive design strategies. Subsequently, on-site air temperature measurements were conducted in three selected case studies representing the most prevalent dwelling types in Seiyun: adobe, concrete, and stone houses. The data obtained from these measurements were utilized to validate the simulation tool and models. Following the validation process, a parametric analysis was performed using thermal simulation. IDA ICE software was employed to model the thermal environment within the three dwelling types. Various passive design strategies were applied to each model to evaluate their effectiveness in enhancing thermal comfort without the use of active cooling. The results of this analysis provided insights into the thermal performance of each housing type and demonstrated the impact of passive design strategies on indoor thermal comfort.

The findings of this study can be summarized as follows:

- The internal operative temperature in the adobe house is lower by 1.87 °C (4.79%) and 1.86 °C (4.77%) compared to the concrete and stone houses, respectively.
- The indoor temperature in the adobe house exhibits greater stability compared to the concrete and stone houses. The variations between the recorded maximum and minimum internal temperatures are 2.1°C for the adobe house, 4.15°C for the concrete house, and 5.07°C for the stone house.
- The use of passive design strategies S11 and S12 is recommended for adobe, concrete, and stone houses, as they have been shown to be highly effective in reducing operative temperature while maintaining high thermal stability throughout the day.

Figure 18 presents a comparison of operative temperatures between the optimal simulated cases and the base models of the studied house types. The graph those made of concrete and stone, highlighting the superior thermal comfort performance of adobe

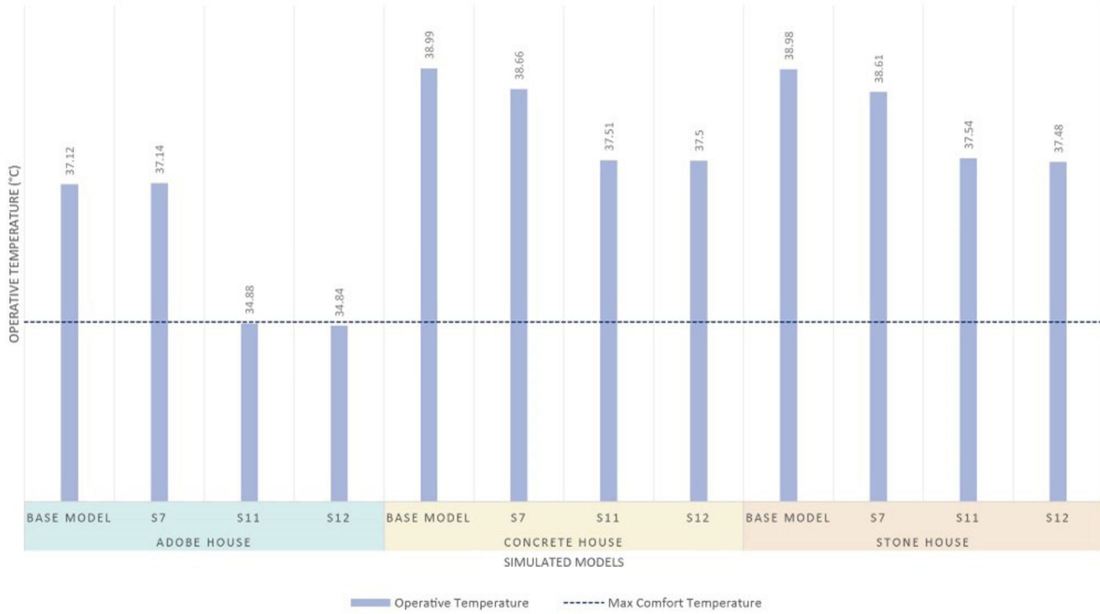

Figure (18). Comparison of operative temperature between adobe, concrete, and stone houses in summer

houses. The adobe house maintained a thermally comfortable indoor environment without reliance on mechanical ventilation or additional thermal insulation.

The findings of this study can identifying the most effective passive design strategies for residential buildings in Wadi Hadramout. Additionally, the study emphasizes the superiority of adobe as a building material in terms of indoor thermal comfort compared to concrete and stone. However, it is important to acknowledge that this research was conducted solely for the summer solstice and focused on three types of local residential buildings due to time and cost constraints. Therefore, future studies should extend the analysis to commercial and educational buildings over longer periods to achieve a more comprehensive comparison between simulation results and real-world conditions.

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تقييم مستوى الراحة الحرارية وتأثير استراتيجيات التصميم السلبي في المباني السكنية المحلية غير المكيفة في وادي حضرموت «اليمن»

عمر الحبشي

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قدم للنشر في ١٥/ ٧/ ١٤٤٦ هـ؛ وقبل للنشر في ٢٢/ ١٠/ ١٤٤٦ هـ.

ملخص البحث. في الدول الأقل نمواً مثل اليمن، يؤدي النقص الحاد في الطاقة الكهربائية إلى الحد من استخدام أجهزة التكييف لتوفير الراحة الحرارية للسكان. في محافظة حضرموت شرق اليمن، بدأت المنازل الطينية التقليدية التي تكيفت مع المناخ الحار للمنطقة لمئات السنين بالتلاشي تدريجياً حيث يتم استبدالها بمبانٍ حديثة لا تراعي الظروف المناخية للمنطقة وتعتمد كلياً على التهوية الميكانيكية لتوفير الراحة الحرارية بخاصة خلال فصل الصيف. تقارن هذه الدراسة الأداء الحراري للمنازل الطينية والخرسانية والحجرية في وادي حضرموت خلال فصل الصيف باستخدام قياسات ميدانية ونماذج محاكاة حاسوبية. بالإضافة إلى ذلك، تبحث الدراسة في التأثير المحتمل لاستراتيجيات التصميم السلبي في تحسين مستوى الراحة الحرارية داخل هذه المنازل. أظهرت النتائج أن درجات الحرارة الداخلية كانت أقل وأكثر استقراراً على مدار اليوم داخل المنزل الطيني مقارنة بالمنازل الخرسانية والحجرية. كما تبين أن بعض استراتيجيات التصميم السلبي لها تأثير ملحوظ في تحسين الأداء الحراري للمنازل التي تم اختبارها.

الكلمات المفتاحية: الراحة الحرارية، استراتيجيات التصميم السلبي، المحاكاة، المباني السكنية المحلية.