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SERVICES FOR SCIENCE AND EDUCATION

Evaluating the Influence of Passive Design Strategies on Cooling Energy Demand in Local Adobe, Stone and Concrete Dwellings in Wadi Hadramout, Yemen

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ABSTRACT

Vernacular architecture is the outcome of hundreds of years of optimization to provide comfortable dwellings and adapt with local climate conditions using available resources and construction techniques. Traditional buildings use passive cooling measures to provide thermal comfort without mechanical systems. In least developed countries like Yemen, severe power deficiency and consequent blackouts limit the use of air conditioning to provide indoor thermal comfort. In Hadramout province east of Yemen, climate responsive adobe dwellings are fading-out gradually and being replaced with modern buildings that neglect local climate and depend entirely on mechanical ventilation to provide comfort specially in summer. This paper investigates energy efficiency and the potential influence of passive design strategies in reducing energy demand for cooling in adobe, concrete and stone local houses in Wadi Hadramout during summer. The results indicated that adobe house requires 51.77% and 51.29% lower energy for cooling compared to concrete and stone houses respectively when refrigerated cooling is used. In case of the evaporative Cooling, adobe house requires 66.03% and 65.82% lower energy compared to concrete and stone houses respectively. Furthermore, the results showed that some passive design strategies have a remarkable impact on improving energy efficiency of the tested houses.

Keywords: Local Houses, Hadramout, Passive Design Strategies, Energy Demand, Simulation.

INTRODUCTION

Fast growth of modern life and the rapid technological advancement led to an increasing demand for energy. Energy demand has increased significantly during the 20 years period between 1984-2004 by 43% with an average yearly growth of 2% [1]. Buildings consume more than 60% of the total energy utilization globally, 20-40% of this energy is consumed in the residential buildings [2]. Moreover, energy consumption in buildings will keep growing by 1.5% per year on average until 2030 according to The U.S. Energy Information Administration [3].

In Yemen, electricity network is out of date and unable to provide sufficient power supplies to the people. Despite having one of the largest populations in the region, Yemen is one of the lowest energy producers in the Middle East. Only 40% of the population of Yemen has access to the electricity according to the world bank [4]. However, even those who have access to the

electricity are suffering frequent power blackouts. Electricity deficit become worse as the Arab spring started affecting the country in 2011, power blackout hours has increased significantly as result of continuous vandalism attacks on energy infrastructure and severe shortage of fuel supplies for the power plants [5]. Most of people living in rural areas can't access to the electricity network and depend on private generators often powered by diesel fuel [6]. However, Fuel prices have surged more than 300% on average as recently as March 2021 since the start of the conflict according to the World Relief organization [7]. This could leave millions of people in rural areas unable to afford fuel and thus without any source of power.

Energy consumption for cooling has increased significantly during the last few decades. This rapid increase highlighted concerns over the escalated depletion of natural resources and the other environmental issues such as global warming. In hot climate zones, most of the energy consumed in buildings is used for air conditioning with traditional HVAC systems. These systems consume 70% of the total energy demand of buildings in the Middle East [8]. In the period between 1990-2000, energy required for cooling purposes has increased significantly and reached 14.6% per annum due to the growing comfort requirements during summer and the decrease of domestic cooling systems' prices [9].

Many researches indicated that using passive design measures have a significant impact on the energy efficiency and thermal comfort in buildings. Various studies discussed the application of passive strategies to reduce energy consumption in buildings [10], [11]. Implementation of passive design strategies can involve several aspects of building such as selection of building materials, orientation of windows and facades, using of insulation and window-to-wall ratio [12], [13]. Moreover, design of shading devices and natural ventilation mechanisms are significant practices of the passive design [14], [15]. Fernandez-Antolin et al. [16] investigated the energy efficiency of residential buildings located in different climatic zones of Spain by applying different passive design strategies using simulation and parametric analysis. Results showed that passive measures such as North to South orientation, applying maximum prescribe U-value of the external walls and 20% or less of window-to-wall ratio provided the optimal energy efficiency for residential buildings.

Many types of cooling systems are used to provide a comfortable thermal environment inside buildings. Selection of the cooling systems should consider several factors such as energy demand, performance and environmental impact. Evaporative cooling is one alternate system for the refrigerated cooling that can be used for air conditioning purposes in residential and industrial sectors. Evaporative cooling units consume only 25% on the energy required for operating refrigerated cooling units [17]. Therefore, turning toward evaporative cooling systems is a promising solution to reduce cooling energy demand for buildings in hot and dry climates.

Evaporative cooling systems are simple to implement and inexpensive to operate. Thus, this cooling technique been used widely for a long time to achieve thermal comfort [18]. Today, many hybrid ventilation systems that combine evaporative ventilation with other ventilation techniques were emerged. These hybrid systems are more energy efficient and adequate to insure specific comfort requirements for different indoor spaces. The concept of the

evaporative cooling is reducing temperature of the air by increasing its humidity. That is to say, cooling air by increasing its content of water vapor. When air is hot and dry, its capability of absorbing water vapor increases. In this case, water transfers to vapor owing to the latent heat of the air. On the other hand, air temperature drops and its humidity increases. Evaporative cooling is more efficient in hot and dry climates where air has higher ability to absorb water vapor and thus become cooler. Evaporative cooling system can satisfy comfort requirements of the occupants as long as humidity remains between 60 and 70% [2]. In contrast, this cooling system is not sufficient in humid climates as air has a limited capacity to absorb mor water vapor.

Evaporative cooling can be classified as direct and indirect according to the type on interaction between air and water as shown in Figure 1. In direct evaporative cooling, air is passed through wet pads to be cooled by evaporation before being supplied to the room. The possible downside of this system is that air becomes more humid as it passes through the water, this can cause a feeling of discomfort for some occupants. On the other hand, indirect evaporative cooling can limit the undesirable air humidity by using two separated channels to prevent moisture from being increased in the air stream heading to the room. However, the cooling efficiency of the indirect evaporative systems in much lower the direct evaporative ones.

Using the evaporative cooling can result in a significant drop down of dry bulb temperature, this reduction can reach up to 10-12 °C depending on the humidity level of the air outside [19]. Ibrahim et al. [20] stated that using 0.08-0.1 m/s air velocity along with 30% increase of humidity can make a drop of 6-8 °C in dry bulb temperature. Another study by Szokolay [21] concluded that using direct evaporative cooling cannot result in more than 11 °C drop in dry bulb temperature.

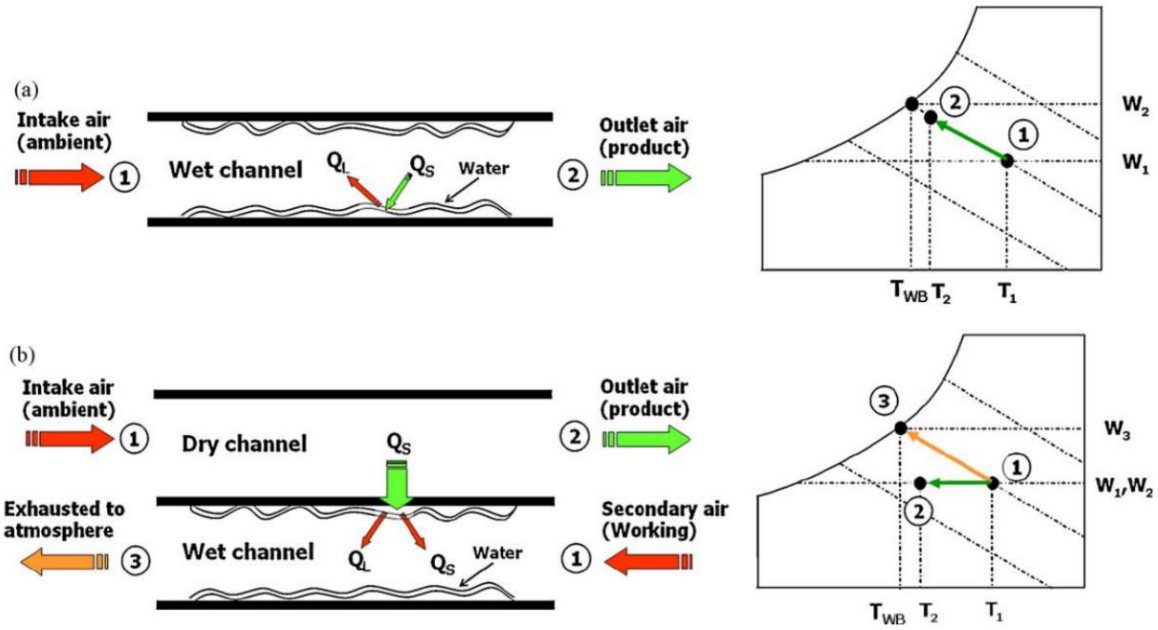


Figure 1 (a) Direct evaporative cooling and (b) indirect evaporative cooling. Source: [2]

Thermal insulation has a significant impact on optimizing energy efficiency and improving thermal comfort in buildings. Insulated buildings consume 20-40% less energy compared to the non-insulated buildings [22]–[24]. Kolaitis et al. [25] Compared the impact of internal and external insulation systems on the energy efficiency of residential buildings using numerical simulation. They found that a significant decrease of energy demand was obtained using both internal and external insulation systems. They also indicated that external insulation performs 8% better than the internal insulation.

The literature review shows that there is a limited number of researches related to the energy efficiency of local domestic buildings in Hadramout. Algifri et al. [26] analyzed thermal behavior of a traditional adobe house and modern concrete house located in the two Yemeni cities of Seiyun and Lahaj. They found that the traditional adobe house shows better thermal appropriateness and consumes less energy compared to the modern concrete house. Al-Motawakel et al. [27] studied the average diurnal rate oh heat loss through several wall types of traditional and modern Yemeni houses. They indicated that heat loss rate is larger in modern wall types compared to the traditional wall types. Aforementioned studies focused on comparing the energy efficiency of traditional and modern houses in Hadramout and Yemen in general. However, there is still a lack of research that highlight the influence of passive design measures on energy efficiency of local dwellings in Hadramout region. The aim of this research is to emphasize the best local house type in terms of energy efficiency and investigate the potential influence of passive design strategies in reducing energy demand for cooling in local house types of Wadi Hadramout, Yemen.

Research Problem

Power deficit becomes worse in summer as energy demand for cooling purpose surges. This continuous power crisis causes a lot of pain for inhabitants particularly those living in hot regions such as Wadi Hadramout. This is due to the fact that majority of modern houses were designed without considering local climatic conditions and totally rely on the mechanical ventilation for cooling in summer. This situation emphasizes the importance of incorporating passive and climate responsive strategies in design of residential buildings.

In the past, vernacular adobe buildings in wadi Hadramout adapted to the local climatic conditions in a way that provided comfort needs for its inhabitants without using any mechanical means. Modern adobe dwellings came as a result of trial and error processes conducted by our ancestors for hundreds of years to provide comfortable shelters. Therefore, these houses incorporate variety of passive cooling methods such as shading devices, high thermal mass, and natural ventilation. However, with the emerge of new building materials, Traditional materials including adobe started to be neglected despite their many environmental and economic advantages [28].

Research Aim and Objectives

The aim of this research is to evaluate the energy efficiency of local adobe houses in Hadramout in terms of energy demand for cooling in summer.

To achieve this aim, the following objectives should be fulfilled:

1. Comparing the energy required for cooling in local adobe, concrete and stone houses.
2. Evaluating the potential influence of applying selected passive design strategies on the energy consumption of the adobe, concrete and stone houses.

METHODOLOGY

Research methodology of this study includes climatic analysis, simulation and parametric analysis. The aim of climatic analysis is to understand the impact of the climate on the internal environment and to determine the most appropriate passive design methods to be used under the existing climatic conditions. This study utilized simulation to assess cooling energy demand of three types of local houses. Parametric analysis was uses to investigate the influence of selected passive design measures on the energy demand for cooling in summer. Finally, tested dwellings and passive measures were then ranked based on their influence on energy consumption of the local houses. Figure 2 demonstrates the framework of this study.

Seiyun city was selected to be the area of this study for two main reasons:

1. Being the capital of Wadi Hadramout for a long time made this city the center of the building revolution in the valley where different modern and traditional building material and techniques exist.
2. Availability of climatic date of Seiyun, as the only weather station in Wadi Hadramout exists in Seiyun international airport.

Climatic Features and Traditional Houses in Seiyun

Seiyun features a tropical climate with hot summer and moderate to cold winter, temperature ranges between 6 - 28 °C in winter and 26 - 42 °C in summer with a low precipitation rate mostly in July and August. Furthermore, there are significant differences in air temperature between day and night as demonstrated in
Figure **3** which represents 30 years of historical weather data for the city of Seiyun.

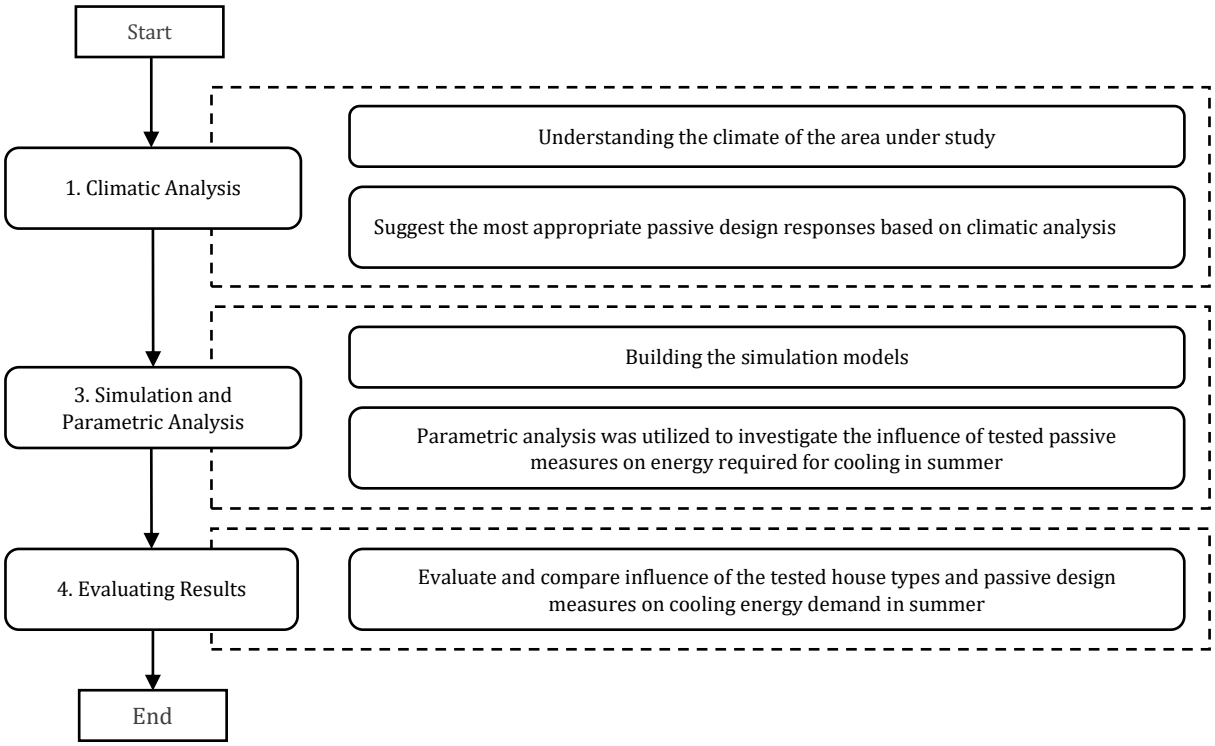


Figure 2 Methodology steps of the study

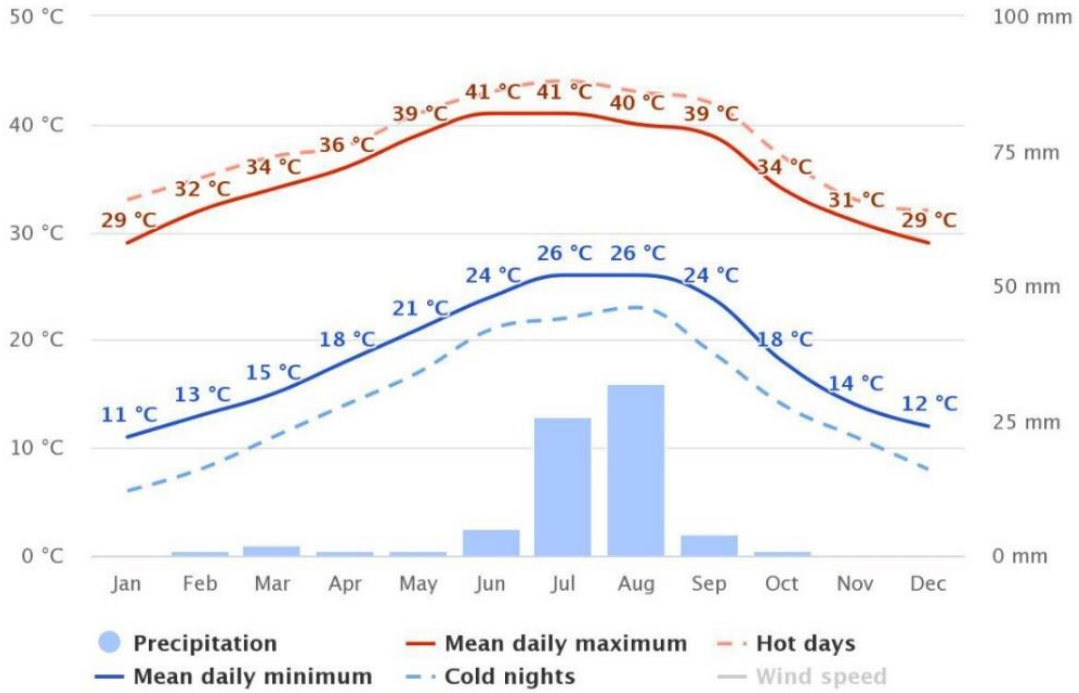


Figure 3 Historical weather data for Seiyun during the past 30 years. Source: [29]

Psychrometric chart is a very useful design tool to create a comfortable indoor environment by recommending a set of design strategies applies specifically to a particular climate. Figure 4 shows the impact of applying the design guidelines recommended by Climate Consultant 6.0 on

the comfort zone of a residential scale building located within Seiyun's climatic region. The chart indicated that occupants will feel comfort in 99.8% of the displayed hours after applying the recommended design strategies. The figure indicates that evaporative cooling, shading of windows and high thermal mass are the most effective passive design strategies in improving thermal comfort in order.

Vernacular houses in Wadi Hadramout are built using adobe brick which is known as "madar" locally. The "madar" is composed of mud mixed with water and chopped straw, the mixture then poured in wooden frames with different sizes and dried with the sun. Thickness of walls vary from the ground floor to the top level. Wall thickness in the ground level can reach up to one meter, this thickness is reduced gradually as the building raise up to about 20-30 cm in the upper level [30].

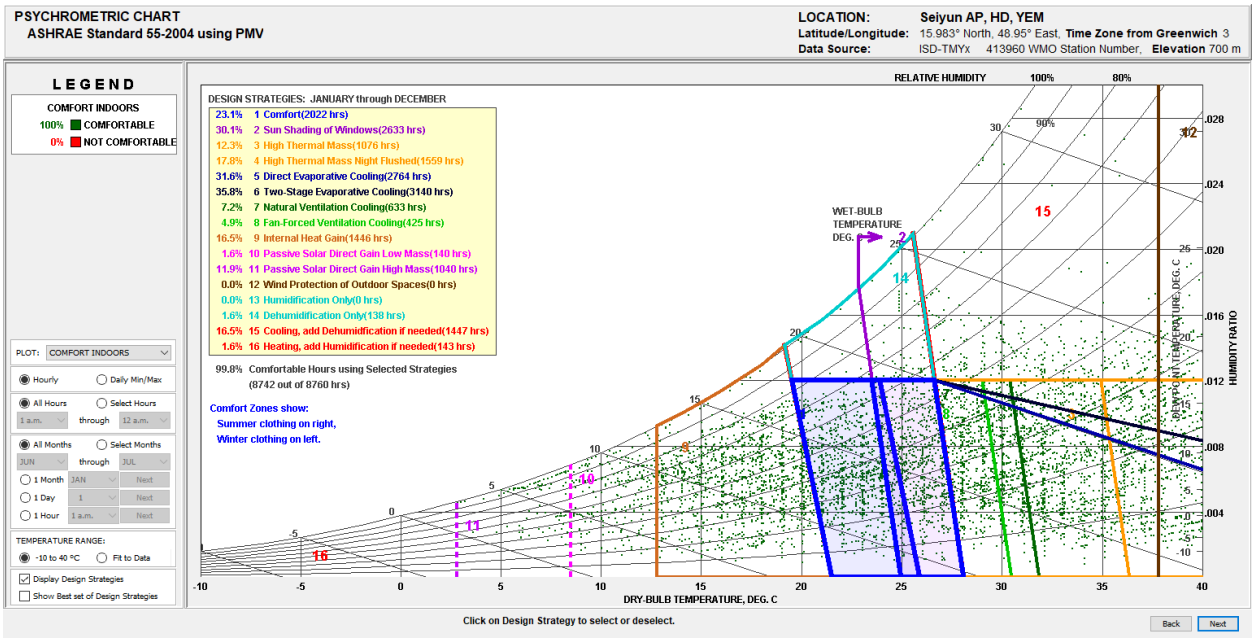


Figure 4 Psychrometric chart and comfort ratio for Seiyun after applying the recommended design strategies, by the author using climate consultant software

Roof in vernacular adobe houses of Wadi Hadramout is constructed in a way to mitigate the impact of direct sun on the internal temperature of the house. Roof construction incorporate multiple layers as following:

1. Timber joists made of trunks of trees.
2. Layer crushed mud brick covering the joists.
3. Layer of soil covering the crushed bricks.
4. 2 layers of mud plaster.
5. 2 layers of lime plaster which known locally as (norah).

Roof needs around three months to dry after construction is completed, being refined and whited with lime. Thermal and Energy Modeling.

Building the Simulation Models

The proposed base model for the simulation was divided into several separated zones as shown in Figure 5. Only seven of these zones are occupied all the time by one occupant for each zone. These zones are kitchen, living room, bedroom 1, bedroom2, bedroom 3, reception room and hall. Only the occupied zones will be considered for assessing cooling loads during the simulation. This model was built in a way that all occupied zones have the same area and arranged around one central zone. This will allow implementing several passive design strategies on the model such as central courtyard, in addition to maintain the maximum connectivity between the indoor and outdoor environments.

Based on the base model, three simulation models representing the most common three dwelling types in Wadi Hadramout were developed. These models are the adobe house (M1), the concrete House (M2) and stone house (M3). The three models were built using IDA ICE with the same layout of the base model shown in Figure 5. However, different thermophysical parameters were used for each envelop, tables 1, 2 and 3 demonstrate the thermophysical properties of the models M1, M2 and M3 respectively.

Typical meteorological year (TMY) weather data of Seiyun which represents annual 8760 hours was used as reference climate file in IDA-ICE.

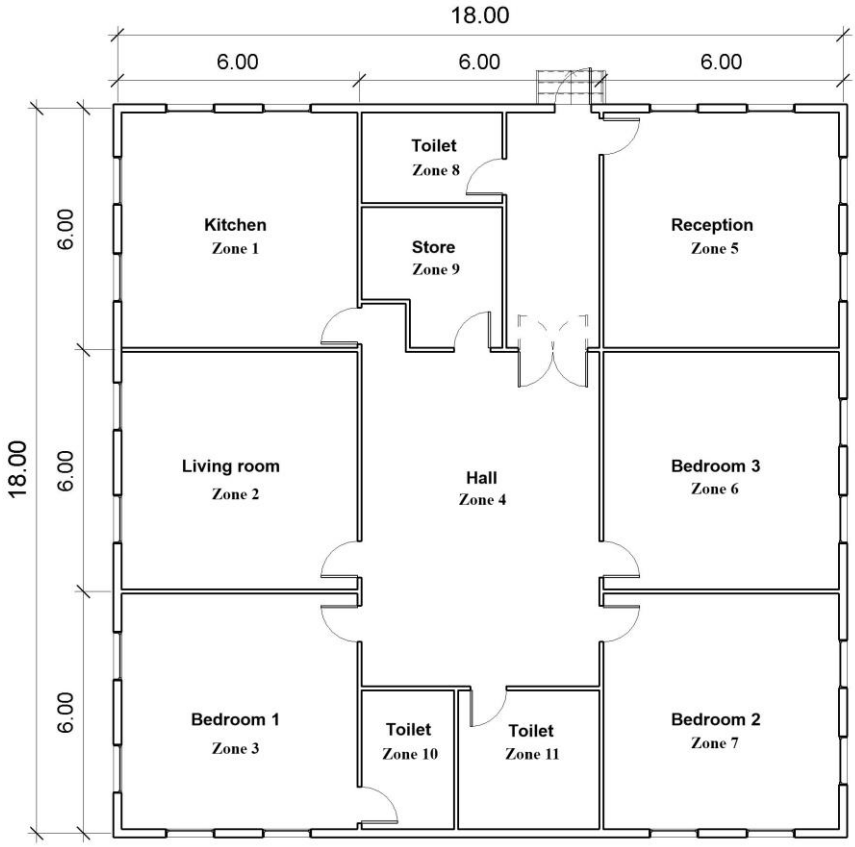


Figure 5 Layout and zones of the base model

Table 1 Thermophysical parameters of the simulated house (M1)

Building element	Material	Thickness (m)	Thermal conductivity (W/mk)	Density (kg/m^3)	Specific heat (J/kg K)	U-value (W/m^{2}K)
External Walls	Adobe	0.45	0.44	1403	1450	1.513
	Gypsum Plaster	0.012	0.22	970	1090	
Internal Walls	Gypsum Plaster	0.012	0.22	970	1090	1.33
	Adobe	0.45	1200	1381	1000	
	Gypsum Plaster	0.012	0.22	970	1090	
Ground Floor	Cement Plaster	0.012	1.7	2300	880	2.619
	Soil	0.2	1.0	1500	800	
First Floor/Roof	Cement Plaster	0.012	1.7	2300	880	0.677
	Clay or Silt	0.25	1.5	1600	1875	
	Branches over a Steel Joists	0.15	0.14	500	2300	
	Gypsum Plaster	0.012	0.22	970	1090	
Doors	Wood	0.03	0.14	500	2300	2.602
Windows	Wood	0.023	0.14	500	2300	2.990

Table 2 Thermophysical parameters of the simulated house (M2)

Building element	Material	Thickness (m)	Thermal conductivity (W/mk)	Density (kg/m^3)	Specific heat (J/kg K)	U-value (W/m^{2}K)
External Walls	Dense Concrete Brick	0.2	1.31	1762	840	2.84
	Gypsum Plaster	0.012	0.22	970	1090	
Internal Walls	Gypsum Plaster	0.012	0.22	970	1090	2.63
	Dense Concrete Brick	0.2	1.31	1762	840	
	Gypsum Plaster	0.012	0.22	970	1090	
Ground Floor	Ceramic Tiles	0.012	1.2	2000	900	1.33
	Cement Mortar	0.02	1.73	2160	950	
	Sand	0.07	0.33	1500	800	

	Aggregregate	0.34	1	1500	800	
First Floor/Roof	Cement Plaster	0.012	1.7	2300	880	2.94
	Concrete	0.12	1.60	2100	880	
	Gypsum Plaster	0.012	0.22	970	1090	
Doors	Wood	0.03	0.14	500	2300	2.602
Windows	Wood	0.023	0.14	500	2300	2.990

Table 3 Thermophysical parameters of the simulated house (M3)

Building element	Material	Thickness (m)	Thermal conductivity (W/mk)	Density (kg/m^3)	Specific heat (J/kg K)	U-value (W/m^{2}K)
External Walls	Limestone	0.2	1.29	2700	909	2.82
	Gypsum Plaster	0.012	0.22	970	1090	
Internal Walls	Gypsum Plaster	0.012	0.22	970	1090	2.61
	Limestone	0.2	1.29	2700	909	
	Gypsum Plaster	0.012	0.22	970	1090	
Ground Floor	Ceramic Tiles	0.012	1.2	2000	900	1.33
	Cement Mortar	0.02	1.73	2160	950	
	Sand	0.07	0.33	1500	800	
	Aggregregate	0.34	1	1500	800	
First Floor/Roof	Cement Plaster	0.012	1.7	2300	880	2.94
	Concrete	0.12	1.60	2100	880	
	Gypsum Plaster	0.012	0.22	970	1090	
Doors	Wood	0.03	0.14	500	2300	2.602
Windows	Wood	0.023	0.14	500	2300	2.990

Simulation Tool

All simulation processes within this study were conducted using IDA ICE (Indoor Climate and Energy). IDA ICE is an innovative energy modeling software managed by Equa to assess the indoor climate and energy efficiency of building. This process can be done for a single zone within the building as well as for the whole building.

IDA-ICE has a user-friendly 3D design environment. CAD and geometry objects can easily be imported, displayed and processed withing the software. In addition, IDA-ICE provide many parameters for building components to be adjusted as needed. This allows us to study the impact of the changes we make in different building components on energy efficiency of the building under study. For instance, adjusting the building materials of walls or roof to

investigate its impact on energy consumption of the building. This feature is crucial in this study since it investigates the impact of different building material and passive design measures on the energy consumption buildings. Furthermore, simulation results in IDA-ICE can be displayed in a tables, charts or 3D diagram what make them easy to understand even by non-professionals.

Tested Passive Strategies

Passive strategies used in this study were selected based on the recommendations of Climate Consultant and weather tool of Ecotect as a result of analyzing climatic data of Seiyun. Passive design measures with the highest impact on thermal comfort were selected to be used in this study. Selected passive strategies are described in Table 4.

Table 4 Tested passive design strategies

Strategy No.	Strategy Description	Details
S1	Window overhangs and fins	Based on sun chart as demonstrated in Figure 6.
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 (Figure 7).
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 Figure 8.
S8	Increasing roof height by 1.5 m	
S9	25 % thicker outer walls	
S10	External window shading	Using drop arm awning as a shading device for windows (Figure 9). Awnings open when the incident solar radiation exceeds 100 W/m^2 on the external surface of the windows.
S11	Combining S1, S3 and S5	
S12	Combining S3, S5 and S10	

Modelling Approach

In Hadramout region, the majority of energy demand of the residential sector comes from mechanical cooling. Weather in Hadramout is hot, dry in summer and moderate in winter. Therefore, people there consider cooling in summer as a necessity. On the other hand, heating in winter is perceived as some sort of luxury. For this reason, energy modeling in this study will be conducted in summer solstice day (21st of June) and only consider cooling loads.

This research will investigate the impact of using selected passive design measures on cooling loads of local houses in Seiyun. Energy required to maintain the internal operative temperature within the acceptable comfort range (22-27 °C according to EN 15251:2007 [31]) in all occupied zones of each model (zones from 1 to 7 as shown in Figure 5) will be calculated. Calculation will be conducted using refrigerated and evaporative cooling systems as they are

the most commonly used systems in Seiyun and Hadramout in general. Modelling process involve creating geometry of the models, applying the selected passive strategies, simulating the models using refrigerated and evaporative cooling systems and finally evaluate energy efficiency of the simulated cases as illustrated in **Error! Reference source not found.**.

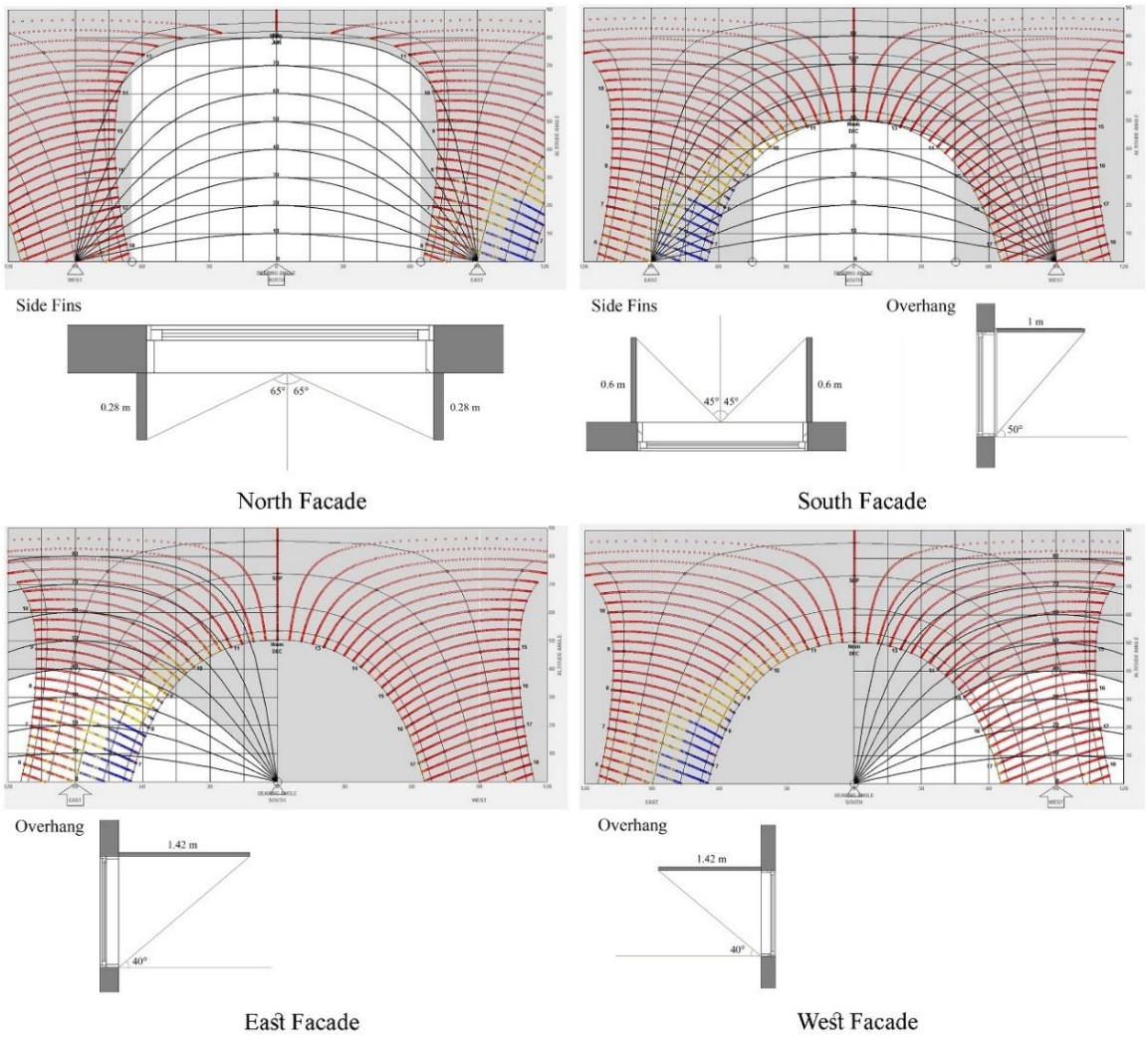


Figure 6 Design of overhangs and fins for windows on the four facades

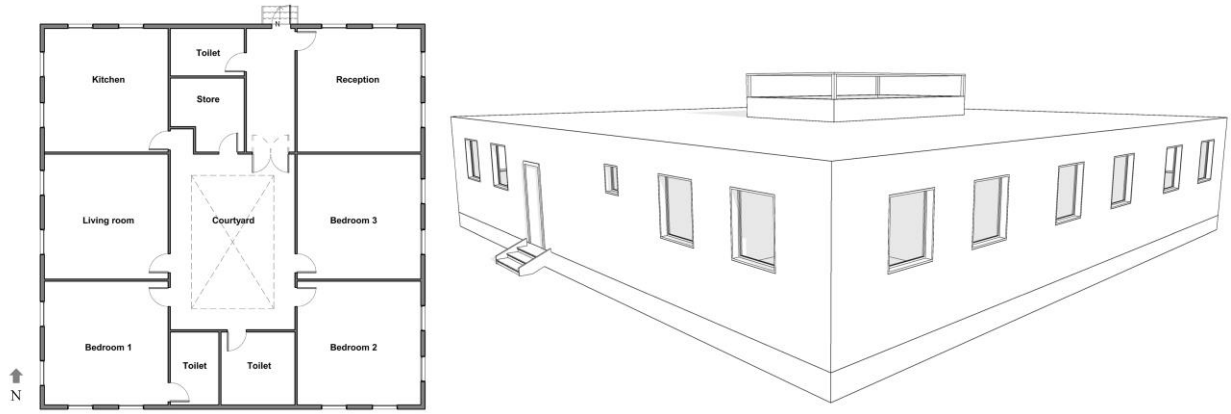


Figure 7 Location of the central courtyard

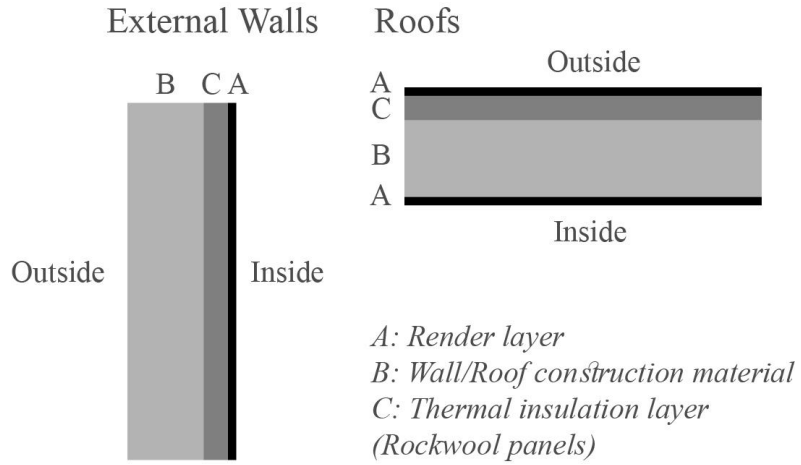


Figure 8 Thermal insulation layers in external walls and roof

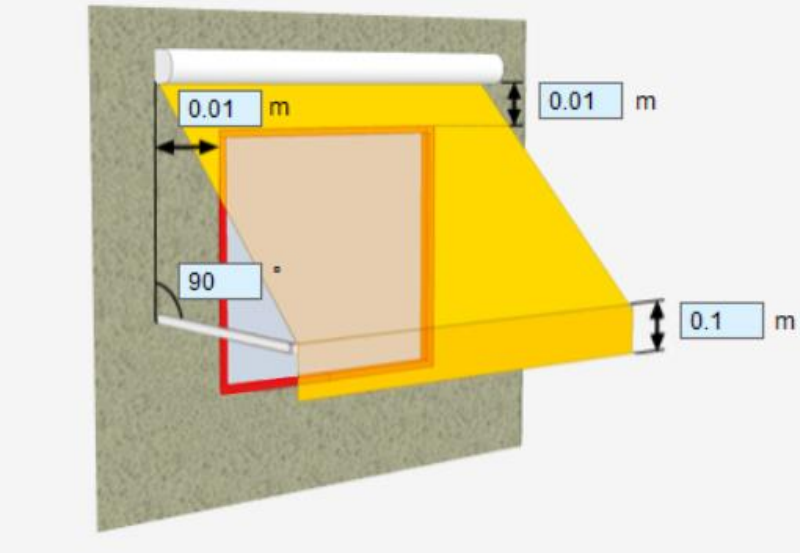


Figure 9 Used model of drop arm awning to shade windows. Source: IDA ICE 4.8 SP1

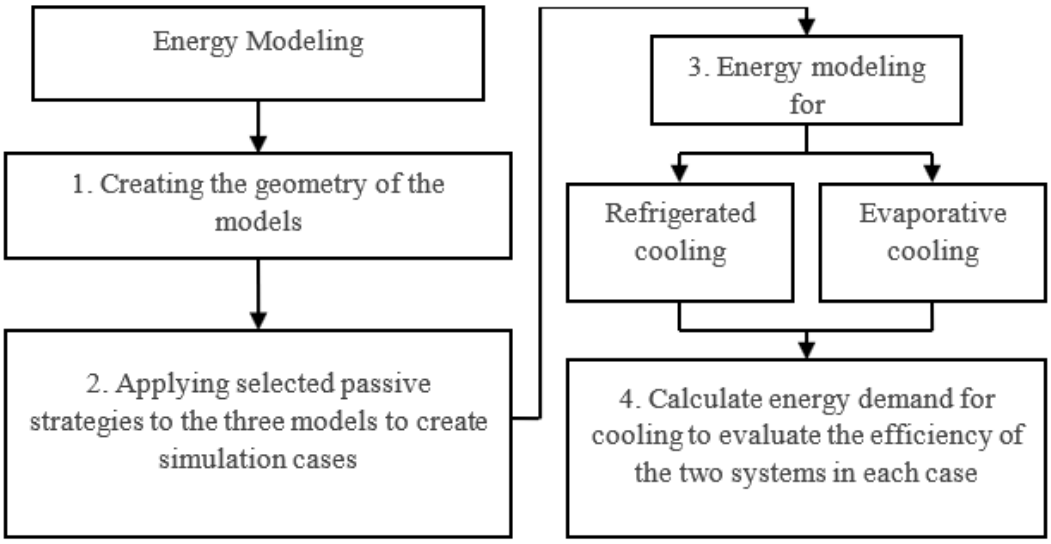


Figure 10 Flowchart of the modeling process

RESULTS AND DISCUSSION

Although using of passive design measures can help mitigate the internal temperature and enhance thermal comfort, it might not be enough to provide a comfortable environment specially in summer. In addition to comparing energy demand for cooling between adobe, concrete and stone local houses, the impact of set of passive design measures on the cooling energy demand for the three models will be assessed. This comparison will be conducted using refrigerated and evaporative cooling systems as the most commonly used systems in the area under study.

Refrigerated Cooling

Figure 11 demonstrates cooling energy demand using refrigerated cooling with the tested passive strategies for the three model. The diagram can be summarized in the following points:

1. Adobe house provided the highest energy efficiency with about only half energy required for cooling compared to the concrete and stone houses in all cases.
2. The concrete and stone houses required almost the same amount of energy for cooling in all cases.
3. Using of shaded courtyards (S4) and increasing roof heights (S8) cause a considerable increase in cooling loads in all three models compared to the other cases.
4. Combinations of passive strategies (S11 and S12) and using of thermal insulation (S7) showed better energy efficiency compared to the other cases in all three models.

Table 5 shows that the cooling energy demand for adobe, concrete and stone houses are 99.3, 205.9 and 203.9 kWh respectively. That means adobe house requires 51.77% and 51.29% lower energy compared to concrete and stone houses respectively. Furthermore, the most effective passive measures in reducing cooling loads for the three models are S7, S11 and S12 in order. However, S11 and S12 showed more influence in adobe house while S7 showed more significant influence in the concrete and stone houses as demonstrated in the table.

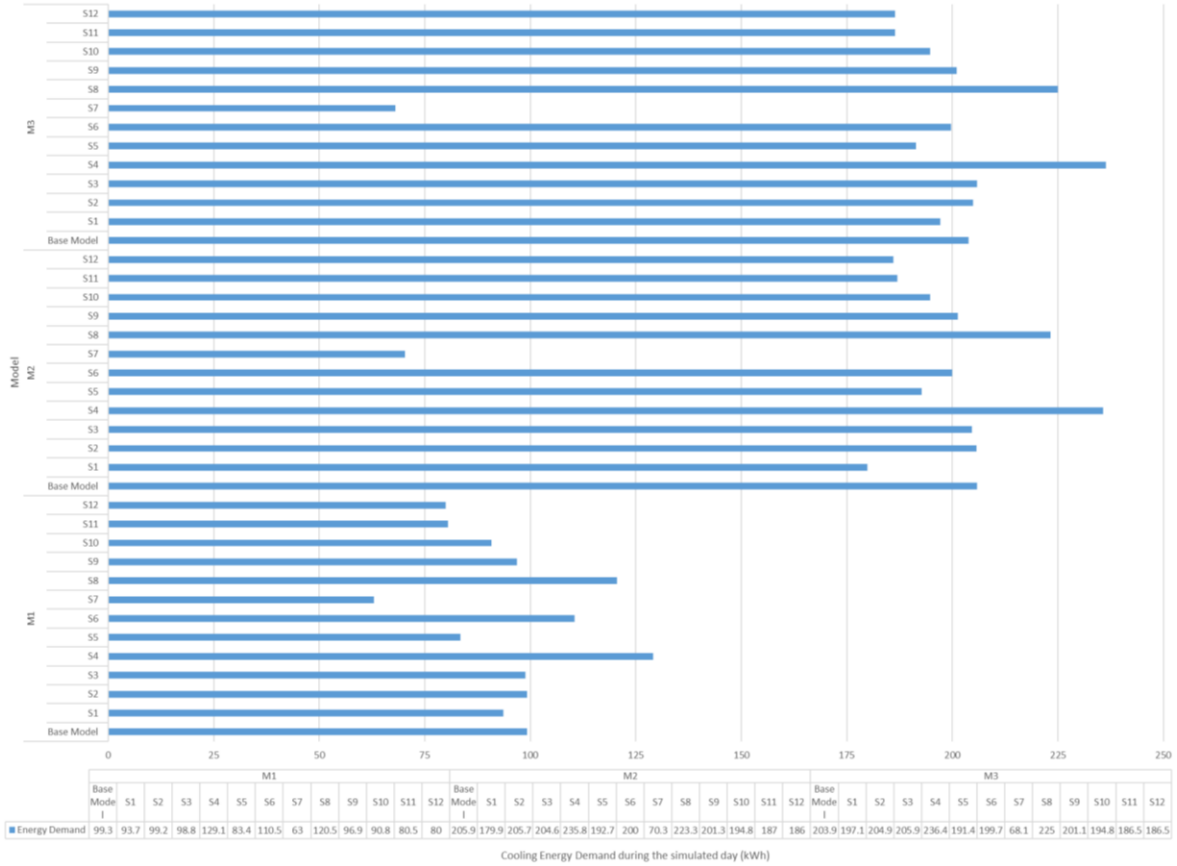


Figure 11 Energy required for refrigerated cooling to obtain the minimum level of thermal comfort in bedroom 1 for the three models using each one of the tested passive strategies during summer Solstice

Table 5 Energy demand and cost of the refrigerated cooling for the base models and the most three efficient passive design strategies in summer solstice according to the tariffs set by ministry of electricity and energy of Yemen [32].

Model	Base Models		Passive Design Strategies			
	Energy Required for Cooling (kWh)	Energy Cost in Yemeni Rial (YER)	Design Strategy	Energy Required for Cooling (kWh)	Energy Cost in Yemeni Rial (YER)	Cost Savings Percentage
M1	99.3	1,886.7	S7	63	1,197	36.56%
			S12	80	1,520	19.44%
			S11	80.5	1,529.5	18.93%
M2	205.9	3912.1	S7	70.3	1,335.7	65.86%
			S12	186	3,534	9.66%
			S11	187	3,553	9.18%
M3	203.9	3874.1	S7	68.1	1,293.9	66.60%
			S12	186.5	3,543.5	8.53%
			S11	186.5	3,543.5	8.53%

Evaporative Cooling

Figure 12 demonstrates cooling energy demand using evaporative cooling with the tested passive strategies for the three model. The diagram can be summarized in the following points:

1. Similar to the refrigerated cooling, adobe house shows the lowest energy consumption in all simulated cases reducing cooling demand up to more than 60% in some case such as S5, S11 and S12 compared with concrete and stone houses.
2. Concrete and stone houses don't show significant variations in their cooling energy demand.
3. Using of the shaded courtyard in S4 and increasing roof height in case S8 resulted in a higher energy consumption in all models.
4. S7, S11 and S12 showed lower cooling energy demand compared with the other cases in addition to S5 in the adobe house.

Table 6 shows that the cooling energy demand for adobe, concrete and stone houses are 54, 159 and 158 kWh respectively. That means adobe house requires 66.03% and 65.82% lower energy compared to concrete and stone houses respectively. Furthermore, the most effective passive measures in reducing cooling loads for the three models are S7, S12 and S11 in order. However, S11 and S12 showed more influence in adobe house while S7 showed more significant influence in the concrete and stone houses as demonstrated in the table. Moreover, S5 showed a significant reduction of cooling energy only in the adobe house.

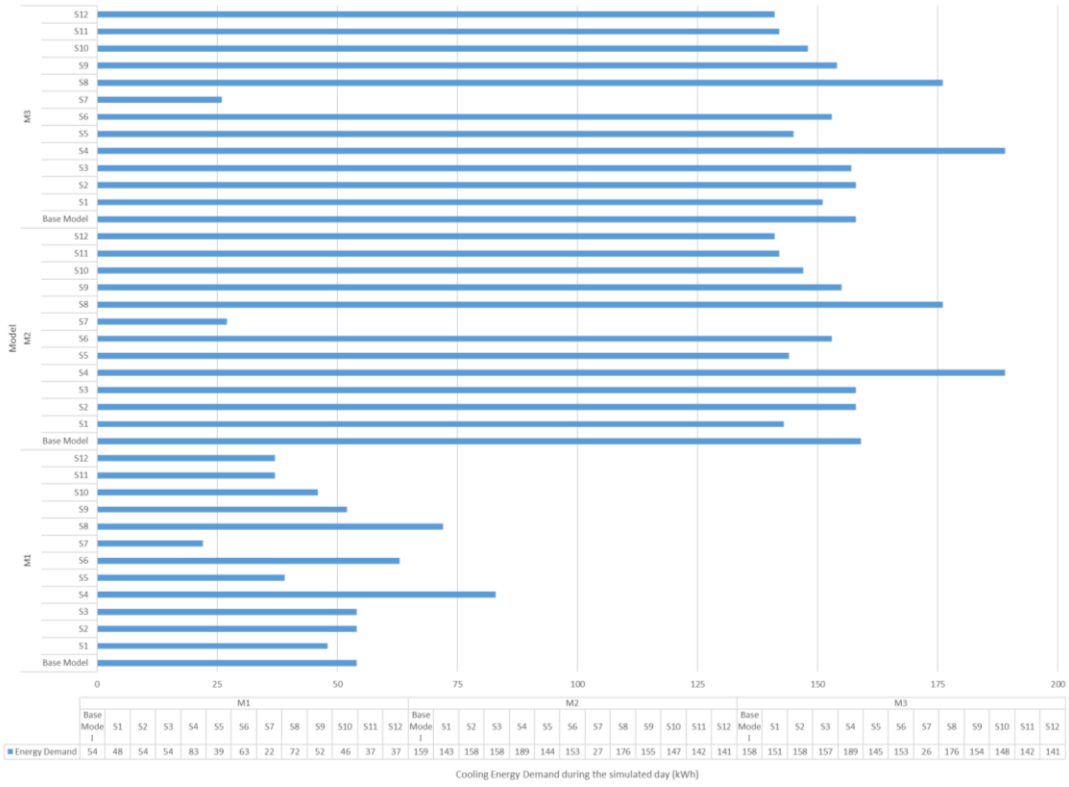


Figure 12 Energy required for evaporative cooling to obtain the minimum level of thermal comfort in bedroom 1 for the three models using each one of the tested passive strategies during summer Solstice

Table 6 Energy demand and cost of the evaporative cooling for the base models and the most three efficient passive design strategies in summer solstice according to the tariffs set by ministry of electricity and energy of Yemen

Model	Base Models		Passive Design Strategies			
	Energy Required for Cooling (kWh)	Energy Cost in Yemeni Rial (YER)	Design Strategy	Energy Required for Cooling (kWh)	Energy Cost in Yemeni Rial (YER)	Cost Savings Percentage
M1	54	1,026	S7	22	418	59.25%
			S11 and S12	37	703	31.48%
			S5	39	741	27.77%
M2	159	3,021	S7	27	513	83.01%
			S12	141	2,679	11.32%
			S11	142	2,698	10.69%
M3	158	3,002	S7	26	494	83.54%
			S12	141	2,679	10.75%
			S11	142	2,698	10.12%

The previous results demonstrates that cooling energy demand can be reduced significantly by using evaporative cooling instead of refrigerated cooling. Table 7 shows a comparison of the cooling energy demands using refrigerated and evaporative cooling systems between the three models. The table demonstrates that there is reduction of 45.61% in energy when evaporative cooling wase used instead of refrigerated cooling in the adobe house (M1). This percentage was increased to 65.07%, 53.75%, 51.55% in cases S7, S12 and S11 of the same model respectively. On the other hand, there was a 22.77% and 22.51% lower cooling energy when the evaporative cooling replaces the refrigerated cooling in concrete and stone houses respectively. However, the highest saving percentages of 61.59% and 62.82% in M2 and M3 respectively were achieved when the evaporative cooling replaced the refrigerated cooling in case S7 as shown in the table.

Table 7 Comparing energy demand of the three models using refrigerated and evaporative cooling systems

Energy demand Using:	M1				M2				M3			
	Base Model	S7	S12	S11	Base Model	S7	S12	S11	Base Model	S7	S12	S11
Refrigerated cooling (kWh)	99.3	63	80	80.5	205.9	70.3	186	187	203.9	68.1	186.5	186.5
Evaporative cooling (kWh)	54	22	37	39	159	27	141	142	158	26	141	142
Percentage savings using evaporative cooling (%)	45.61	65.07	53.75	51.55	22.77	61.59	24.19	24.06	22.51	61.82	24.39	23.86

CONCLUSION

This study is one of few research works to highlight the impact of building material on the energy consumption of local domestic buildings in the city of Seiyun, Yemen. This research investigates the impact of using passive design measure and evaporative cooling on the energy efficiency of different types of local houses in Seiyun.

To meet the aim of the study, climatic data of Seiyun was analyzed to understand the thermal conditions of the area and determine the best sustainable passive responses to be applied. Next, a parametric analysis was conducted using simulation. IDA ICE was used to simulate cooling energy demand of the three models.

Different passive design measures were applied to each model to investigate their impact on energy demand for cooling using refrigerated and evaporative cooling systems. Results of this process highlighted the efficiency of each cooling system and the influence of applying passive design strategies on energy required for cooling.
Results of the energy modeling can be summarized in the following points:

1. Adobe house requires 51.77% and 51.29% lower energy compared to concrete and stone houses respectively when refrigerated cooling is used. In case of the evaporative Cooling, adobe house requires 66.03% and 65.82% lower energy compared to concrete and stone houses respectively.
2. Concrete and stone houses consume almost the same amount of energy for cooling.
3. The most effective passive measures in reducing cooling loads for the three models are S7, S11 and S12 in order. However, S11 and S12 showed more influence in adobe house while S7 showed more significant influence in the concrete and stone houses as demonstrated in the table.
4. Using of the shaded courtyard in S4 and increasing roof height in S8 resulted in a higher energy consumption in all models.
5. Evaporative cooling is way more energy efficient compared to the refrigerated cooling specially in the adobe house.

Figure 13 shows a comparison of the energy demand for cooling between the best simulated cases and base models of the three house types in summer solstice. The graph highlights the advantage of adobe house over the concrete and stone houses from energy efficiency point of few. The adobe house required lower energy for cooling even without using of thermal insulation.

The results of this study can help local builders and architects to determine the best passive measures and cooling systems for local houses. Furthermore, it highlights the superiority of adobe over the other building materials from energy efficiency perspective. However, it should be noticed that this study was carried out in summer solstice day and just for three types of local domestic buildings due to the time and cost limitations. Therefore, further research should include commercial and educational buildings for longer periods to get more comprehensive comparison between simulation results and reality.

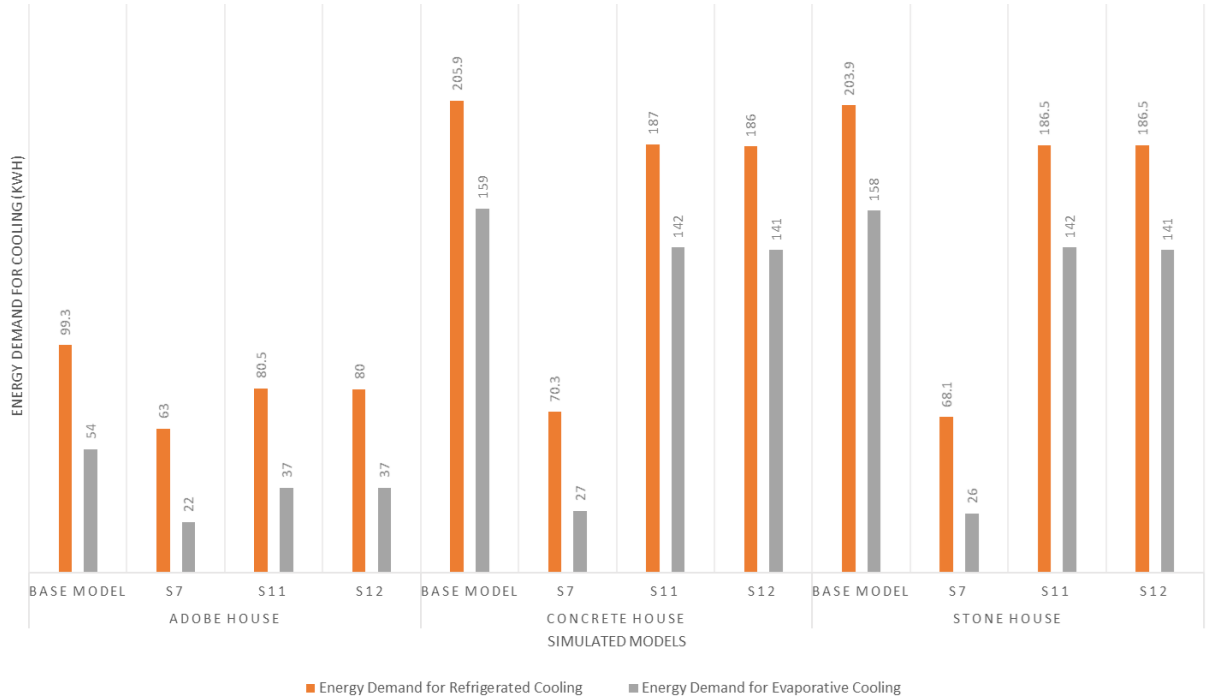


Figure 13 Comparison of the energy demand for cooling between the adobe, concrete and stone houses in summer solstice.

References

[1] L. Pérez-Lombard, J. Ortiz, and C. Pout, "A review on buildings energy consumption information," Energy Build., vol. 40, no. 3, pp. 394–398, Jan. 2008.

[2] P. M. Cuce and S. Riffat, "A state of the art review of evaporative cooling systems for building applications," Renew. Sustain. Energy Rev., vol. 54, pp. 1240–1249, 2016.

[3] IEA, "World Energy Outlook 2006 Edition," SourceOCDE Energ., vol. 2006, 2006.

[4] "International - U.S. Energy Information Administration (EIA)," 2020. [Online]. Available: https://www.eia.gov/international/analysis/country/YEM. [Accessed: 02-Jan-2022].

[5] H. Al-Shabi Mohammed and A.-S. Rami, "The Current Situation and Future Prospects of the Energy Sector in Yemen Ministry of Electricity & Energy," in Korea–Yemen Energy Forum, 2014.

[6] A. S. Rawea and S. Urooj, "Strategies, current status, problems of energy and perspectives of Yemen's renewable energy solutions," Renew. Sustain. Energy Rev., vol. 82, no. July 2017, pp. 1655–1663, 2018.

[7] OCHA, "Yemen commodity tracker (January - March 2021) - Yemen | ReliefWeb," 11-May-2021. [Online]. Available: https://reliefweb.int/report/yemen/yemen-commodity-tracker-january-march-2021. [Accessed: 03-Jan-2022].

[8] O. Amer, R. Boukhanouf, and H. G. Ibrahim, "A Review of Evaporative Cooling Technologies," Int. J. Environ. Sci. Dev., vol. 6, no. 2, pp. 111–117, 2015.

[9] C. A. Balaras, K. Droutsa, E. Dascalaki, and S. Kontoyiannidis, "Heating energy consumption and resulting environmental impact of European apartment buildings," Energy Build., vol. 37, no. 5, pp. 429–442, May 2005.

[10] S. Gou, V. M. Nik, J. L. Scartezzini, Q. Zhao, and Z. Li, "Passive design optimization of newly-built residential buildings in Shanghai for improving indoor thermal comfort while reducing building energy demand," Energy Build., vol. 169, pp. 484–506, 2018.

[11] K. M. Al-Obaidi, M. Ismail, and A. M. A. Rahman, "Passive cooling techniques through reflective and radiative roofs in tropical houses in Southeast Asia: A literature review," Front. Archit. Res., vol. 3, no. 3, pp. 283–297, 2014.

[12] A. Gagliano, M. Detommaso, F. Nocera, F. Patania, and S. Aneli, "The retrofit of existing buildings through the exploitation of the green roofs–a simulation study," Energy Procedia, vol. 62, pp. 52–61, 2014.

[13] A. Gagliano, F. Nocera, A. D'Amico, and C. Spataru, "Geographical information system as support tool for sustainable Energy Action Plan," Energy Procedia, vol. 83, pp. 310–319, 2015.

[14] G. Pérez, J. Coma, I. Martorell, and L. F. Cabeza, "Vertical Greenery Systems (VGS) for energy saving in buildings: A review," Renew. Sustain. energy Rev., vol. 39, pp. 139–165, 2014.

[15] F. Nocera, A. Lo Faro, V. Costanzo, and C. Raciti, "Daylight performance of classrooms in a mediterranean school heritage building," Sustainability, vol. 10, no. 10, p. 3705, 2018.

[16] M. M. Fernandez-Antolin, J. M. del Río, V. Costanzo, F. Nocera, and R. A. Gonzalez-Lezcano, "Passive design strategies for residential buildings in different Spanish climate zones," Sustain., vol. 11, no. 18, 2019.

[17] Y. Cerci, "A new ideal evaporative freezing cycle," Int. J. Heat Mass Transf., vol. 46, no. 16, pp. 2967–2974, 2003.

[18] Y. Jiang and X. Xie, "Theoretical and testing performance of an innovative indirect evaporative chiller," Sol. Energy, vol. 84, no. 12, pp. 2041–2055, Dec. 2010.

[19] D. K. Bhamare, M. K. Rathod, and J. Banerjee, "Evaluation of cooling potential of passive strategies using bioclimatic approach for different Indian climatic zones," J. Build. Eng., vol. 31, no. January, p. 101356, 2020.

[20] E. Ibrahim, L. Shao, and S. B. Riffat, "Performance of porous ceramic evaporators for building cooling application," Energy Build., vol. 35, no. 9, pp. 941–949, 2003.

[21] S. SZOKOLAY, INTRODUCTION TO ARCHITECTURAL SCIENCE : the basis of sustainable design. [Place of publication not identified]: ROUTLEDGE, 2017.

[22] C. A. Balaras, K. Droutsa, A. A. Argiriou, and D. N. Asimakopoulos, "Potential for energy conservation in apartment buildings," Energy Build., vol. 31, no. 2, pp. 143–154, Feb. 2000.

[23] Z. Fang, N. Li, B. Li, G. Luo, and Y. Huang, "The effect of building envelope insulation on cooling energy consumption in summer," Energy Build., vol. 77, pp. 197–205, 2014.

[24] B. Farhanieh and S. Sattari, "Simulation of energy saving in Iranian buildings using integrative modelling for insulation," Renew. Energy, vol. 31, no. 4, pp. 417–425, 2006.

[25] D. I. Kolaitis, E. Malliotakis, D. A. Kontogeorgos, I. Mandilaras, D. I. Katsourinis, and M. A. Founti, "Comparative assessment of internal and external thermal insulation systems for energy efficient retrofitting of residential buildings," Energy Build., vol. 64, pp. 123–131, 2013.

[26] A. H. Algifri, S. M. Bin Gadhi, and B. T. Nijaguna, "Thermal behaviour of adobe and concrete houses in Yemen," Renew. Energy, vol. 2, no. 6, pp. 597–602, Dec. 1992.

[27] M. K. Al-Motawakel, S. D. Probert, and B. Norton, "Thermal behaviours of vernacular buildings in the Yemen Arab Republic," Appl. Energy, vol. 24, pp. 245–276, 1986.

[28] F. R. Arooz and R. U. Halwatura, "Mud-concrete block (MCB): mix design & durability characteristics," Case Stud. Constr. Mater., vol. 8, no. November 2017, pp. 39–50, 2018.

[29] "Climate Seiyun - meteoblue." [Online]. Available: https://www.meteoblue.com/en/weather/historyclimate/climatemodelled/seiyun_yemen_70981. [Accessed: 28-Mar-2021].

[30] F. H. Ai-shibami, "Thermal comfort and energy efficiency in yemeni houses," 2004.

[31] CEN, "Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics," EN 15251, 2007.

[32] "*التعرفـة – وزارة الكهرباء والطاقة!*" [Online]. Available: https://moee-ye.com/site-ar/*التعرفـة*/. [Accessed: 16-Sep-2021].