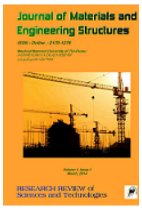

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Research Paper

Study of the performance of passive cooling strategies in buildings under arid weather conditions

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ABSTRACT

In Algeria, the building sector accounts for approximately 43% of total primary consumption and accounts for more than one-third of energy-related greenhouse gas emissions. It should be a primary focus for reducing energy consumption and greenhouse gases (GHG) emissions. The new buildings, particularly in the hot and arid southern regions, are completely unsuitable for the climate. The use of inefficient building materials results in high energy consumption. The goal of this project is to investigate passive cooling solutions in order to reduce discomfort and the use of air conditioning systems inside buildings. A two-pronged approach combined chart-based bioclimatic analysis with building performance simulation. The impact of some passive cooling strategies on typical buildings constructed with conventional and local materials was investigated. The study found that when a building uses passive cooling strategies, total cooling needs can be reduced by up to 27% with conventional materials and up to 40% with local materials. In addition, average daily operating temperatures in local buildings can be reduced by up to 2.5 °C and about 1.5 °C in conventional buildings.

1 Introduction

According to the 2018 United Nations World Situation Report, construction and operation accounted for 36% of global final energy consumption and nearly 39% of energy-related carbon dioxide CO2 emissions in 2017 [1]. Furthermore, space heating and cooling applications in the residential and commercial sectors consume approximately 40% of the energy consumed in buildings [2]. According to the International Energy Agency (IEA), these rates are expected to rise significantly as the economy grows and living standards rise [3].

Due to rapid population growth and urbanization, Algeria's construction industry is one of the most dynamic in the country. This has resulted in a housing shortage, and government officials have prioritized the following construction criteria:

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speed and low cost. Even in a hot arid climate like Algeria's south, most buildings are not climate-responsive and use the same material as external walls: double hollow brick cavity (DHB). Overheating is expected in DHB buildings during the summer, and using air-conditioning systems to achieve acceptable thermal comfort levels became unavoidable, increasing energy consumption.

The country therefore has to face the double problem of the carefree use of energy resources and the fight against pollution caused by air conditioning systems [4].

Some promising approaches to reduce energy consumption in buildings include:

- the use of passive cooling systems to improve summer comfort;
- construction in eco-friendly materials with low conduction coefficient.

Numerous studies worldwide have investigated the potential of passive cooling techniques in saving energy and lowering indoor temperatures under various climatic conditions. Comprehensive state-of-the-art overviews of these techniques' working, applications, and recent developments have been carried out [2, 5-7]. The researchers discovered that using passive devices improves building thermal performance and saves energy [8-12].

Furthermore, the use of eco-friendly construction materials with low conduction coefficients, which can save energy portions ranging from 32% to 58% and up to 85%, has a significant impact on the building's energy-saving potential [13-15]. Several researchers have studied the impact of using locally available materials, including earthen ones, to reduce environmental impacts by minimizing industrial processes [16-18]. According to the findings, thermal performance is improved, especially in arid and hot climates.

This study investigates the utility of passive cooling strategies to improve thermal performance and lower energy consumption in residential buildings in hot arid climate settings, specifically Bechar in Algeria. By analyzing several comfort parameters such as operating temperature, PMV and PPD, and overheating, this study aims to demonstrate the theoretical benefits of using traditional (local) building materials rather than actual (modern) building materials in the southern regions of Algeria in terms of energy efficiency and thermal performance. As a result, this research not only adds to the body of knowledge on passive construction but is also valuable for identifying the most efficient cooling strategies and best combinations of them, which could result in the most significant energy savings for cooling while also promoting the sustainable development of local materials in Algeria.

Due to the goals of this research, a dual approach combining chart-based bioclimatic analysis with a computer-based simulation approach is used. Several researchers have used this approach in recent years. Santy et al. used bioclimatic charts and energy simulation to investigate the climate characteristics of Indonesian regions [18]. Pajek & Košir applied the approach to the Slovenian climate [19], and Khambadkone and Jain created a bioclimatic analysis tool to investigate the comfort potential of various passive heating and cooling strategies for composite climate locations in India [20]. Some Algerian climatic zones have also been studied [13, 21].

The research is divided into two parts: first, a bioclimatic analysis was conducted using only climatic data to assess the bioclimatic potential of passive cooling strategies in a semi-arid climate. Second, TRNSYS software was used to simulate building performance. The impact of integrating these strategies and using locally available (traditional) materials on indoor air temperature and energy consumption was evaluated using an actual case building. The obtained results were compared to those obtained using modern (actual) materials.

2 Energy consumption in Algeria and environment

An examination of Algeria's energy balance reveals that final internal consumption is rising. It increased from 48.14 megatons oil equivalent MToe in 2018 to 50.36 MToe in 2019, representing a 4.6% annual increase [22]. Figure 1 depicts the distribution of final energy consumption by sector of activity, with the residential and tertiary sectors accounting for 23.5 MToe (46.6%). This is especially concerning given the annual increase in the housing stock.

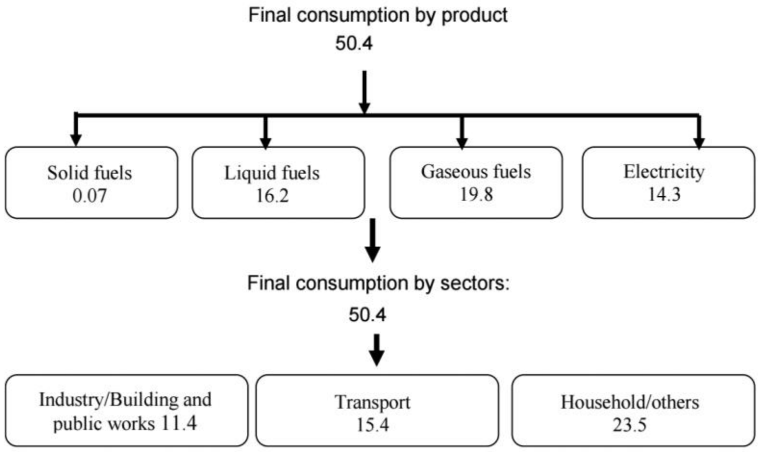


Fig. 1 – Final consumption by product and sector, 2019 [22] (Adapted by the author)

Furthermore, according to the APRUE final energy consumption report [23], the building materials sector is increasing its share of the industrial balance sheet, rising from 22.7% in 2001 to 42.8% in 2019, making it the most energy-intensive sector. According to the same source, the residential sector accounts for 36% of total emissions of GHG (figure 2). The building materials industry leads the way in terms of emissions, accounting for 63% of total emissions. This is primarily due to the generalization of cement-based concrete construction. As shown in Table 1, cement production accounts for the vast majority of CO2 emissions in the construction building materials sector (roughly 99%). This situation compels us to take a closer look at this industry, which continues to be the source of the most CO2 emissions.

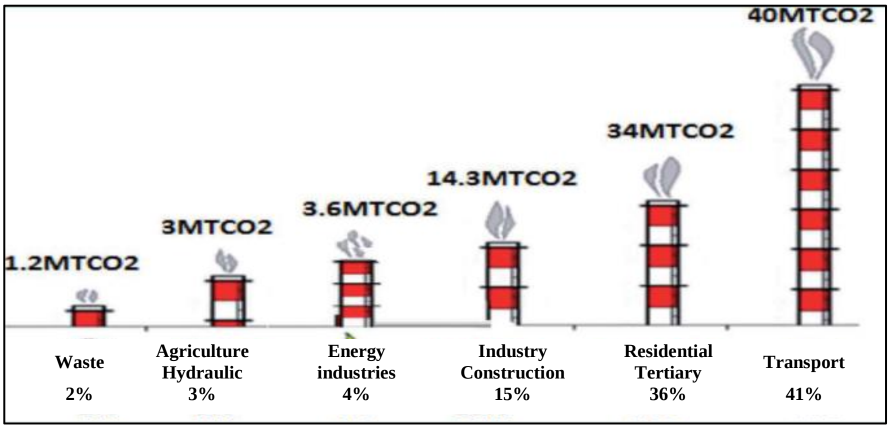


Fig. 2 – GHG emissions from different sectors, 2017 [23]

Table 1– Distribution of CO_2 emissions due to mineral products [23].

Products	**Emission CO_2 (gigagrams)**
Cement	3196.58
Lime	35.50
Dolomite limestone	3.36
Soda (use and production)	9.53

3 Materials and methods

In the first part of this work, A bioclimatic analysis was conducted and assessed the air conditioning potential of passive systems in a semi-arid climate zone represented by the city of Bechar in southwest Algeria in the first part of this work. The

Ecotect Weather tool created the psychrometric chart [24]. The Auliciems' approach to adaptive thermal comfort is used in this tool to determine the neutral temperature at which a person feels thermally neutral [25]. The zone comfort boundary limits are defined by absolute humidity and dry bulb temperature (DBT). While the absolute humidity limits are fixed at 12g/kg and 4g/kg, the DBT upper limits vary according to the neutral temperature calculated from the monthly mean temperature, Tmean, through Auliciems equation: $Tn = 17.6 + (0.31 \times Tmean)$ °C.

Different passive design strategies, such as natural ventilation or evaporative cooling, can extend the limits of thermal comfort inside. Thermal mass, natural ventilation, night ventilation, and direct and indirect evaporation are the passive systems studied in this study. According to Algerian climatic zoning, Bechar is located in zone D [26]. The monthly mean temperature ranges from 5 to 16 ° C in January to 30 to over 40 ° C in the summer, with relative humidity ranging from 30 to 78% in January to 12 to 30% in July.

In order to generate the hourly values of global solar radiation, stochastic (random) models are used. These models make it possible to generate intermediate data having the same statistical properties as the measured data. This generation process approaches physical characteristics as much as possible. This method shows that data generated in this way can be used satisfactorily in place of long-term measurement data [27].

The second part of this work involved numerical modeling with the TRNSYS software [28]. Some constructions that are similar to those found in Algeria were studied. Numerous simulation studies use the primary investigative approach to predict building thermal behavior and energy performance. Moret Rodrigues et al. analyzed the natural ventilation conditions of a dwelling in a Mediterranean climate and their impacts on thermal and energy performance using an advanced building energy simulation tool [29], Taleb tested the usefulness of applying some passive cooling strategies to improve building performance in the hot arid climate of the United Arab Emirates by using Energy simulation software - namely IES [30], Khoukhi & Fezzioui evaluated passive cooling strategies of modern and traditional housing in Algeria using TRNSYS [12], TRNSYS was also used by Ali-Toudert & Weidhaus to perform dynamic energy modeling in order to determine the best design strategies for affordable energy efficient residential buildings in Algeria [11].

The buildings were simulated during the summer to determine the impact of the design elements on the comfort level and the energy consumption of the various buildings. In this study we have considered the following passive concepts:

- the thermal mass of building;
- sun protection on windows;
- cooling by natural night ventilation (windows open from 8 post meridiem to 6 ante meridiem.).

Each time, the following criteria were adopted to assess the performance of the different buildings:

- evolution of the indoor temperature;
- evaluation of comfort indices: Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) [31];
- evaluation of the cooling need.

4 Results and discussion

4.1 Bioclimatic analysis of Bechar

The bioclimatic analysis allows us to determine the best building design strategies for improving indoor thermal comfort. Figure 3 shows the psychrometric chart that was created using hourly weather data. Up to 80% of Bechar city's climatic data appear outside the comfort zone. Passive strategies such as natural ventilation, thermal mass, thermal mass combined with night ventilation, and direct and indirect evaporative cooling can be used to extend this one. Because it covers a large portion of the climatic data, high thermal mass combined with a night ventilation strategy appears to be the most effective in this climate. Indirect evaporative cooling is the next most efficient strategy.

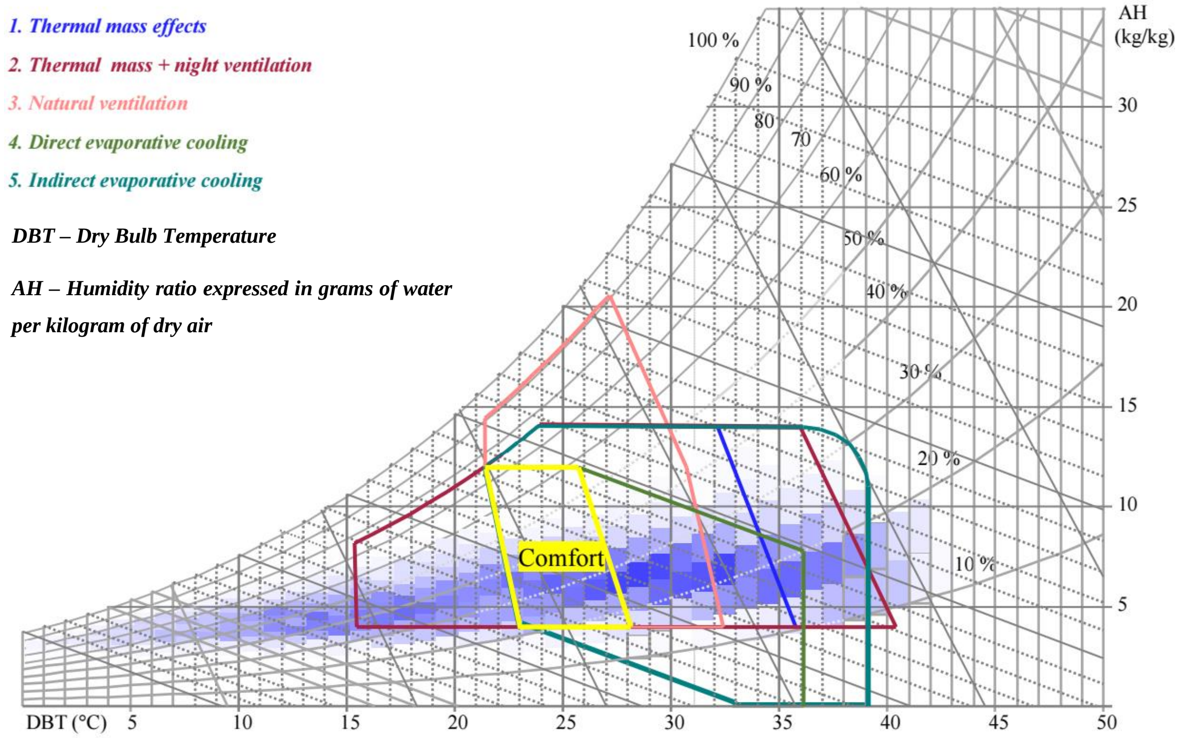


Fig. 3 – Bioclimatic charts for Bechar province

Figure 4 represents the percentage of each bioclimatic cooling strategy's potential. It stands for the time during which the comfort is achieved by using these strategies. The cumulative comfort potential is the proportion of the total time of the studied period (April-October) when comfort is achievable by applying these techniques.

It shows that:

- Weather in Bechar is found to be naturally comfortable only for 15% of the total time during April to October period.
- By applying the above strategies, comfort improvement was noticed in all Cases.
- In the summer months, thermal mass, combined or no with night ventilation, and indirect evaporative strategies improve significantly the comfort:
- In June and September, the thermal inertia with night ventilation re-establishes comfort for more than 90% of time. The results showed the improvement of thermal comfort from 25% to 99%, i.e., an increase of 74% in June.
- In July and August, which are the hottest months, the percentages of comfort improvement range from 77 to 80% using these two strategies.
- Direct evaporation cooling can also be considered as an effective strategy, it provides comfort in more than 60% of the time during the summer.
- Natural ventilation gives lower percentages of improvements, ranging from 28 to 31% during June to September period. These values exceed 40% with using direct evaporative cooling.

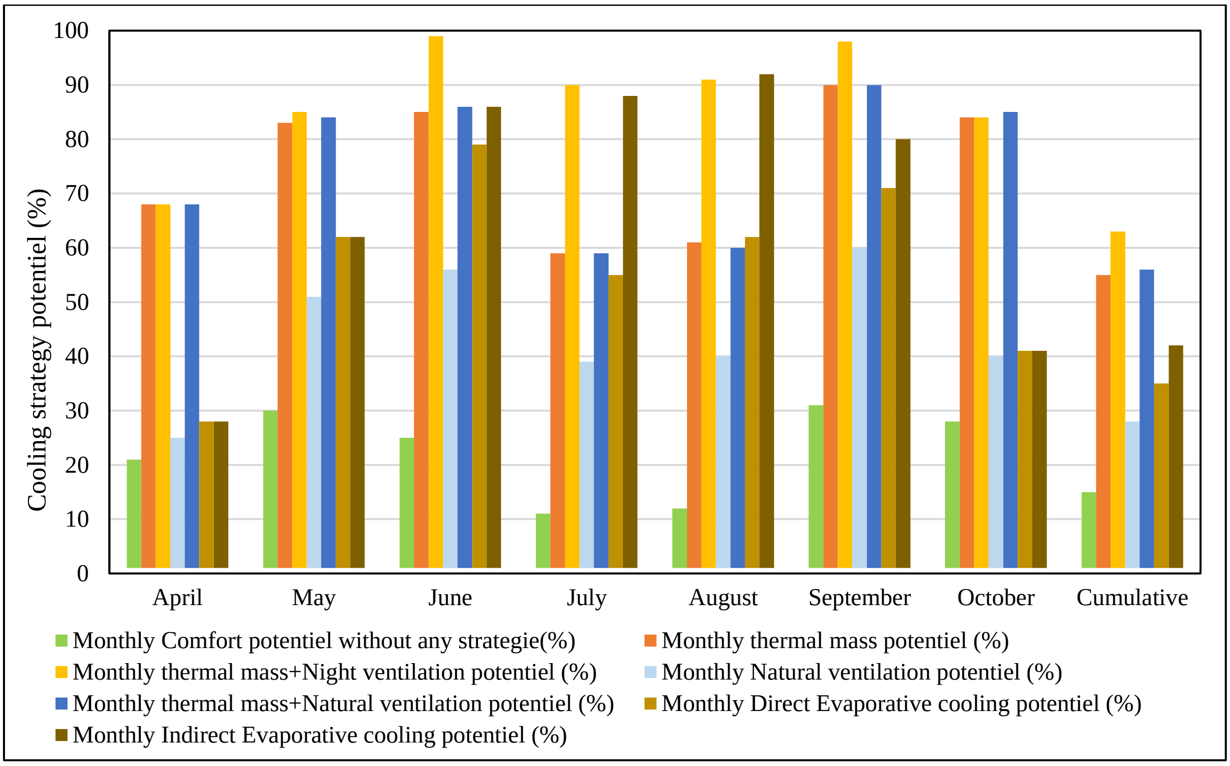


Fig. 4 – Comfort time percentages with the different passive cooling strategies. Bechar city

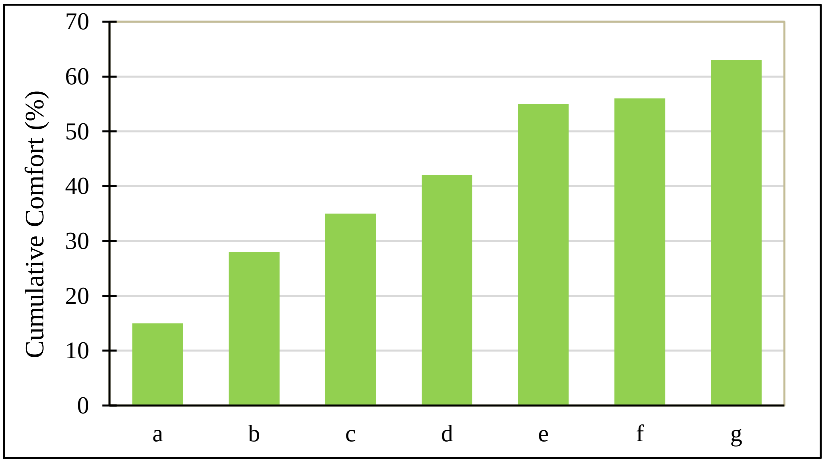


Fig. 5 – Comfort time percentages with the different passive cooling strategies. Bechar city: a- Without any cooling strategy; b- Natural ventilation, c- Direct evaporative cooling; d- Indirect evaporative cooling; e- Thermal mass; f- Thermal mass + Natural ventilation; g- Thermal mass + Night cooling

Figure 5 shows the comparison between the cumulative comfort (during studied months) obtained with the different passive cooling strategies. As seen in figure 5, it indicates that the base comfort period without the use of any passive cooling strategies is about only 15%. Bechar shows the highest cooling potential for thermal mass combined with night ventilation whereas the lowest one is obtained with natural ventilation. Thermal mass can extend comfort period by about 40% against 27% with indirect evaporative cooling, 20% with direct evaporative cooling and only 13% with natural ventilation.

4.2 Thermal analysis

This section presents some common constructions in Algeria that were studied: old traditional buildings and current modern buildings. The terms “traditional” and “modern” refer to the materials used in construction: stone and adobe for the traditional, bricks and concrete for the modern. The goal is to investigate the impact of replacing currently used materials with locally available materials in arid climates. Indeed, current Algerian buildings are inadequately insulated. Regardless of region, the exterior walls are still built in double hollow brick walls with an air layer or in concrete. For intermediate floors, hollow-core concrete elements are used, while concrete is used for ground floors. Table 2 lists the thermophysical properties of the materials used. The adobe material was characterized at the LaSIE laboratory at the University of La Rochelle in France [32].

Table 2 - Characteristics of the building materials constituting the exterior walls [27].

Wall	Adobe	Stone	Double brick			Concrete
			Hollow brick	Air	Hollow brick	
λ (W/m°K)	0,427	1,000	0,5	0,025	0,5	1,75
ρ (kg/m^3)	1494,2	1700	900	1,18	900	2400
C (kj/kg.°K)	0,687	0,936	0,794	1,000	0,794	1,080
e (m)	0,30	0,40	0,15	0,05	0,10	0,15

The buildings were simulated during the summer, and Table 3 lists the main simulation settings assumed in TRNSYS.

Table 3 –TRNSYS simulation settings.

Issue	TRNSYS Setting	
Cooling set temperature	26°C	
Summer conditions		
Light clothing	0.5 clo	According to [32]
Sedentary activity	1.2 Met	//
Wind speed	v = 0.1 m/s	
The lighting's heat gain load	19 w m^{-2}	
	Period: between 8 PM to 6 AM	
	Radiative fraction: 60%	

A boundary surface was used to model the underground floor. The soil temperature calculated with TYPE 77 is the boundary temperature. The convective heat transfer coefficient was set to a very low value (0.001 kJ/h/m2) to force the floor's outside surface temperature to equal the soil temperature beneath the floor.

The thermal mass of the building, sun protection on windows, and natural night ventilation by simply opening the windows from 8 PM to 6 AM were all considered passive concepts. Fixed horizontal shading provides sun protection above windows (overhangs). To evaluate the performance of the various buildings, the following criteria were used each time:

- evolution of the indoor temperature;
- evaluation of comfort indices: Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD);
- Evaluation of the cooling need.

The modeled building is a single zone type construction (Figure 6) because the goal here is to show only the impact of the exterior wall construction materials on the performance of the buildings.

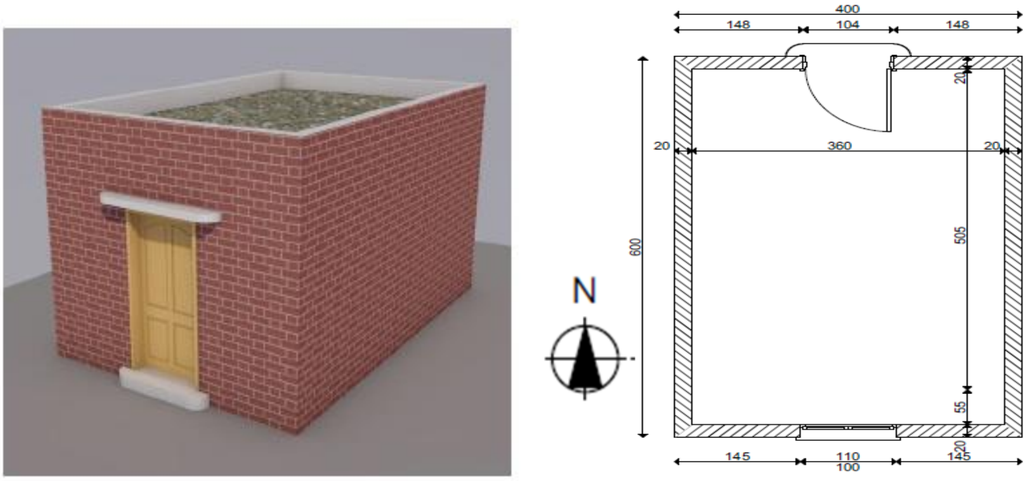


Fig. 6 – Plan of the studied building

4.2.1 Temperature evolution

TRNSYS was used to investigate the effect of the building's exterior wall configurations on internal temperature. Figure 7 depicts the evolution of indoor temperatures in various reference buildings on the hottest day, compared to the outside temperature (Text). It can be noted that traditional buildings have the lowest temperatures. Indeed, the inertia of these materials allows for a reduction in the daily amplitude of the interior temperature. This identifies a good comfort index with improved thermal stability. The difference between outside and inside maximum temperatures reaches 10 °C in the adobe building, 9 °C in the stone building, 6.7 °C in the brick building, and 4.8 °C in the concrete building while the indoor temperature amplitude is 0.77, 0.54, 3.44 and 5.09 °C respectively. This is consistent with other studies cited in the literature.

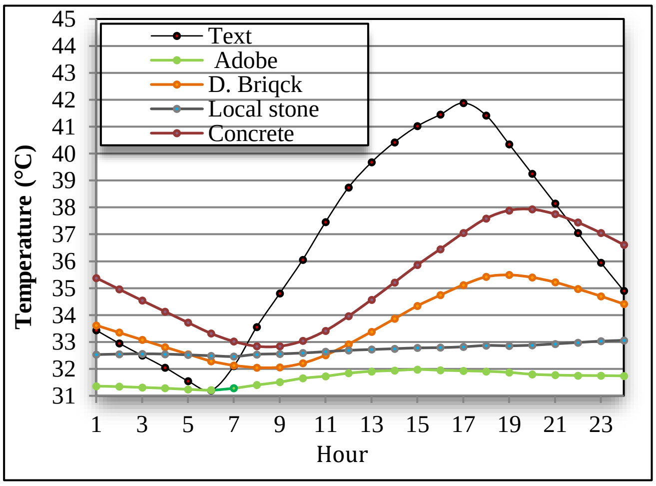


Fig. 7 – Evolution of outside and inside air temperatures in the various reference buildings. Hottest day, Bechar city

When M. Nadarajan et al. [33] compared conventional brick and mud blocks to their thermal comfort capability using CFD simulation, the authors discovered that air temperature was lower inside the house in the case of mud block and higher in the case of a brick-walled house. In F. Ashraf's study, a thermal mass efficiency test was performed on a case study house in Jordan's semi-arid climate, which consists of two parts of different thermal masses. The house's original rooms were built with clay bricks in 1938, and the additions were built with concrete bricks in 1977 [34]. The findings show that in July and August, the temperature inside the clay room during the day and night was about 5°C lower than in the concrete room, which agrees with the results.

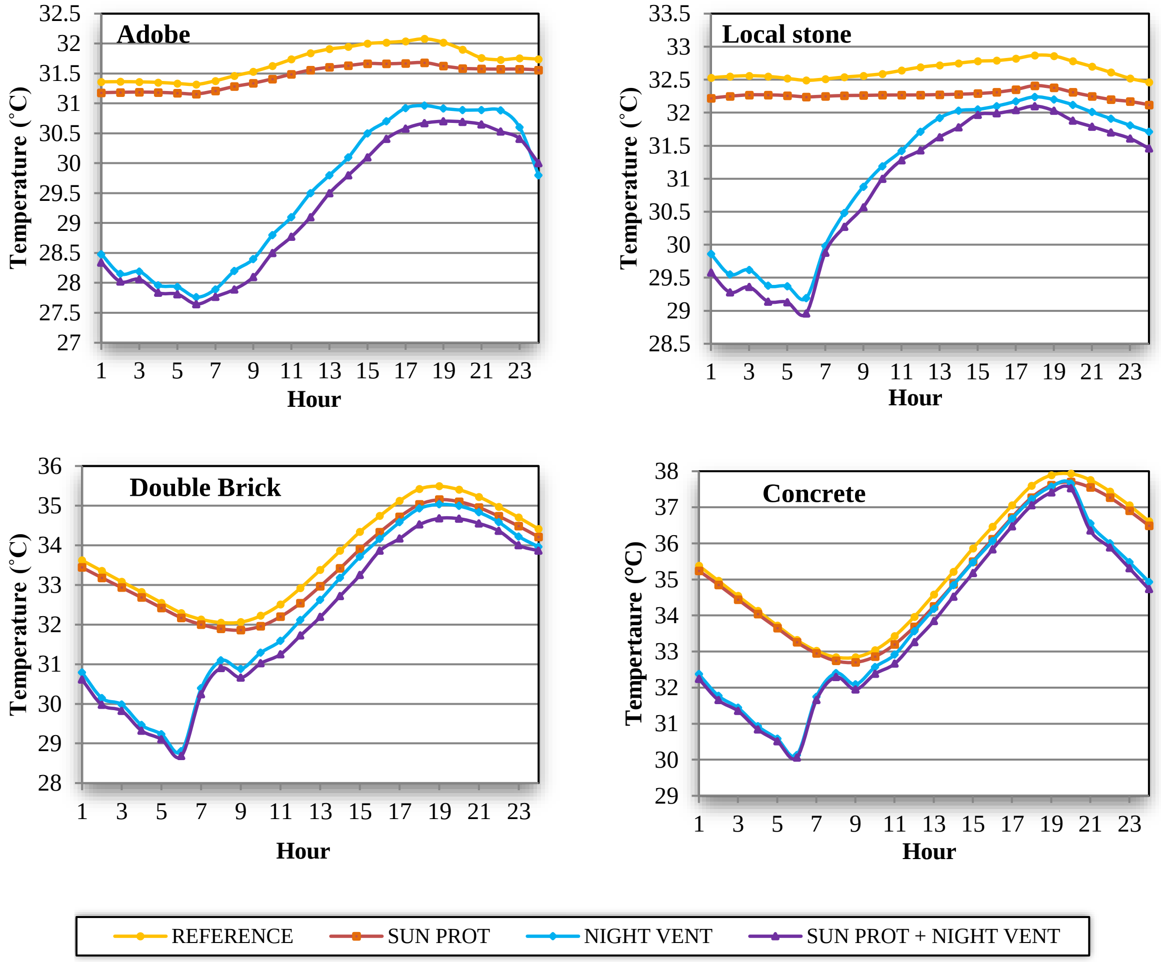
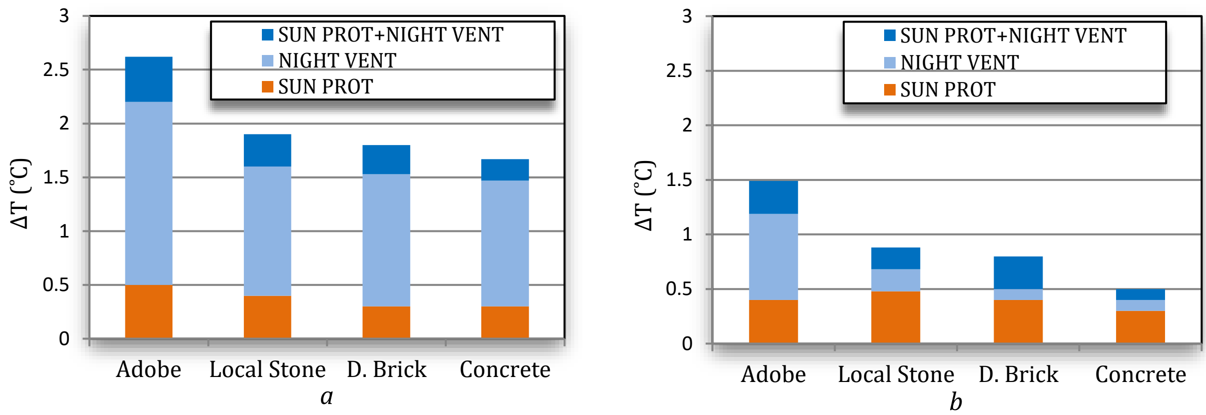


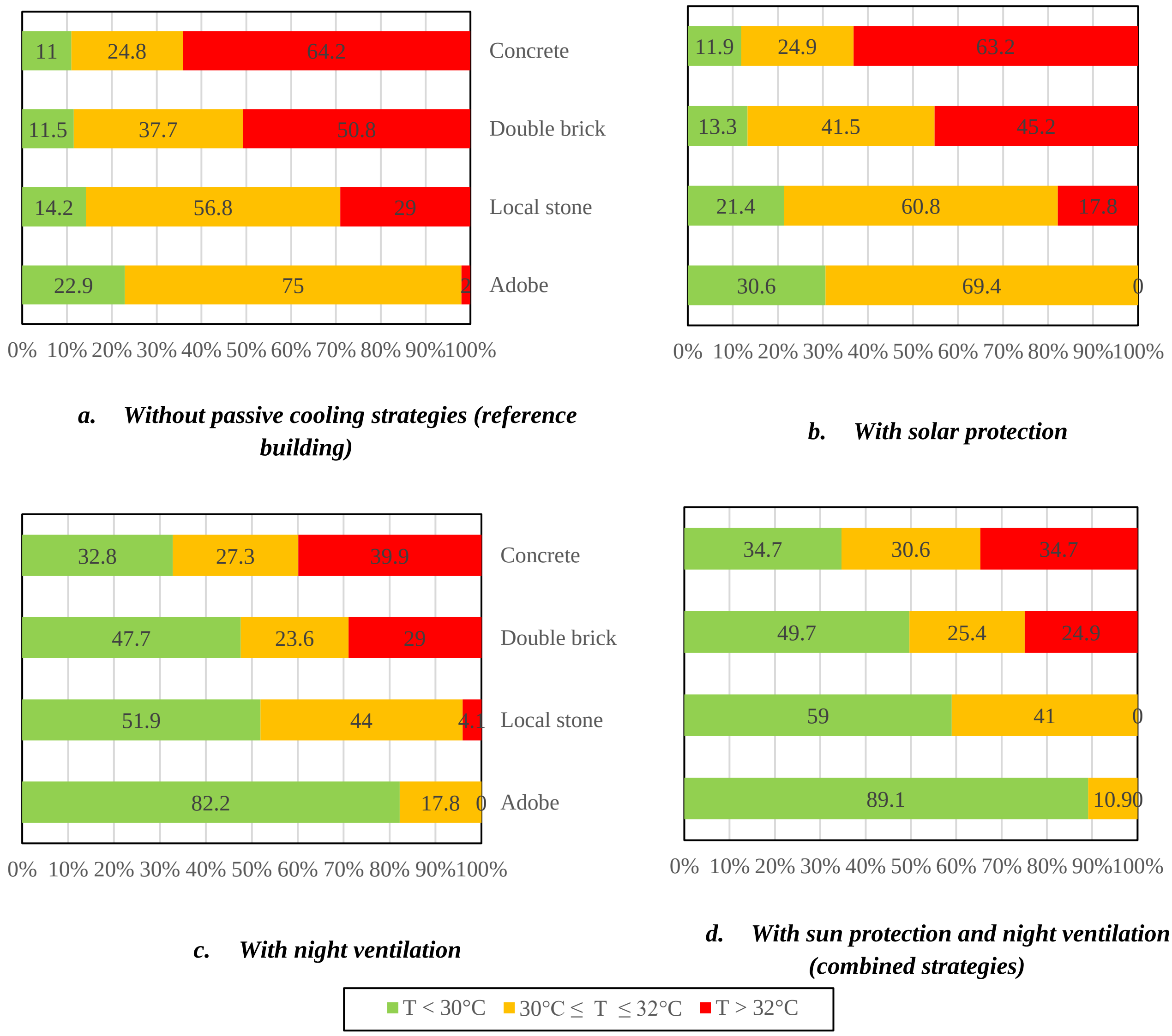
Fig. 8– Building air temperature evolution during a typical summer day (Bechar location)



a- Average daily temperature *b- Maximum hourly temperature*

Fig. 9 – Lowering of temperature with different systems in different buildings

Figure 8 illustrates the temperature evolution in various buildings equipped with solar protection, night ventilation, or both processes simultaneously. The temperatures obtained were compared to those obtained in the reference buildings (without any cooling strategy). It is worth noting that the various modelled systems allow for temperature reduction. However, the results show that night ventilation outperforms overhangs. Night ventilation reduces air temperature, especially at night, with a maximum difference of 3.55 °C in the adobe building, 3.3 °C in the local stone building, 3.49 °C in the hollow brick building, and 3.19 °C in the concrete envelope. During the day, the reductions are approximately 2.34 °C, 0.98 °C, 0.81 °C, and 0.4 °C.



a. Without passive cooling strategies (reference building)

b. With solar protection

c. With night ventilation

d. With sun protection and night ventilation (combined strategies)

Fig. 10 – Percentage of hours when the indoor temperature is lower than 30 °C, between 30 and 32 or higher than 32 in the different reference buildings. Bechar; Months of July and August

Figure 9 depicts the degree of reduction in indoor temperatures recorded using the various concepts. Moreover, a greater reduction in the mean daily temperature in all buildings than in the maximum hourly temperature can be observed. However, the savings are greater in traditional buildings, particularly adobe structures. The effect of thermal inertia, and thus the storage potential that characterizes traditional materials, enables them to store freshness overnight to restore it when the temperature rises.

During the hottest months, the percentage of hours where the indoor temperature is lower than 30°C, between 30 and 32°C, and higher than 32°C was calculated to better characterize the level of thermal comfort (July and August). Temperatures in traditional buildings are usually between 30 and 32 °C, as shown in Figure 10, whereas temperatures in modern buildings are above 32 °C. By incorporating passive systems, these temperatures fall below 30 °C for adobe and stone buildings and remain between 30 and 32 °C for brick and concrete structures.

4.2.2 Assessment of comfort indices

The PMV and PPD indices were also assessed for each building and cooling concept. Figure 11 depicts the PMV frequency distribution, i.e., the percentage of hours when it is between -1 and +1 (slightly cool to slightly warm), between 1 and 2 (slightly warm to warm), and greater than 2 (hot).

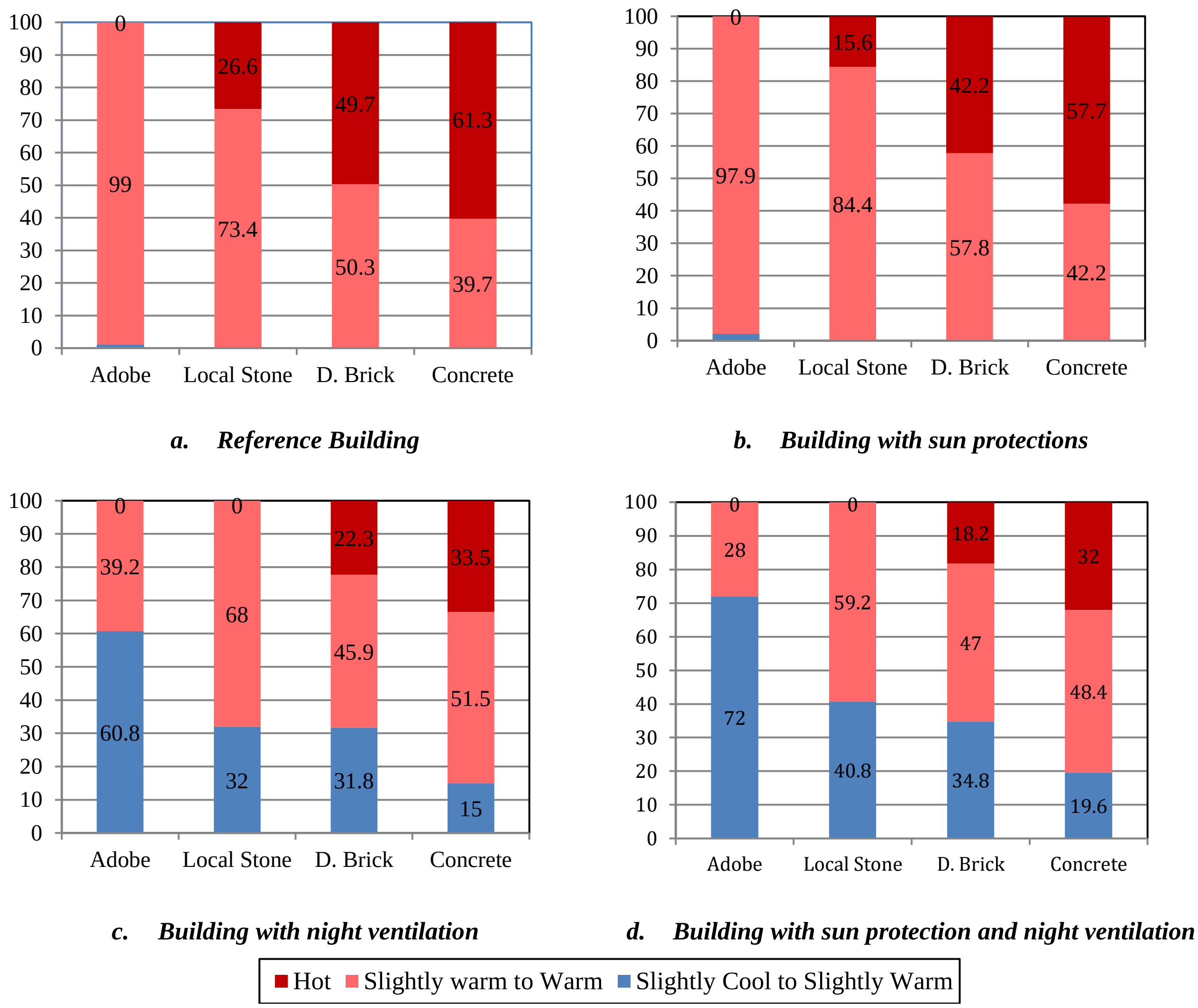
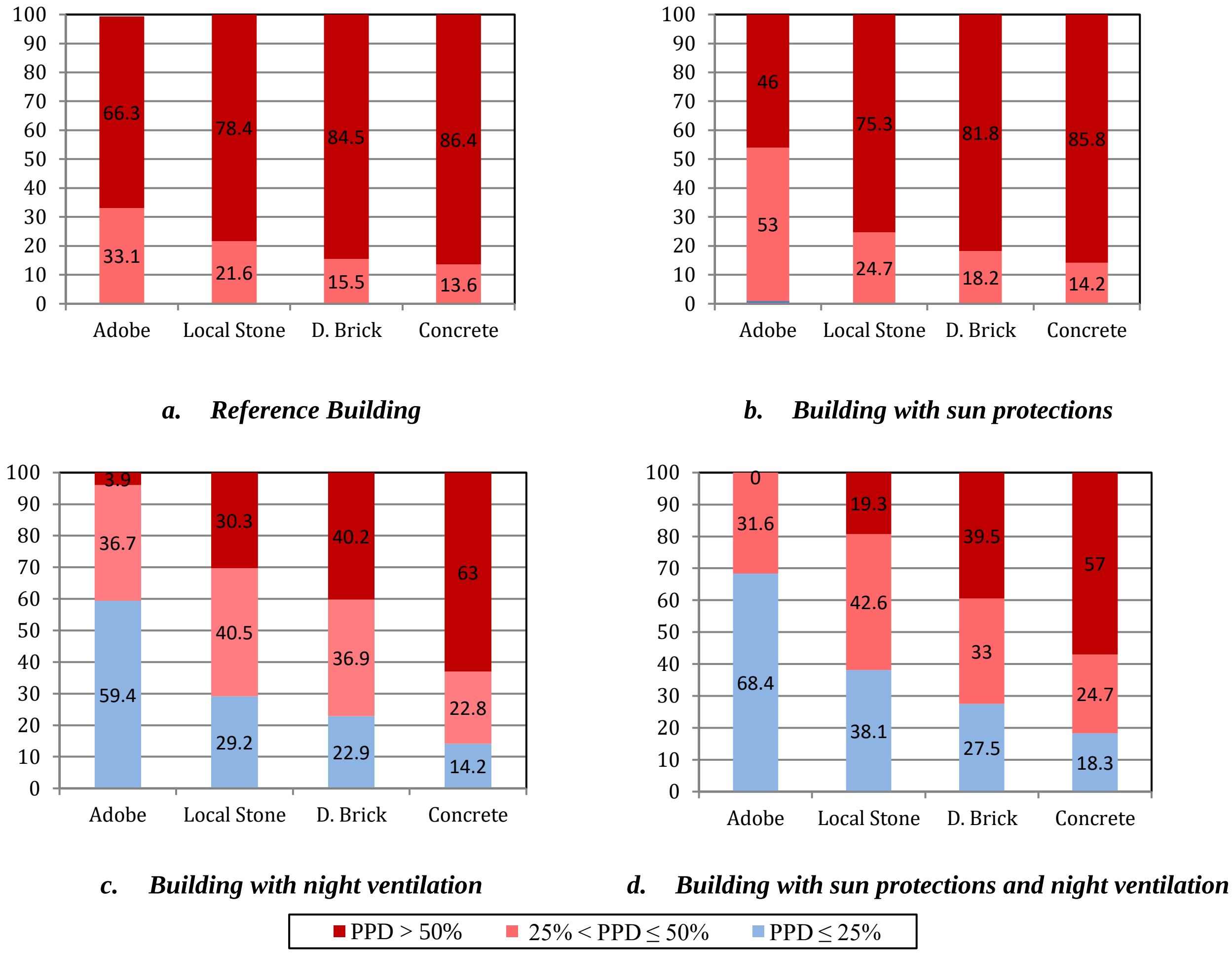


Fig. 11– Frequency distribution of the PMV comfort rate during the summer period (Bechar location)

The results show that in reference buildings, the unbearable feeling of heat is never felt in adobe buildings, but it is recorded 26.6% of the time in stone buildings, 50% of the time in brick buildings, and more than 60% of the time in concrete buildings. Traditional buildings have a slightly warm to warm feeling: 99% with adobe and 73.4% with stone, compared to 50.3 and 39.7% in brick and concrete buildings. The thermal conditions inside buildings improve with sun protection. The frequency of unbearable heat sensation decreases by 10% in stone buildings compared to 7 and 4% in brick and concrete buildings, respectively. However, night ventilation significantly reduces this feeling, and a slight freshness to slight warmth appears in all buildings. It is found 60% of the time in adobe structures, 32% in stone and brick structures, and 15% in concrete structures. It is important to note that the sensation of solid heat vanishes entirely in stone buildings but remains in brick and concrete structures.

The percentage of dissatisfied people (PPD) in basic buildings exceeds 50% of the time (Figure 12): 66% of the time with adobe, 78% with stone, 84% with brick, and 86% with concrete. Unlike the adobe building, sun protection improves these values slightly, but this rate remains greater than 50% more than three-quarters of the time. With night ventilation, the PPD does not exceed 25% 60% of the time with adobe, 30% with stone, and 23% and 14% with brick and concrete, respectively. The percentage of dissatisfied customers who are more than 50% of the time remains relatively high, especially in modern buildings (40 and 63% of the time). Both methods reduce the time when the PPD exceeds 50% and increase when it does not exceed 25%.



a. Reference Building ***b. Building with sun protections***

c. Building with night ventilation ***d. Building with sun protections and night ventilation***

Fig. 12 – Frequency distribution of the PPD comfort rate during the summer period. Bechar location

4.2.3 Evolution of cooling needs

To evaluate the energy performance of the various materials, the cooling requirements of a typical Algerian residential flat were calculated (Figure 13). Figure 14 depicts the obtained results. The useful cooling demand for common constructions is clearly higher than for those made with local materials, and it amounts to 35% if no cooling strategy is used, 40% with solar protection, 52% with night ventilation, and 55% with both night ventilation and sun protection. These findings are consistent with those obtained by Ali-Toudert & Weidhaus [12], who evaluated a residential house as part of a MED-ENEC pilot project and compared it to a typical conventional brick construction in the D climate zone.

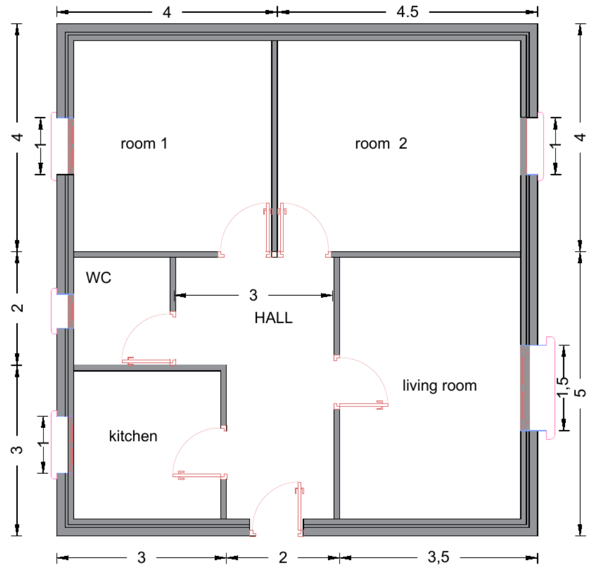


Fig. 13 – Schematic of the studied dwelling as simulated in TRNSYS

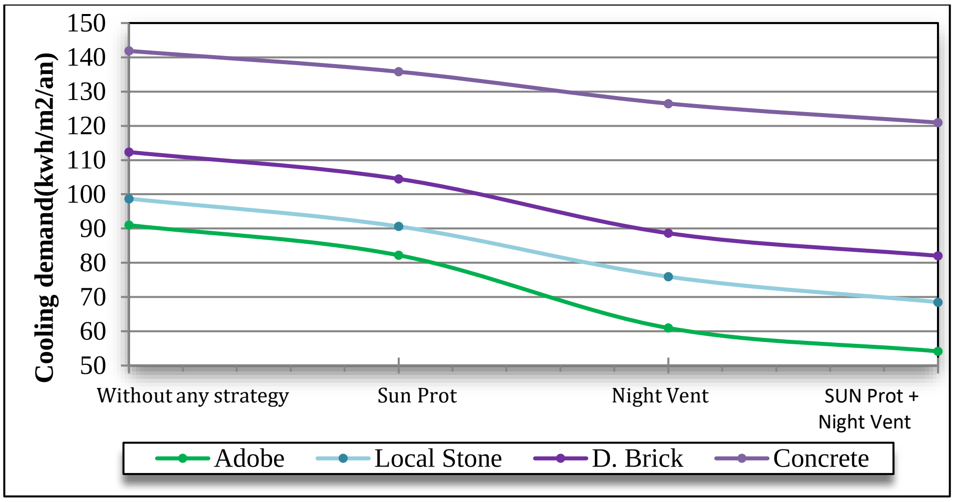


Fig. 14 – Annual cooling needs evolution in the different buildings. Bechar location

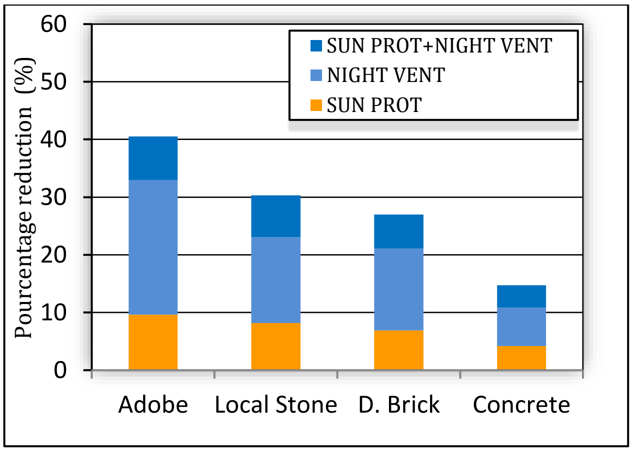


Fig. 15 – Percentage reduction in annual cooling demand compared to reference

Figure 15 shows the reduction rates of cooling needs compared to the reference cases. We noted, for the adobe building, a reduction in needs of 40% with the concept of night ventilation combined with sun protection, 33% with night ventilation and approximately 10% with sun protection.

These values gradually decrease for the stone building (30%, 23% and 8%), the double brick (27%, 21% and 7%) and finally the concrete one with 15%, 11% and 4.2%.

5 Conclusion

This work primarily focused on the bioclimatic analysis of an arid climatic zone in Algeria, namely Bechar, and a numerical study of some standard buildings encountered in this zone using TRNSYS. The efficacy of some bioclimatic design strategies was investigated. The paper includes a numerical study on using traditional rather than modern building materials as a passive mechanism for improving thermal comfort inside buildings in the hot climate of the Bechar region. The main simulation tool was TRNSYS software. The following are the main conclusions:

- The bioclimatic analysis of the arid zone studied using the Szocolay method reveals that air conditioning systems are unnecessary in the early and late summer. Thermal comfort can be improved with passive cooling strategies.
- It appears that natural ventilation is the least efficient strategy. It is most effective during the wet months (May, June, and September) when it can increase comfort levels by 50-60%.
- During the hot months (when humidity is low), indirect evaporative cooling and thermal mass combined with night ventilation are the most efficient strategies. The combined cooling potential of these two strategies was approximately 90%.
- The analysis revealed that natural ventilation has no significant potential for comfort improvement when thermal mass is used, unlike night ventilation.
- Changes in indoor temperatures revealed that traditional materials (adobe or stone) provide better thermal behavior. The thermal gradient reduced significantly, and the indoor environment became more stable.
- During the summer, temperatures above 32 °C are non-existent with adobe, rare with stone, but common with brick and concrete.
- The performance of passive cooling techniques is strongly related to the materials used in building construction which are more efficient in traditional structures. Using night ventilation and sun protection on windows can reduce the average daily temperature in adobe buildings by more than 2.5°C compared to 1.6°C in concrete.
- The results show that in the summer, the level of discomfort is very high, and most of the time, occupants feel the heat with a PPD value greater than 50%. Incorporating passive cooling techniques in various buildings reduces the percentage of dissatisfied people by 30 to 60%.
- Traditional buildings have much lower cooling energy requirements than modern buildings (1.7 to 3 times smaller). Using passive cooling concepts reduces these requirements, but the reduction rates recorded with traditional materials are higher. The broad impact of building thermal mass on the degree of reduction is also very clear in this case.

The selection of an appropriate passive concept for building applications in relation to the local climatic conditions is critical, as climatic conditions necessitate differences in design. Overhang integration should be prioritized in the early stages of the design process for this type of climate. Depending on the climate and building characteristics, the optimal dimensions should be the subject of future research. Future research should investigate thermal comfort in Algeria's climatic zones and develop climate-specific design recommendations.

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