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Research paper

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Residential building forms and energy efficiency in the Saharan climate: the case of Adrar, Algeria

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Summary

Algeria is a country that has witnessed rapid development as a result of its abundant oil supplies. The country's GDP to energy consumption ratio clearly shows the need to adopt energy efficiency policies. Taking into account the regulation of excess solar radiation in the desert environment, this study examines the relationship between the shape of different buildings and their energy use. This research was divided into two stages. In the first stage, the ideal building shape for the city of Adrar, in terms of energy consumption, was determined by studying three basic geometric shapes, including square, rectangular, and triangle shapes. According to simulation research conducted using Design Builder (version 6.1.0), a square building was the best shape to maximize energy performance. To analyze the thermal behavior of different building shapes, all structures with expanded shapes were simulated based on the ideal shape discovered in the first stage. Of the three extended alternative cases, the case of the Mini Arrival offers the best energy efficiency and sufficient natural lighting thanks to its 90 cm depth and no vertical offset from the top of the window. By adding design principles to the design process, this study helps improve the energy efficiency of new buildings and also gives another angle on research methods for solving energy performance issues regarding desert buildings.

Keywords

energy performance • residential building • passive design • building shapes • desert climate

1. Introduction

According to the International Energy Agency, buildings consume between 20 to 40% of the world's total energy demand [Ferrari and Valentina 2012], which is a problem for global sustainability [Benaissa and Khalfallah 2021], especially if buildings are to create lasting healthy and comfortable indoor conditions, regardless of external climatic conditions [Lotfabadi and Polat 2019].

There is growing concern about the increase in energy consumption in buildings and their negative impact on natural resources and the environment. Globally, buildings contribute to the consumption of 35% of materials, 40% of energy, and 12% of potable water [Šujanova et al. 2019]. Therefore, designers had to ensure thermal comfort for residents through good design and reduce the number of months in a year in which residents rely on the use of electric cooling and heating devices.

Buildings gain heat from natural energy sources such as solar radiation entering through the building partitions. It is important to calculate the amount of solar gain emitted into the buildings taking into account the climatic conditions of the region in order to control the amount of energy the building needs for heating and cooling. Intense solar radiation and a high humidity level create the need to use mechanical cooling mechanisms that contribute significantly to the energy consumption of buildings [Wang et al. 2007].

In hot climates, heat gains from solar radiation raise indoor temperatures, requiring appropriate design standards such as shading and natural ventilation. In contrast, thermal gains from solar radiation in cold climates reduce dependence on heating if solar energy is efficiently exploited by designing passive design strategies [Abu Qadourah et al. 2022]. Hence, when considering appropriate limits for insolation and controlling overheating in the initial building design, extra costs can be avoided. This will ensure both thermal comfort and low electricity usage [Pathirana et al. 2019].

The types of residential buildings differ from each other in terms of functional characteristics, space, and design and can be divided into the form of the building and the area. In Adrar, individually owned residential buildings with varying numbers of floors are the most common types. These buildings have special designs and plans that consider the region's climate. Engineers and architects need to take into account the population's adaptation for achieving thermal comfort during the design phase [Šujanova et al. 2019].

The focus of this research is on how to save energy through the forms of residential buildings in the desert state of Adrar, which is characterized by a hot climate throughout the year and receives large amounts of average solar radiation per day, with an abundance of solar radiation estimated at 11 hours per day.

2. Materials and methods

2.1. Location and climate type

The site of the study is Adrar, one of the Algerian desert cities, which is located in southern Algeria between longitudes 01 east and 03 west and between latitudes 20 and 30 north of the equator. It is characterized by a very large area, while the prevailing climate in this region is the desert climate known for its high temperature in summer and low in winter, which leads to the expansion of thermal tide, as the seasons of the year are usually similar in weather. Adrar is very rich in Solar energy, due to the average brightness of the sun of about 6 kWh/m^2. The hottest months are May (39°C–42°C), June (42°C–43°C), July (43°C–50°C), August (42°C–50°C), September (43°C–45°C).

Table 1. Climatic data from the Adrar region

	June	**July**	**August**
Max. W/m^2 flow	1052	1051	1040
Tmax [°C]	42.4	47.8	47.7
Tmin [°C]	25.6	32.5	39.0
Duration of the day [h]	14	14	13
Sunrise [h]	5	5	6
Sunset [h]	19	19	19

Source: Ourdane et al. [2017]

2.2. Study framework

The use of software that runs in a dynamic system is essential to ensure the simulation is as close as possible to reality [Renghi et al. 2021] and other research groups have focused on building energy, and developed various architectural and mechanical techniques to reduce energy consumption in buildings. The development and evaluation of these techniques require experimental and/or computer simulation methods [Kim and Yeo 2020]. Although many studies have focused on the relationship between building elements and energy performance, most have analyzed building design and system rather than construction engineering [Sanaieian et al. 2014].

Three basic geometric shapes: square, rectangular, and round were taken into account during the creation of the basic designs in this study in order to determine the best residential building shape for the city of Adrar in terms of energy use. DesignBuilder software was used for modeling and energy simulation. DesignBuilder is a simulation program that can take into account the casing and interior elements of buildings [Mohsenzadeh et al. 2021], and also gives a prediction of the energy performance of the modular building, which could give greater benefit to studies related to energy efficiency and environmental comfort during the project [Montenegro et al. 2021]. The adoption of an upward approach ensures good accuracy of the results, which is enhanced by the presence of the EnergyPlus, a construction simulation software created and updated by the US Department Energy [Alghoul 2017], that allows consideration of the impact between buildings and contemporaneous energy loads [Ascione et al. 2021].

The EnergyPlus engine, which has a three-dimensional interface and a meteorological database, is the foundation for DesignBuilder. In Adrar, three engineering ideas were studied to enhance energy efficiency, thermal comfort, and natural daylight at the same time. After choosing the first step of the best basic shape, DesignBuilder is used to simulate three-story buildings of different shapes under the same climatic conditions to analyze the energy consumption of different building shapes.

2.3. Modeling and simulation

In our research, the optimization process consists of two steps.

In the first step two design criteria (location and orientation) were adopted in order to analyze the energy performance of the various shapes and samples that were proposed with an area of 225 m^2 (Table 1). The direction was not determined because the models were compressed.

Table 2. Basic plan geometry

Shape*	1	2	3
Dimension [m]	15 × 15	12 × 18.75	8.46 × 8.46

* Shape: 1 – square building, 2 – rectangular building 3 – circular building

Source: Authors' own studies 2023

Information about buildings and their characteristics was entered into Design Builder through its building characteristics databank in accordance with ASHRAE 90.1 standard and tested. The comparison and analysis were carried out by EnergyPlus, the construction energy simulation software, and Table 2 shows the operating details and simulation inputs.

Table 3. Building characteristics, operating details, and simulation inputs for buildings

Parameter	Specification
Building properties	
Normalized power density	2.50 W/m^2–250 lux
HVAC system type	Major HVAC system
Shading	Without inside shading
Window-to-wall ratio (WWR)	30%
Building operation details	
Heating set point temperature	21°C

Fuel	Natural Gas
	Electricity from grid
Cooling set-point temperature	25°C
Type of lighting	LED
Lighting target illuminance	300 lux
Control temperature	Operating temperature
Occupancy density	0.014 people/m^2
Mecha wind per surface [l/s–m^2]	0.305
Seasonal heating system	0.150
Total building area [m^2]	225

After determining the ideal shape in the first step, other options for self-shading building forms were considered in the second step. The models of the buildings were 3 floors high with an area of 225 m^2, with three distinct floor plans for each building. The height of the building is set at 10.5 meters, with a health protection rate of 30% for all façade heights.

3. Results and discussion

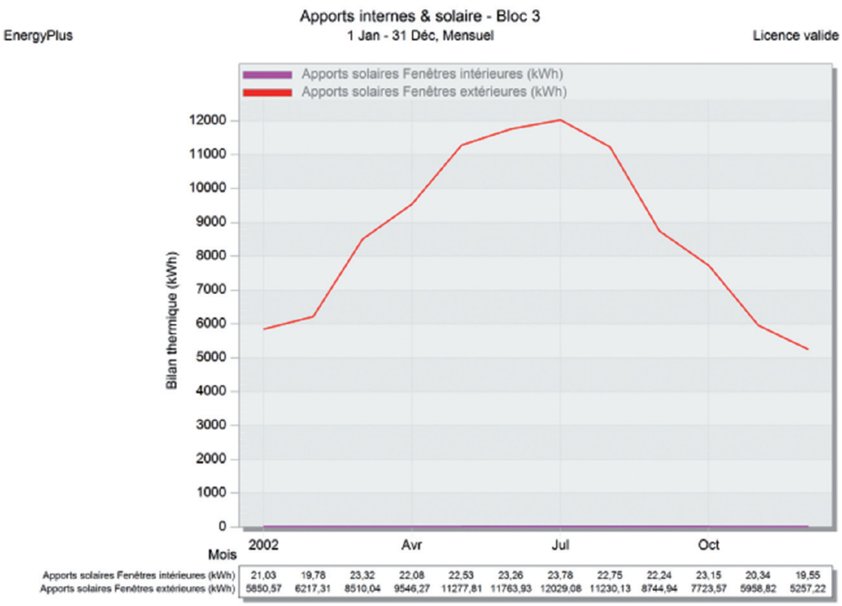
The results of the research indicated that there is a large amount of solar energy in the city of Adrar and on buildings, which makes various types of buildings in increasing demand for mechanical cooling mechanisms. Although solar radiation is a factor of great importance in equalizing the value of thermal transfer, intensive solar radiation affects the requirements for the use of mechanical cooling mechanisms and significantly increases the energy consumption of buildings. Hence, designing the building through its shape can help with Energy Efficiency in Buildings [Chel and Geetanjali 2018].

The results obtained and the comparison between the three shapes of buildings confirmed that the square shape achieved the lowest consumption of about 10043.16 kWh in one year. The round shape achieves the highest consumption at about 12468.05 kWh per year. Rectangular shapes consume about 10884.26 kWh

The results of this study showed that the amounts of thermal and solar energy received by buildings in the city of Adrar depend on the shape of the completed buildings, and looking at the unified area between them, we find that the square shape achieved the best energy performance with a capacity of 237.75 Wh/m^2 because it gets the least amount of energy. For thermal and solar energy, the circular shape had the third best energy performance B, while the rectangular shape got the second best energy performance.

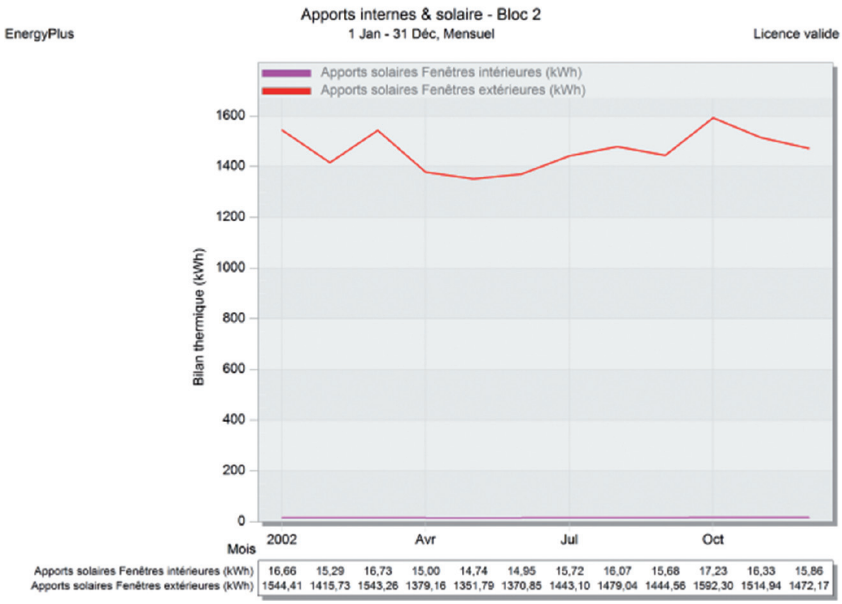
The data also showed that as a result of the high solar energy gain in the city of Adrar, cooling loads accounted for the largest demand. The demand for public lighting did not vary significantly. Intense solar radiation affects the need to use mechanical cooling systems and significantly increases energy consumption in buildings as solar radiation is the most important element in the equation of the total thermal transfer value. Therefore, using the shape of the building to create building designs that are compatible with the desert climatic nature can help increase the energy efficiency of the building. The results of the analysis also showed that the shape of the square building received approximately 68% of the total solar energy exchange, with the circular and rectangular shapes receiving about 61% and 59%. When comparing the three basic shapes, we find that the circular shape consumes the most energy, while the square shape consumes the least energy.

Looking at the same space for each design, the square shape of the building had the highest energy performance, achieving about 78.02 kWh/m^2, due to the lowest solar gain, 17551.30 kWh. However, the rectangular shape had the greatest solar gain, which affected the cooling load and, consequently, the amount of energy consumed. Circular shapes also absorbed the second largest amount of energy and obtained the most solar gain.



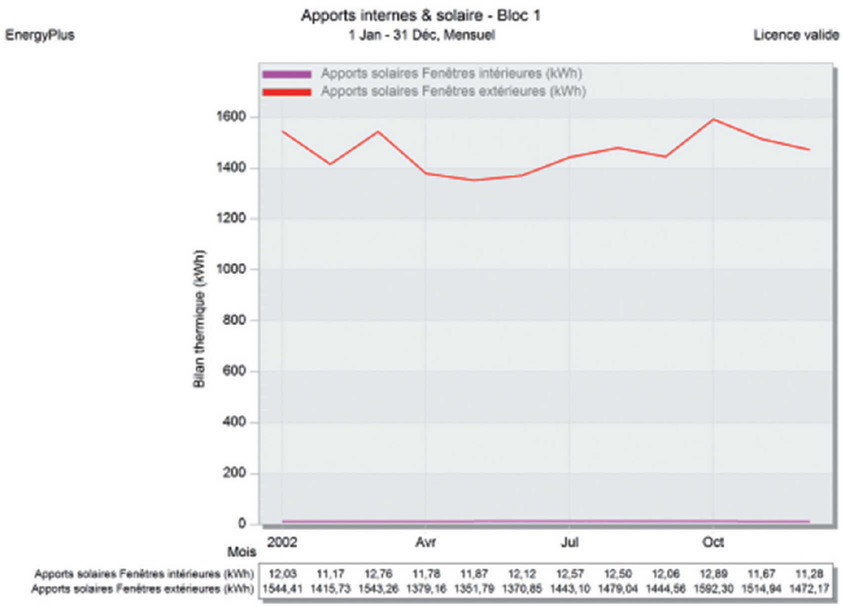
Source: Authors' studies based on Design Builder 2023

Fig. 1. Energy consumption of a single-story building



Source: Authors' studies based on Design Builder 2023

Fig. 2. Energy consumption of the double-story building



Source: Authors' studies based on Design Builder 2023

Fig. 3. Energy consumption of the three-story building

3.1. The effect of the building form factor on daylight assessment

The level of illumination is an important factor as sufficient sunlight creates a pleasant and relaxed interior atmosphere in the building. Reliance on electric lighting can be significantly reduced by getting enough sunlight and daylight. However, high brightness leads to increased glare and heat. Projected shading devices and building design in the simulation prevented potential glare areas. One-, two-story, and three-story buildings were within the typical range of interior lighting, generally a three-story building produced the largest average daylight factor, while a one-story building had the lowest average daylight factor, about 19% lower than case 1. The one-story building produced about 569.75 lux from the average annual daylight factor, the two-story building received 572.29 lux, and the three-story building received 461.54 lux.

3.2. The effect of the building form factor on energy consumption

A large number of efforts have been made in the literature to ascertain the complexity related to building energy consumption and to seek an accurate depiction of the energy performance of a construction [Yixuan et al. 2018]. Assessing the energy consumption of a building is an essential step in improving its performance [Mohsenzadeh et al. 2021]. In this section, the analysis focuses on the impact of building shape on annual energy consumption and energy (EEI). The electrical power index (EEI) refers to the ratio of energy consumption (kWh) per unit of floor area (m^2). Caruso and Kämpf [2015] analyzed the optimal three-dimensional shape of buildings that reduce energy consumption (air conditioning needs) due to solar radiation using an evolutionary algorithm. Furthermore, the coefficient of form is defined as follows [Depecker et al. 2001]:

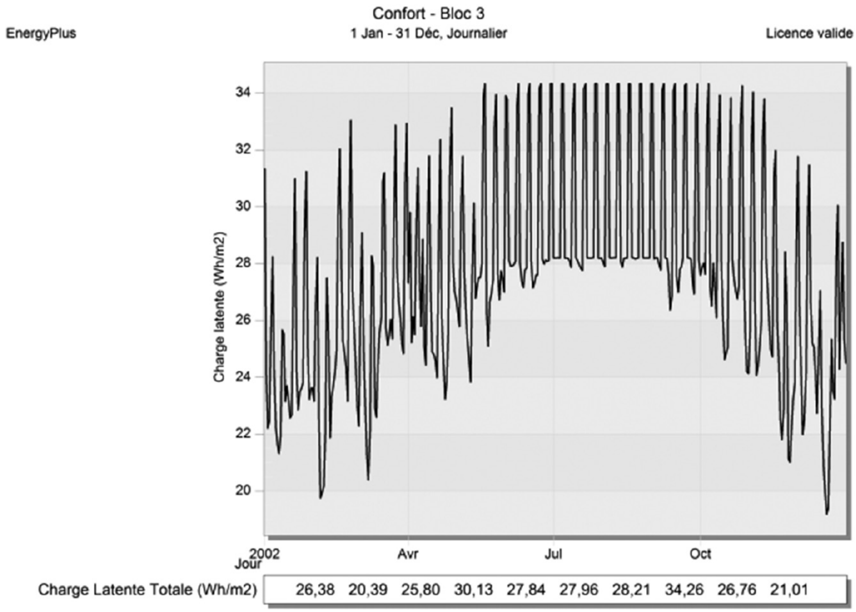
$$C_f = S_e / V \tag{1}$$

where:

S_e – the envelope surface area,
V – the inner volume of the building.

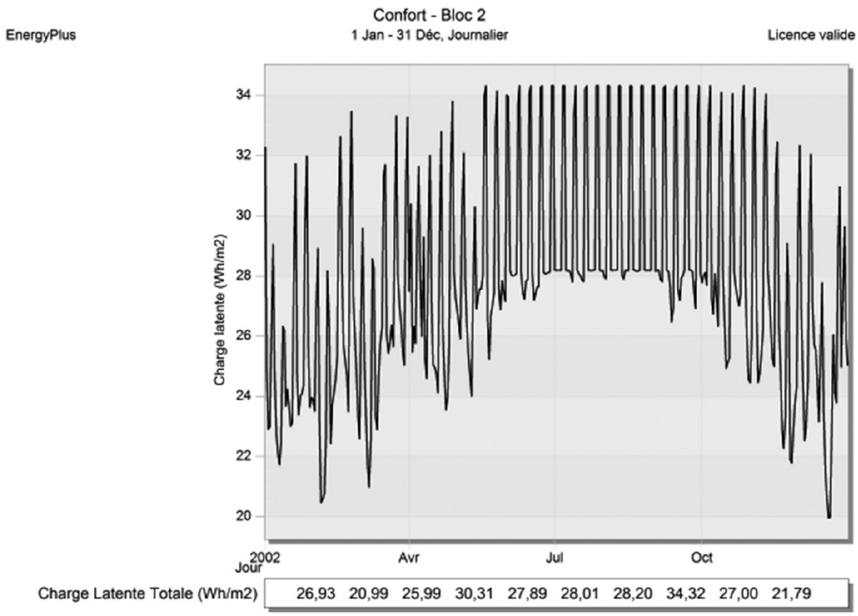
The results show that there is a relationship between the energy consumed and the amounts of solar radiation emitted, as it was found that the single-story building has the largest solar energy gain and the lowest energy consumption of 10045.44 Wh/m^2. While two- and three-story buildings had similar results in terms of energy consumption and access to solar radiation, it can be said that building forms have the ability to reduce the acquisition of direct solar energy. The proposed acceptable range of the Electric Power Initiative (EEI) for residential buildings is 150–400 kWh/m^2.

In order to assess the effects of the building model on energy performance, the total cooling loads of each building were verified, and according to the solar route chart in Adrar, solar radiation increases during the months with the highest temperatures. Figure 4 shows the cooling loads for the year with the highest cooling load in August and the lowest in February. The single-story building showed the lowest cooling load



Source: Authors' studies based on Design Builder 2023

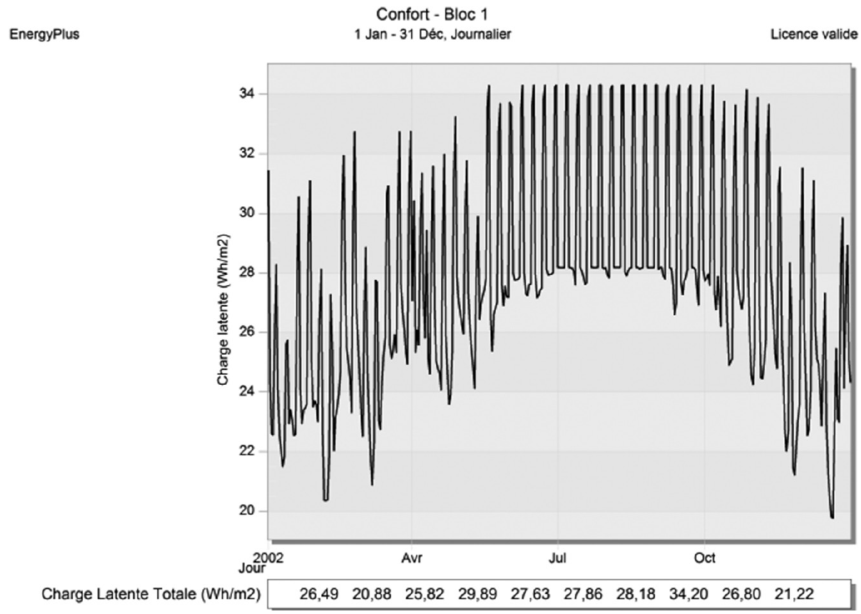
Fig. 4. Energy consumption of a single-story building



Source: Authors' studies based on Design Builder 2023

Fig. 5. Energy consumption of a double-story building

quantities while the highest cooling load was for the three-story building. The results of the study indicate that the demand for cooling is mainly related to solar radiation that is on the vertical surface of building envelopes.



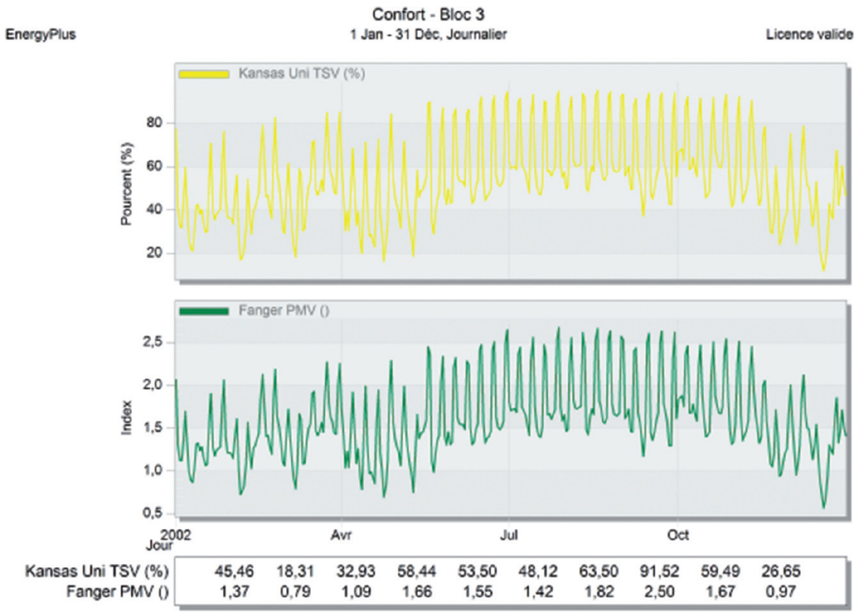
Source: Authors' studies based on Design Builder 2023

Fig. 6. Energy consumption of the three-story building

3.3. The effect of form factors on thermal comfort

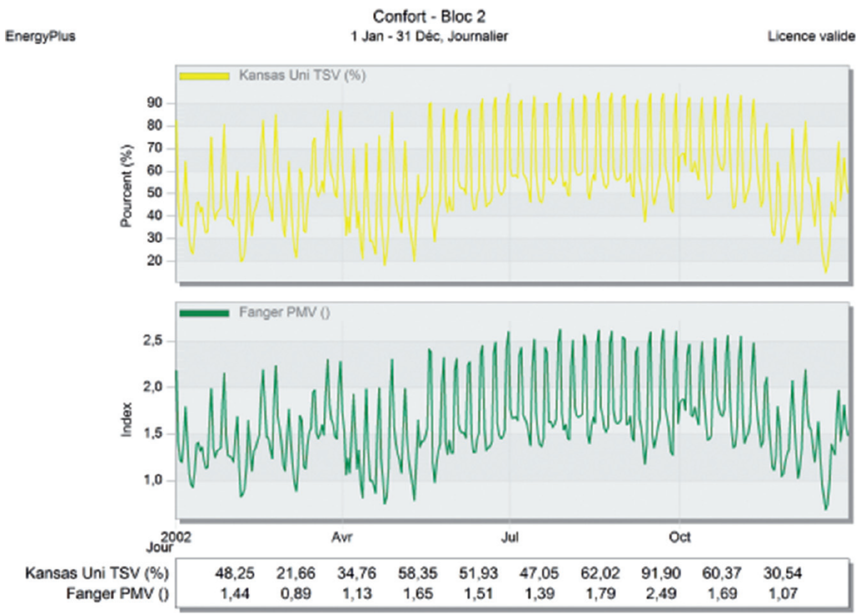
Analysis of thermal comfort according to the three modes is an important factor by examining the average rating index (PMV) as the prominent thermal comfort index [Mohsenzadeh et al. 2021]. Thermal comfort was measured by the Fanger PMV model based on the following factors: air temperature, air velocity, radiant temperature, and relative humidity as they are all considered environmental factors. The PMV indicator determines the degree of comfort and is shown as a psychological measure of the physicist hot (+3), warm (+2), slightly warm (+1), neutral (0), slightly cold (–1), cold (–2) and cold (–3). The most suitable range is between –1 and +1 [Enescu 2017].

PMV values range from +0.86 to +2.51, and since Adrar sees temperatures above 35°C, especially in summer, the results were to indicate that there is no thermal comfort within the acceptable range in all buildings. The single-story building showed the highest thermal comfort and the lowest PMV, while the two-story and three-story buildings displayed the highest PMV index.



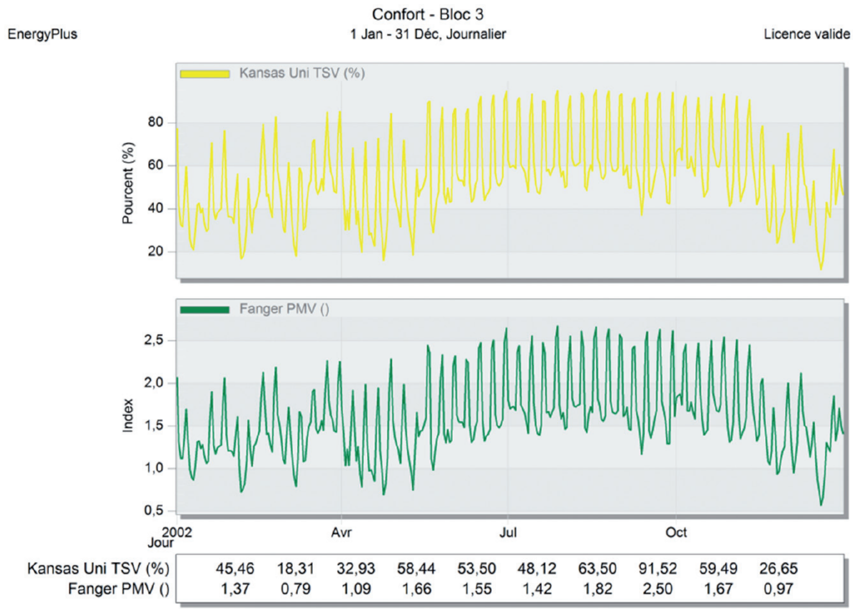
Source: Authors' studies based on Design Builder 2023

Fig. 7. PMV for single-story building



Source: Authors' studies based on Design Builder 2023

Fig. 8. PMV indicator for double-story building



Source: Authors' studies based on Design Builder 2023

Fig. 9. PMV indicator for the three-story building

In Adrar, there is an increasing demand for energy for cooling, especially in the summer, as a result of the solar radiation to which the roofs of buildings are exposed. The current study researches the effects of the shape of buildings to control excessive energy consumption through designs, where a comprehensive and integrated approach was adopted to control solar radiation with an increase in thermal comfort and energy performance. In the first phase of the study, three forms of buildings (rectangular, square, circular) with a uniform area of 225 meters were analyzed. The results showed that the shape that has effective energy performance is the square shape, and in the second stage, the interface was researched based on the shape that had effective energy performance and increased the thermal comfort obtained based on the climate of the city of Adrar in the first phase.

The approved floor plans for the study in the city of Adrar were designed with traditional dimensions to align with the urban and architectural characteristics of the area. The design took into account factors like solar energy potential and simplicity. After considering various alternatives, it was found that a 225 square meter area with a single floor in a square shape had good energy performance, achieving a 1.59 PMV rating. The daylight factor was acceptable with satisfactory performance, indicating its adequacy within the building.

Similarly, depending on the number of floors, the results showed that the three-story model is the one that uses the highest energy levels of 1.64 PMV with an acceptable daylight factor of about 1.64 PMV. Finally, the two-story building showed good energy performance and is close to the single-story building as the energy consumption is close to 1.61 PMV. It also got a good rate in the daylight factor on this basis. The ideal model and alternative in terms of energy performance and thermal comfort index is a building with one floor.

Shading is an important factor in architectural designs because it plays an important role in reducing the building's energy consumption [Mohsenzadeh et al. 2021], a finding that is consistent with the findings of Capilloto [2003], who found that advanced shading reduces energy consumption per building per year by an estimated 20.5%.

The two-story building showed better energy performance compared to the one-story building and the three-story building due to the design and engineering specifications, and the results showed that the vertical displacement to the top of the window in which the depth of the deception is effective in terms of improving energy performance, and the three buildings were compared with each other where it was revealed that the two-façade building has the lowest energy consumption. The results of this study show that improving the shape of buildings according to design standards leads to a reduction in energy consumption, as the self-shading method in buildings continues to have a significant contribution to reducing energy consumption. On this basis, the current study can be considered one of the important steps in the broad understanding of the impact of the shape of buildings and the number of floors on energy performance in desert areas.

4. Conclusions

The results of this study can also be relevant in similar hot regions with the same climatic conditions. At the same time, it is just preliminary, and based on this study, many other aspects of passive design can be further investigated. The fixed WWR value is one of the limits of this work. It will require exploring how different building types and WWR types affect energy efficiency and solar gain. Various significant shortcomings of this study that require future research include non-consideration of operating costs, solar PV potential, various forms, and other climatic zones.

Energy efficiency is one of the main objectives of the country's energy strategy and it can be improved by embedding specific design methods in the design process; this study contributes to improving this process. Evidence reveals that architects and designers focus more on aesthetics than on climate and energy efficiency when constructing structures. In the meantime, many people living in apartment buildings are unaware of how much energy they use or lose during daily activities. Therefore, experts need to devise creative technology to conserve energy while taking into account the daily needs of people.

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