

Energy Performance of Vernacular Architecture in Various Desert Climates

¹ Magali Massia, ² Philippe Devillers

¹ École Nationale Supérieure d'Architecture de Montpellier, 179 rue de l'Espérou 34 093 Montpellier cedex 5, France.

email: magali.massia@montpellier.archi.fr

<https://orcid.org/0009-0006-8400-3752>

² Laboratoire Innovation Formes Architectures Milieux, École Nationale Supérieure d'Architecture de Montpellier, France.

email: philippe.devillers@montpellier.archi.fr

<https://orcid.org/0000-0002-7026-1818>

Abstract

Summer 2022 is officially the 2nd hottest summer in France since 1900. It resulted in three episodes of heat waves over a total of thirty-three days. Heat waves are characterized by very high temperatures (exceeding seasonal averages) during the day and night for at least three consecutive days. According to initial estimates, it caused a surplus of more than 11,000 deaths in 2022 in France. In France, despite new thermal standards, the thermal comfort of new housing in hot weather remains very inadequate. Thanks to these empirical developments vernacular architecture has demonstrated its adaptation in particularly harsh climates. The objective of this research is to understand the design strategies of four vernacular houses located in four deserts (Algerian Sahara, Arizona, Libyan desert and Yemen) to ensure summer comfort in hot environments. The thermal behavior of these four vernacular houses has been studied through dynamic thermal simulations performed with the software 'ArchiWIZARD', using the same climate conditions. The results are interpreted in terms of operative temperature and related to building compacity. They show how vernacular architecture, located in desert climates, considered summer thermal comfort with design strategies. The thermal inertia of the four case studies is characterized by the daily thermal damping. The results also show the contribution of natural night ventilation on the energy performance of these four vernacular architectures in hot and arid climates.

Keywords: Vernacular Architecture; Desert Climate; Dynamic Thermal Simulations; Night Ventilation; Design Strategies.

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1. Introduction

Summer 2022 is officially the 2nd hottest summer in France since 1900. It resulted in three episodes of heat waves over a total of thirty-three days (Santé Publique France, 2022). Heat waves are not a new phenomenon. It is characterized by very high temperatures (exceeding seasonal averages) during the day and night for at least three consecutive days. Its recurrence in the same summer and its long duration alert us to future risks. According to initial estimates, it caused a surplus of more than 11,000 deaths in 2022 in France (Santé Publique France, 2022). It is due to the presence of a stationary dome of high pressure in the upper atmosphere which causes a rise in the temperature of air enclosed under this dome. Despite new thermal standards in France, the poor thermal performance of modern buildings is impressively questionable. Vernacular architectures, located in desert climates, have instead shown their adaptation to

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hot and arid climates without technical devices (Alp, 1990). To understand the keys to summer comfort, this study focuses on the thermal comfort of four vernacular dwellings located in desert climates.

Vernacular architecture is a domestic production that escapes the market. It is a product of space and time that results from the interactions between resources, culture, and environment (Frey, 2010). Vernacular architecture merits our study for its principles and the intelligence of its constructive strategies. Throughout history, many vernacular materials such as adobe construction have been used in different regions of the world, under different climates with different constructive cultures (Aziz et al., 2011; Fitch, 1960). Many vernacular design strategies such as courtyard houses and passive cooling systems have been successfully used in contemporary buildings (Hyde, 2008).

In its bioclimatic design, contemporary architecture is not satisfied with a biomorphism, it implements natural mechanisms to integrate elements in the project: air, light, heat, coolness, and water. In its form and spaces, it is designed from the dynamic exchanges between man, buildings, and natural elements (Madec, 2021). The bioclimatic design is based on morphology, solarization, transparency, porosity, insulation, inertia, and ventilation. In hot and arid climates, solar radiation is the main source of heat. The openings are small, and the surface of the exterior walls is white to absorb a minimum of heat by radiation. Dwellings in arid regions of the world are built with earth or stones because of their relative availability, ease of transport, and durability, as well as their potential for maintaining a comfortable interior environment. The walls serve as thermal mass, slowing down the transfer of heat from exterior to interior spaces during the day and performing the opposite function at night.

To understand the thermal performance of vernacular dwellings in desert climates, several approaches are available. Matthews (1985) performed thermal measurements in a dwelling in Sana'a, built with sun-dried bricks 40 cm thick, and with a traditional earth roof. The walls were coated outside with earth, and inside with plaster. The outside temperature, the internal room temperature, and the ceiling temperature were measured during the cold season. The ambient temperature is between 19°C and 21°C over a day, while the outdoor temperature ranges from 6°C to 27°C. The ceiling temperature fluctuated between 21°C and 25°C. Gil Crespo and al. (2014) use bioclimatic charts such as Olgay or Givoni's to assess the thermal performance of vernacular architecture. Starting from numerical simulations Alrashed et al. (2017) study the role of courtyard, mushrabyah, and sun-dried bricks in the five main Saudi climatic zones. Stefanizzi et al. (2016) study the thermal behavior of circular structures built entirely with a stone called «Trulli» using in situ measurements and numerical simulations. Identical results were obtained by Cardinale et al. (2011) on the same building using in situ measurements and numerical simulations. In summer the indoor temperature always remains below 26°C. In winter, the heat accumulated during the summer in the massive stone walls is restored, which helps maintain a comfortable indoor temperature. In this study, after a detailed presentation of the four case studies and their environment, the four dwellings are first modeled in three dimensions. Dynamic thermal simulations (DTS) are then carried out with a single climate file during April which corresponds in terms of average temperature to a summer month in France. The simulations are performed with and without natural night ventilation. The results are interpreted in terms of operative temperature and related to building compactness. The thermal inertia of the four case studies is characterized by the daily thermal damping.

2. Literature Review

2.1 Vernacular architecture in desert climates

In desert climates, due to the large daily outdoor temperature range, strong inertia of the walls and roof are required to maintain a comfortable indoor temperature throughout the day without any technical devices (time-lag greater than 8 hours).

2.1.1 Location and environment of the four case studies

The different case studies have particularities to their history, cultures, and religions, making their approach unique and adapted to the place and the inhabitant. Figure 1 gives the location of the four case studies in the map of Köppen — Geiger, climate classification. Table 1 gives the height and the precise location of the four case studies. Most Saharan cities, like Balat and Ghardaïa are located near to a valley or Oasis for the adaptation of the climate conditions (Benyoucef et al. 2018).

Table 1: Location of the four case studies.

	Balat, Egypt	Ghardaïa, Algeria	Tohono O'odham, USA	Sa'dah, Yemen
Latitude	25°33'50" north	32°29'00" north	31°34'07" north	16°56'09" north
Longitude	29°15'57" east	3°41'00" east	111°03'02" west	43°45'52" east
Height	127 m	566 m	635 m	1800 m

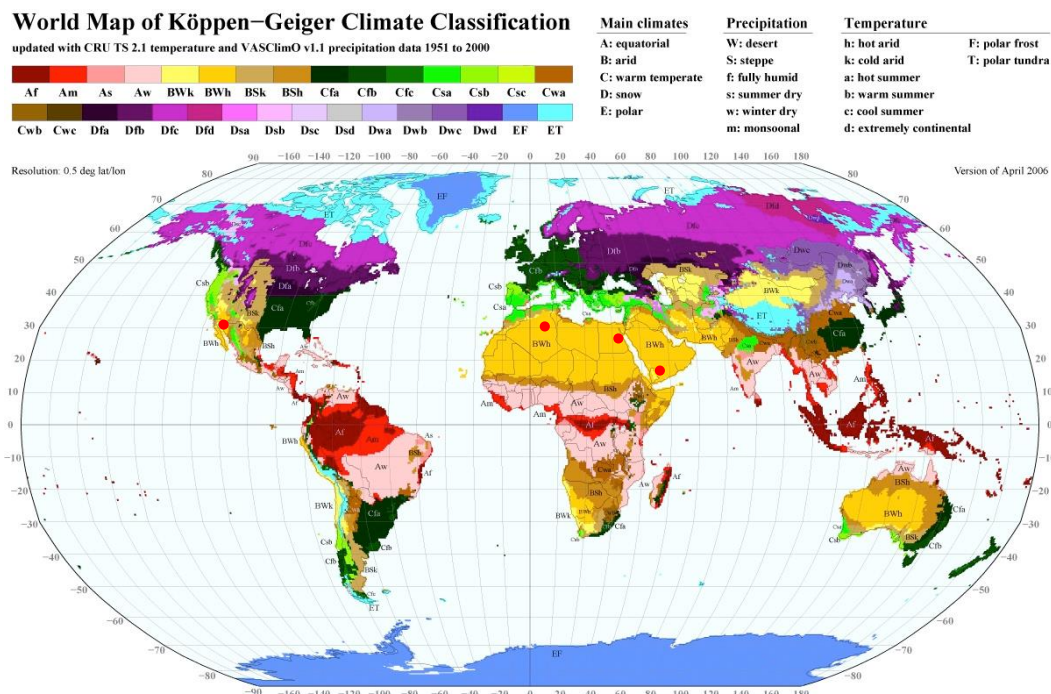


Figure 1. Location of the case studies in the map of Köppen — Geiger, climate classification. (Kottek et al., 2006).

Like many desert towns, Balat is located near an oasis, Dakhla Oasis, in the western Egyptian desert (Bard, 1999). The urban morphology of Balat (Figure 2a) shows a network of voids of different sizes ranging from small shaded streets to large sunny squares. This specific urban fabric creates a flow of fresh air from the narrowest alleys to the widest spaces (Dabaieh, 2011). This organization of urban space also corresponds to a gradual transition from public to private space by varying degrees of accessibility.

The M'Zab has kept a kind of independence because of its isolated location (600 km south of the capital Algier). The M'Zab valley has not been marked by invasions. This is due to the layout of the fortified ksour limiting the impact of attacks. The M'Zab valley is known for its architecture designed to adapt to the harsh climatic conditions of the region. Each 'ksar' (castle) is located on a rocky promontory overlooking the valley (Gueliane, 2019). The very compact urban shape of the ksar protects it from sandstorms while having a minimal footprint (Figure 2b). This very compact urban shape also minimizes the exposure of the walls to solar radiation while allowing shaded narrow streets.

In the southwest Arizona, The O'odham aborigines settled in the Sonoran Desert based on water availability. Tribal dwellings consist of individual houses separated by large areas of natural vegetation (Figure 2c). When the tribe expanded new housing was built. This dispersed dwelling leads to a loose morphology. Sa'dah, located in the 'Sarawat' Mountains, is one of the first medieval cities in Yemen. Sa'dah has a cohesive tissue (Figure 2d), consisting of markets and mosques. In Yemen, society is made up of different tribes divided into clans and families. The vertical buildings are dominant and form the residential communities (Attia, 2020). The urban form is much less compact than that of Balat and Ghardaïa.

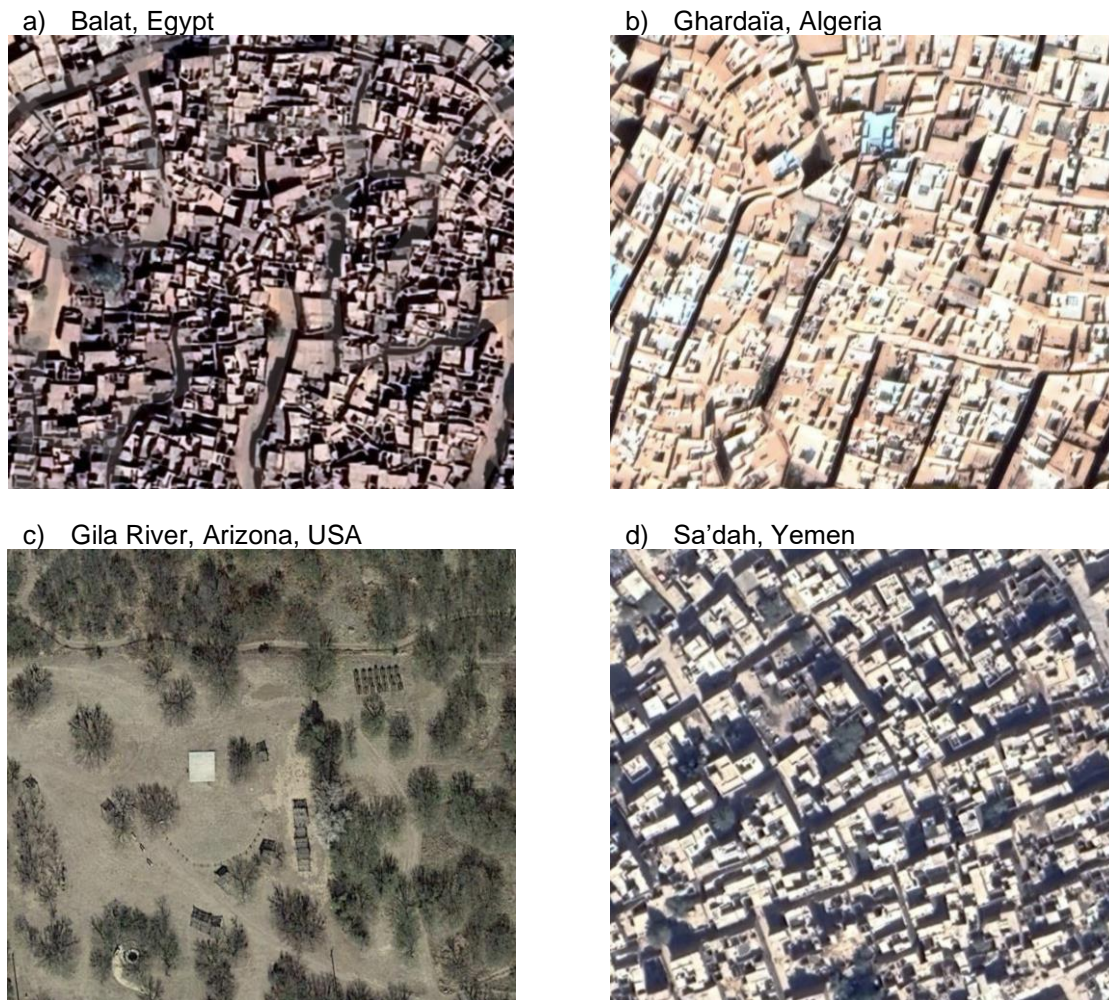


Figure 2. Environment of the four case studies.

2.1.2 Description of the four case studies

One of the main characteristics of the houses of the city of Balat is their softness due to the absence of sharp angles and the use of a very fine finishing plaster made of silt and clay (Figure 3a). The Balat case study consists of two stories of mud brick construction (Figure 4a). It is rectangular in plan with a few overhangs and has a floor area of 99 m² spread over two floors as well as an accessible roof terrace of 33 m². The house consists of a living room, a kitchen, three bedrooms and a storage room. The overhangs located on the west facade protect the walls from intense solar radiation. The two windows on the first floor are narrow (0.40m x 0.50m) and high up. The stairwell is used for natural ventilation by chimney effect. In addition, terracotta bottomless vases are included into the floor of the flat roof to promote natural ventilation and bring light. During cold winter nights these holes can be closed. The walls, 55 cm thick, have a great thermal inertia and are made of sun-dried bricks. The ceiling height is around 2.25 m. The floors are made with acacia logs and palm branches and leaves. The whole is covered with a layer of earth mortar (2 cm), on which is placed a layer of sun-dried brick. As a finishing touch, 10 cm of earth plaster is put in place to flatten the ground.

The house in Ghardaïa is a typical interior courtyard house which is the most effective and adaptive house in this environment. The ground floor occupies an area of 92.1 m² and has seven rooms and no opening except the front door (2.33 m²) usually left open for ventilation. Indeed, the house has no facades. The dwellings of the ksar are glued together and therefore have a large number of adjoining walls to minimize exposure to solar radiation. Most of them have only one facade on public space allowing access. The 50 cm thick limestone walls are 2 m high and support palm joists spaced 30 cm apart. A slat of very tight fins rests on the joists and supports a layer of 23 cm of compacted sand and a 14 cm thick lime mortar screed.

This intermediate floor is broken through by the “chebeq” which opens onto the patio of the first floor (Figure 3b). The first floor of an area of 78.7 m² is much more open and has four rooms. To guarantee the minimum of natural lighting and ventilation, it runs towards the interior on a patio (Figure 3b). The porticoes on the first floor open onto the patio and face south-east and north-west (this part of the house is the much more open toward the exterior and is exposed to climatic conditions). The patio allows minimal lighting of the rooms on the ground floor. It is also used as a climate regulator. In summer the “chebeq” is covered in the day to prevent sunlight from entering the house. During the night it is open to allow the exit of warm air from the house and the penetration of cooler outdoor air (Figure 4b). In winter it is the opposite that happens the “chebeq” is closed during the night to protect from the cold and open during the day to take advantage of the heat of the sun. Thus, this horizontal and introverted architectural composition is intended to best adapt to the harsh climatic conditions. As in the summer only ground floor is used, in this study, only the ground floor will be considered for dynamic thermal simulations.

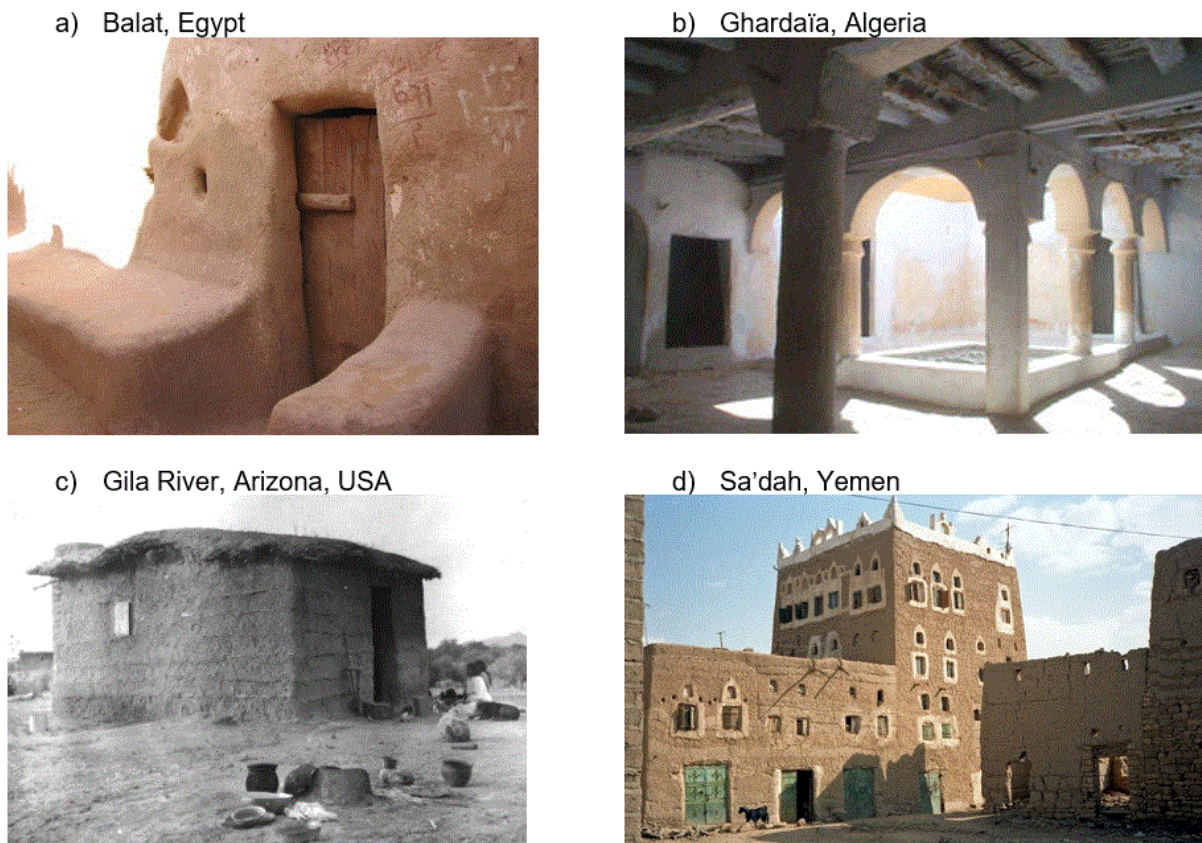


Figure 3. Atmosphere within the four case studies.

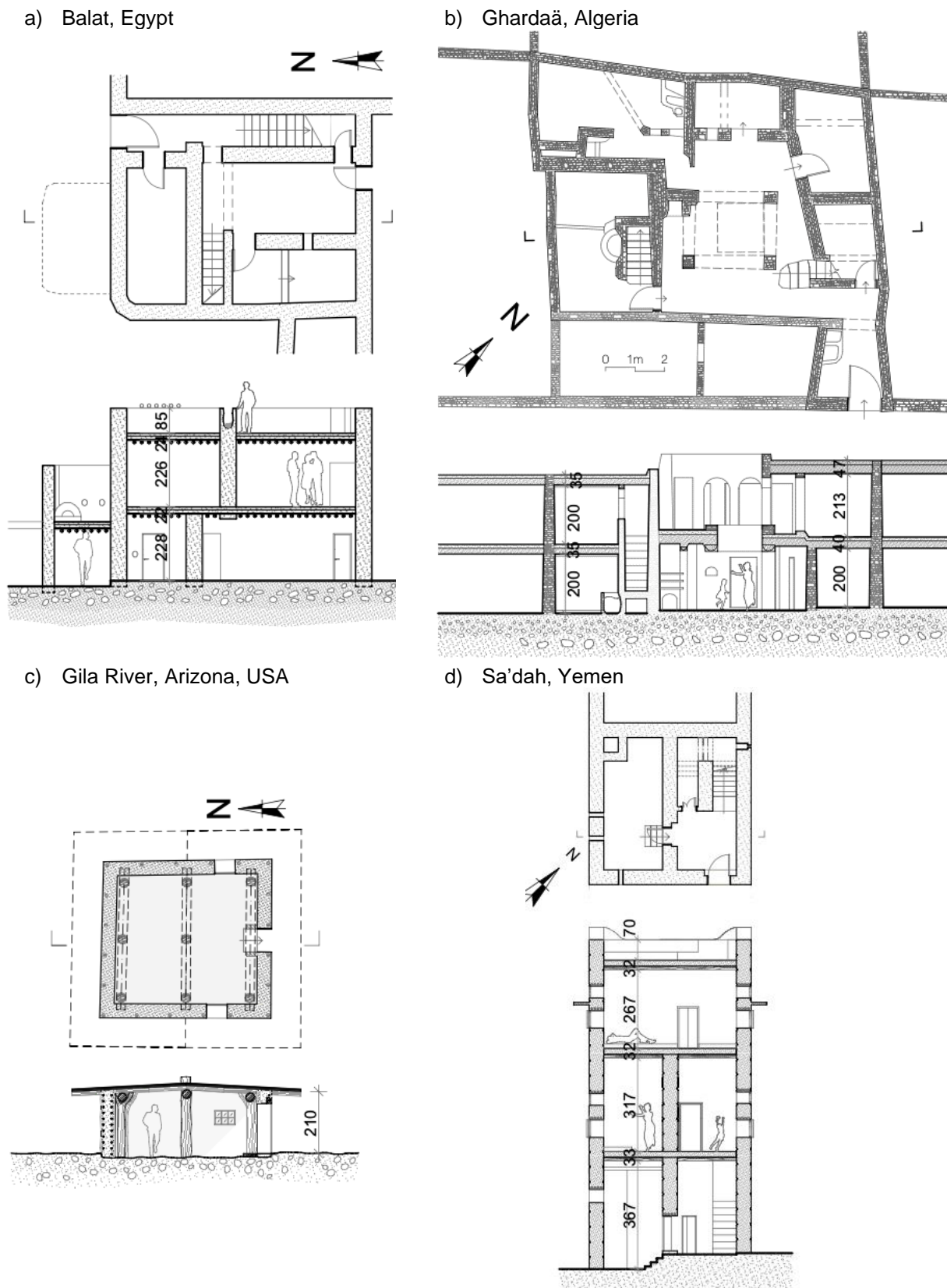


Figure 4. Layout of the ground floor and cross section of the four case studies (scale 1/200).

The O'odham house (Figure 3c) is a rectangular single-cell detached dwelling (5.40m x 5.80m), with low walls (2.30 m), and a gabled roof (3%). A wood frame of nine forked posts supporting three primary log

beams (Figure 4c) is enclosed in adobe walls (48 cm). On this primary structure are attached secondary beams (Saguaro branches) covered with willow thatch. The final layer consists of 5 cm mud. Historically, the O'dham used wattle and daub to fill voids between posts. Embedding adobe between posts is a technique borrowed from Hispanics (Hardin, 2003). The originally rounded dwellings became also rectangular. The O'dham house has two windows (0.50m x 0.70m) and a front door (0.80m x 1.70m). In Yemen, the upland zone, including Sa'dah (1800 above sea level), has comfortable conditions by day and considerable cooling at night (Attia, 2020). The traditional architecture consists of tower buildings (Figure 3d). The cob house studied consists of three floors and has a square plan shape. The roof terrace is accessible. There is no garden. The floor area of each level is approximately 16 m². The house is adjoining the ground floor on the north-west facade. The ground floor is used for animal breeding. The way of life and spatial organization of the houses reflect Yemeni society. The typologies of housing are organized so as to benefit from solar contributions in winter with the living rooms in the south and the distribution spaces in the north (Figure 4d). There are ten windows composed of wooden carpentry and glazing. All windows have shutters. The windows on the top floor also have a cap. Traditionally, in Yemen, the two functions of a window are dissociated: windows allow light to enter and wooden carpentry allow air to enter. The walls are 50 cm thick. Traditional earthen roofs consist of a layer of 25 cm of earth whose waterproofing is ensured by a thin finishing layer of clay and sand. The structure consists of main wooden beams supporting tamarisk stems.

3. Materials and Methods

To understand the thermal behaviour of these vernacular houses located in desert climates, dynamic thermal simulations have been performed over a month with the same climate.

3.1 Climatic data

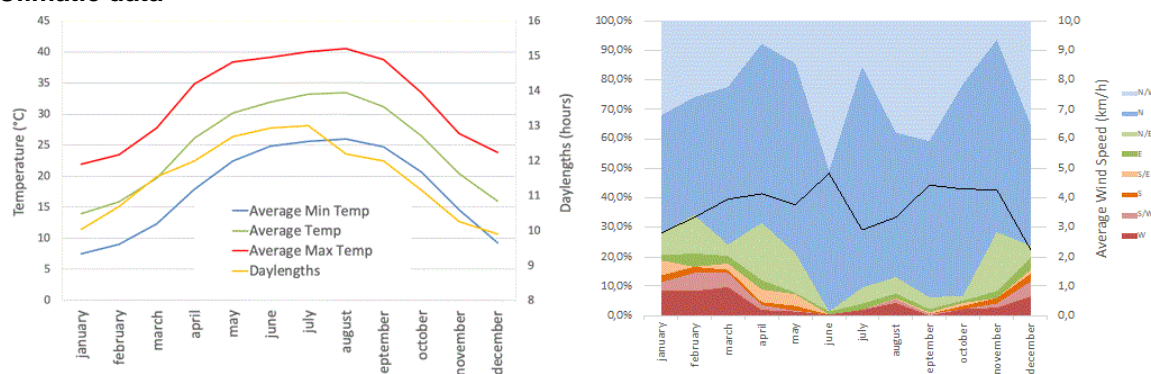


Figure 5. Khargha Al Wadi al Jadid (Egypt), Climate Graphs.

The meteorological data used came from the 'Al-Kharga' weather station, located in the southernmost of the five major oases of the Libyan desert in Egypt. Located about 200 km from the Nile Valley, it extends for 150 km but its width does not exceed 30 km. This station (25°26'18" north, 30°33'30" east, 32 m) was selected because it is located less than 150 km west of one of the case studies, Balat. Figure 5 gives the main monthly climatic data. The main wind direction during all the year is north and the average wind speed is between 2.3 m/s and 4.4 m/s. For the dynamic thermal simulation, the month of April was chosen because the average temperature is 26.1°C, near the average temperature that can be recorded during the summer months in France. In addition, this month includes three heat waves that will allow to see the thermal performance of the case studies (7 to 11 April, 16 to 21 April and 23 to 27 April).

3.2 Thermal simulations

(ArchiWIZARD) is a digital software dedicated to thermal calculation. Its main advantage is to import the geometry of the existing model from all the currently existing formats, and perform in real time the thermal calculation. The DTS EnergyPlus module provides access to all the necessary possibilities for dynamic thermal simulation covering the building envelope, inertia phenomena, glazing, sun shading, from the same energy model. Table 2 gives the thermal properties of the different material used in the four case studies for walling, flooring and roofing. For the purpose of this study, wooden exterior carpentries with single glazed windows will be considered. All these data are required for the ArchiWIZARD simulations. As it is not possible to define sharing walls in the software, all the adjoining walls will be insulated from the outside with 30 cm of glass wool. The composition of this type of wall has therefore only an influence on inertia. In this study only, a single thermal zone will be considered for each case study.

Table 2: Thermal properties of the different materials used in the case studies.

	Thermal conductivity (W.m ⁻¹ .K ⁻¹)	Specific heat capacity (J.K ⁻¹ .kg ⁻¹)	Density (kg/m ³)
Limestone (Pestre et al., 2022)	0.86	738	1882
Cob (Griffiths et al., 2017)	0.8	870	1720
Lime mortar (Walker et al., 2015)	0.8	864	1820
Mud plaster (Andres et al., 2016)	0.35	1096	1368
Medium sand (Hamdhan et al., 2010)	0.27	800	1700
Sun-dried brick (Michael et al., 2016)	0.5	996	1405
Willow thatch (Simpson et al., 2022)	0.07	180	240

For dynamic thermal simulations considering natural night ventilation, windows and doors are open between 0h00 and 5h00 in the morning. The air flow is obtained by multiplying the average wind speed over the month of April (4.1 m/s) by the surface of the openings.

4. Results and Discussion

4.1 Results

The results are interpreted in terms of operative temperature because this quantity is directly related to thermal comfort. The results are interpreted in two stages. First the hourly outside temperatures and the hourly operative temperatures (with and without night natural ventilation) will be plotted for each case study. Then the daily average operative temperature (with and without night natural ventilation) will be plotted for the four case studies in order to compare them.

4.1.1 Example of results

Figure 6 gives the results for Balat's case study during five days (12-16 April). This period corresponds to the end of the first heat wave. The blue line corresponds to the operative temperature, which is very steady. Its daily variation is at most 1.2 °C while the daily variations of the outside air temperature reach 19.6 °C. While the outside air temperature starts to decrease from April 13, the operative temperature increases slightly until April 14 and starts to decrease only from April 15. These results show that walls, floorings and roofing of the house have a great inertia and pilot the indoor operative temperature. In Figure 6 the blue dotted line corresponds to the operative temperature with night ventilation which is systematically lower than the operative temperature without night ventilation (Exizidou et al., 2017). The maximum difference is 7.9 °C on 16 April at 6 AM. The decrease in temperature at the opening of the windows is all the greater the difference between outside air temperature and operative temperature. It is the case for the three last days. The rapid increase of the operative temperature at the closing of the openings shows the high thermal inertia of the walls and floorings. To know the impact of natural night ventilation simulations have been performed with windows and doors open between 0h00 and 5h00 in the morning. Natural night ventilation increases also the daily variations of the operative temperature which are between 3.6 °C and 5.4 °C. While the outside air temperature starts to decrease from April 13, the operative temperature increases slightly until April 13 and starts to decrease only from April 14. Natural night ventilation therefore decreases the thermal phase shift. In Figure 6, the fine black lines correspond to the range of variations of the outside air temperature during the day of April 12, the fine red lines to the range of variations of the operative temperature. These values will be used to characterize the thermal inertia of the four case studies through the daily thermal damping df_{env} defined as follow:

$$df_{env} = \frac{T_{op,max} - T_{op,min}}{T_{ext,max} - T_{ext,min}} \quad \text{-----}(1)$$

Where $T_{op,max}$ is the maximum operative temperature of the day, $T_{op,min}$ is the minimum operative temperature of the day, $T_{ext,max}$ is the maximum air temperature of the day and $T_{ext,min}$ the minimum air temperature of the day. The daily thermal damping during these five days varies from 3.0 % to 8.2 % which means that Balat's case study is able to absorb heat waves.

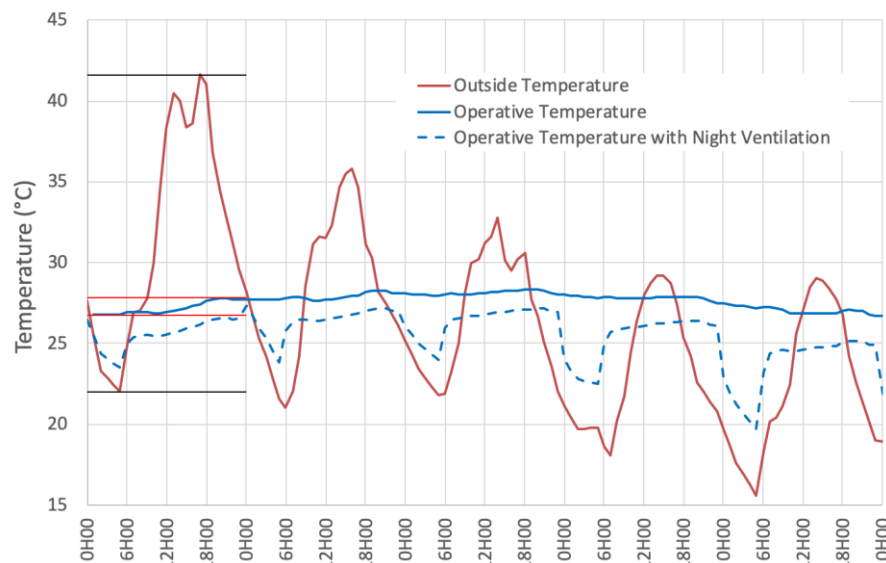


Figure 6. Results of Archiwizard simulations for Balat, Egypt at the end of the first heat wave (12-16 April).

4.1.2 Results for the four case studies

Figure 7 gives the daily average operative temperature for the four case studies with and without night ventilation. Two case studies, Balat and Sa'dah show similar curves with or without night natural ventilation. For each case study, the dashed curve, which corresponds to simulations with night natural ventilation, is systematically under the solid line curve corresponding to simulations without ventilation. The maximum average daily operative temperature is recorded for Tohono O'odham case study with and without night natural ventilation (Table 3). This case study is the one with the greatest variations in daily average operative temperature from one day to the next (Figure 7). This may be explained by an average thermal damping four times higher for this case than for the other three (Table 3). Without night natural ventilation, this case study also shows the smallest average daily operative temperatures for the days of 16 and 17 April after the first heat wave. Over the whole month, except for these two days, 'Ghardhaia' has the lowest average daily operative temperatures, with and without night natural ventilation. This is also confirmed by the monthly average temperature which is the lowest (Table 3). Without night natural ventilation, the average monthly operative temperature of the three other cases is very close (Table 3). With night natural ventilation, the monthly average operative temperature of 'sa'dah' and Balat is one degree lower than that of Tohono O'odham (Table 3). The average thermal gap between night ventilation and no ventilation varies from 1.5°C to 2.4°C, while the maximum thermal gap can reach 4.2°C for Balat.

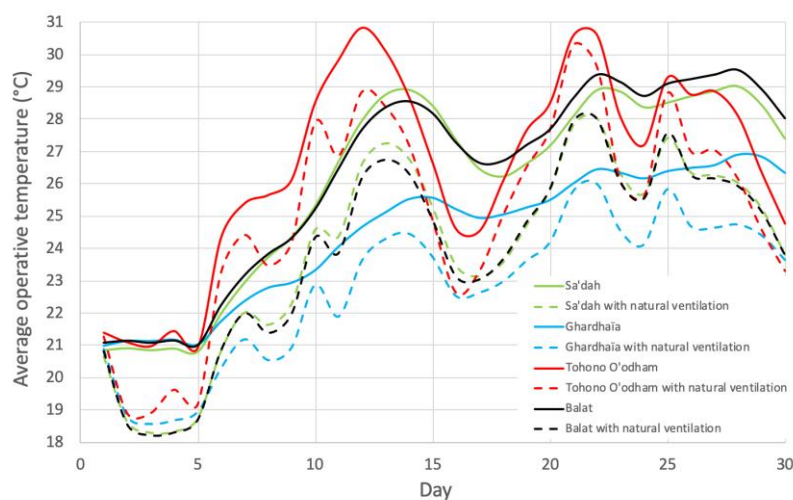


Figure 7. Average daily operative temperature for the four case studies during April.

Table 3: Main results for the four case studies during April.

	Yemen	Egypt	Arizona	Algeria
Average thermal damping	5.1%	6.3%	23.0%	5.6%
Average monthly operative temperature (°C)	26.1	26.3	26.6	24.5
Average monthly operative temperature with night ventilation (°C)	24.0	23.8	25.0	22.8
Maximum average daily operative temperature (°C)	29.0	29.5	30.8	26.9
Maximum average daily operative temperature with night ventilation (°C)	28.0	28.0	30.3	26.0

4.2 Discussion

The new French thermal rules RE2020 introduce a new requirement, on summer comfort, with a new calculation method that incorporates the August 2003 heat wave to consider future climate changes. The indicator used to assess summer comfort is the hour degrees of discomfort expressed in °C.h. It represents the level of discomfort perceived by the occupants. More concretely, this indicator is similar to a counter that cumulates, over the summer period, each uncomfortable degree of each hour of the day and night. Uncomfortable degrees are conventionally those that exceed a comfort temperature. The day period in summer is by convention 7am-10pm, during this period the discomfort threshold is set at 28°C, at night it is set at 26°C. For detached or semi-detached houses, below the low threshold 350 °C.h, the building is considered comfortable in scorching summer. Above the high threshold 1250 °C.h the building is non-statutory with excessive discomfort. Between these two thresholds the building meets the regulatory requirement but to encourage the achievement of the low threshold with passive levers, a cooling package is added to the energy consumption.

The results of the calculation method to assess summer comfort are given in table 4. Considering that in France the summer period lasts three months, without ventilation only the case study of Ghardaïa will be considered comfortable in scorching summer (below 117 °C.h for one month). The three others case studies are non-statutory with excessive discomfort (above 417 °C.h for one month). With natural night ventilation, Sa'dah, Balat and Ghardhaïa case studies are comfortable in scorching summer, while Tohono O'odham case study meets the regulatory requirement but is just below the high threshold.

Table 4: Indicators to assess summer comfort during April month.

	Yemen	Egypt	Arizona	Algeria
Compactness ratio	1.32	0.67	1.52	0.42
Hour degrees (°C.h)	473.3 (122.5+350.8)	577.6 (158.7+418.9)	712.6 (378.2+334.4)	19.0 (0+19.0)
Hour degrees with night ventilation (°C.h)	83.8 (6.4+77.3)	84.6 (5.7+78.8)	411.0 (259.6+151.4)	10.1 (0+10.1)

Building compactness will have a significant impact on heat transmission through the building envelope. The compactness ratio C_f is directly related to the heat flow that passes through the different walls in contact with the external environment. The higher the ratio, the more heat gain (Ratti et al., 2003):

$$C_f = \frac{1}{V_b} \sum_{i=1}^n S_{ei} \quad \text{-----}(2)$$

Where V_b is the living volume, S_{ei} the area of the exterior surface i and n is the number of exterior surfaces of the building. The Tohono O'odham house has the least summer comfort. This is a detached house located in a rural area. Its compactness ratio (Table 4) is very high because it is a single-story house with a small footprint. While the walls have a strong inertia, this is not the case of the roof which is only 10 cm thick with 5 cm of willow thatch. This leads to the maximum average daily thermal damping of the four case studies (Table 3). The lack of summer comfort for a self-sufficient desert living civilization may be explained by the way of life the Tohono O'odham. Indeed, much of the life of Tohono O'odham takes place outside the house with specific buildings dedicated to cooking or storage. With natural night ventilation, Sa'dah and Balat case studies are comfortable in scorching summer. Although their compactness ratios are really different (Table 4), the average daily operative temperatures are very close (Figure 7). The small footprint of Sa'dah case study is compensated by the effect of the tower building shape on the thermal gain in summer. Despite one floor less, the compactness ratio of Balat case study is lower due to a larger footprint and more adjacent walls. These two case studies have heavy walls at least 50 cm thick. Roof and floors

present a medium inertia and are between 22 and 32 cm thick. This leads to a weak average daily thermal damping almost identical for the both case studies. The very compact urban form of the Ghardhaia ksar leads to no external wall subjected to solar radiation. The only non-adjacent walls are those that overlook the patio whose “chebeq” remains covered during the day to prevent the sun from entering the house. This architectural design leads to minimal compactness ratio (Table 4), the weakest of the four case studies and smaller than the value of 0.584 obtained by Ratti et al. (2003) for the medina of Marrakech with courtyard houses of 9m high. The intermediate floor and the roof are very thick, respectively 40 and 45 cm, and have a strong inertia. This architectural and urban design results in optimal summer thermal comfort, as shown by the results and interpretations of dynamic thermal simulations, but with an extreme introversion of inhabited space.

5. Conclusions

As vernacular architecture has demonstrated its adaptation in particularly harsh climates, the objective of this research was to understand the design strategies of four vernacular houses located in four deserts (Algerian Sahara, Arizona, Libyan desert and Yemen) to ensure summer comfort in hot environments. The thermal behavior of these four dwellings has been studied through dynamic thermal simulations performed with the software ArchiWIZARD, using the same climate conditions. The best design strategy is to envelop the building to protect it from outside environments, especially from the intense solar radiation characteristic of desert climates. The environment and urban morphology play a key role in this protection. This study shows that only very high inertia can achieve a satisfactory level of comfort in hot climates. Even with natural night ventilation, one of the four case studies, with heavy walls but a light roof is not comfortable. The results of this research also show the impact of natural night ventilation which allows two of the four case studies to meet the selected summer thermal comfort criterion. The perspectives opened by this study are diverse and varied. First, this study is not exhaustive and the number of case studies could be extended to other desert regions of the world such as the Middle East (Iran, Saudi Arabia) or Australia located in the southern hemisphere, in order to enforce the hot climate design strategies. Three of the four case studies use earth as a construction material. One of the main advantages of indoor earth coatings is that they regulate the relative humidity of the air inside buildings. Indeed, earth materials have a high capacity of adsorption or desorption of water vapor. The dynamic thermal simulations could be then improved by considering the relative humidity which is an important parameter of comfort.

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Conflicts of interest

The Authors declare that there is no conflict of interest.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors/s.

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