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Exploring building's envelope thermal behavior of the neo-vernacular residential architecture in a hot and dry climate region of Algeria

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Abstract

It is well known that the passive strategies applying in traditional buildings respond satisfactory to climatic requirements and succeed to provide maximum indoor comfort with minimum energy consumption. From this point of view, it is interesting to quantitatively assess the effectiveness of the vernacular strategies to improve the environmental performance of the building's envelope under desert climate conditions. The research tries to address this issue and was undertaken in southern Algeria where a very hot and arid climate prevails. The effect of some selected passive cooling strategies on enhancing the building's envelope climate performance was examined. These strategies are inspired from the local vernacular architecture, and they are expected to provide satisfactory indoor thermal comfort for users and to reduce the energy cooling demand from residential buildings. Applying field and computational investigations, two existing residential buildings were tested: a typical residential unit and a contemporary vernacular (neo-vernacular) building. In the latter, climate responsive strategies inspired from vernacular architecture were applied. A comparison based on site measurements was carried out on the two selected buildings which differ from their envelope design properties and components.

Keywords

architectural envelope;
neo-vernacular architecture;
cooling passive strategies;
thermal comfort in hot dry climate;
computer simulation;
residential sector

Article History

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1 Introduction

Like most developing countries, since its independence, Algeria had to face several challenges including an overgrowth and a demographic explosion as well as a massive rural exodus and urban overcrowding. Given this situation, the public authorities were obliged to take emergency decisions, notably in the building sector by carrying out building construction projects that, among other things, were out of line with architectural quality standards and neglected climatic and environmental issues. Unfortunately, such emergency measures not only have negatively affected the quality of life of the inhabitants in terms of indoor thermal comfort, health and well-being, but have also led to buildings that are fully dependent on mechanical air-conditioning to provide livable indoor environments and subsequently they are huge energy consumers (Rais et al. 2019; Semahi et al. 2019; Zeinelabdein et al. 2019)

This regrettable situation which weighs on the building sector in Algeria is in contradiction with the global trend towards a sustainable future. Indeed, facing the risk of global warming and the prominent disappearance of fossil fuels, the protection of the planet has become a major concern that all sectors should take into consideration to ensure a safer future and a healthier environment for future generations. Therefore, nowadays the building sector consumes about one-third of the total energy consumption worldwide and it is responsible for an equal portion of carbon dioxide emissions in both developed and developing countries (Rais et al. 2019). From this point of view, it becomes imperative to minimize the use of non-renewable energies in buildings by proposing long-term alternatives.

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Fortunately, many opportunities exist to deploy energy-efficient and low-carbon solutions for buildings and construction. Amongst these solutions, the building envelope is one of the most important components which can reduce energy demand (as well as the relevant carbon dioxide emissions), improve thermal comfort, and decrease the indoor peak temperature (Harvey 2009; Mwasha et al. 2011; Koch-Nielsen 2013; Stazi et al. 2014; Mohamed et al. 2017; Zeinelabdeinet al. 2017; Samy et al. 2019; Ameur et al. 2020; Zhang et al. 2020).

Ancient vernacular architecture has succeeded to develop ingenious climate-responsive solutions that provided a satisfactory built environment with natural means. The passive cooling strategies used in traditional buildings respond to climatic requirements and achieve thermal comfort conditions with no need for air-conditioning. As such these vernacular strategies can be used as design tools to improve the environmental performance of the building envelope (Alrashed et al. 2017; Leo Samuel et al. 2017; Al-Sallal and Rahmani 2019; Rais et al. 2019)

In Southern Algeria, vernacular architecture features provide rational responses to the harsh desert climate. For instance, in the hot and arid region of El-Oued the focus was to minimize heat gains during summer. With this purpose, several cooling design strategies were developed, such as, high thermal inertia, self-shading form and compactness, local materials, small windows that were shaded and properly oriented, clustering buildings, curved roofs and light colors.

In this regard, vernacular architecture offers a greatest potential for the development of useful insights for designing contemporary buildings of high quality and more responsive to local environmental conditions (Bouchair et al. 2013). Nevertheless, while it seems that there is recently a renewed interest towards the passive design strategies of ancient building architectures; it remains a lack of information relating to eventual studies that have been carried out on existing projects where climate responsive strategies inspired from vernacular architecture have been effectively applied.

The neo-vernacular approach was able to successfully re-interpret the sustainable features of ancestral traditional architecture, notably, the passive design strategies. As such this approach has a real potential to enhance the deficient integration of the climate dimension into new constructions from both building thermal performance and human thermal comfort considerations (Kersenna and Chaouche 2018).

This paper, discusses the contribution of different climate-responsive strategies developed in vernacular architecture and re-used in neo-vernacular residential projects to assure thermal comfort conditions in a desert region of Algeria.

The approach used is based on the thermal performance evaluation and comparison of two existent contemporary residential buildings considering their envelope design and material characteristics. The selected examples represent respectively a typical residential unit and a contemporary vernacular (neo-vernacular) building. The latter was designed by referring to climate responsive strategies inspired from local vernacular architecture. A comparison based on indoor in-situ measurements was carried out on the two selected buildings which differ for their envelope design properties and components.

In this regard, the results obtained support the assumption that passive strategies can be feasible for contemporary buildings and that they could contribute greatly towards improving indoor thermal comfort whilst reducing buildings' energy demands.

2 Research methodology

In order to better understand the passive design strategies impact on enhancing the thermal performance of the architectural envelope under hot and arid weather conditions, the study was essentially based on two main steps.

In the first step, a theoretical basement is developed by focusing on aspects that are most relevant for the analysis of the thermal performance of the building's envelope in a desert climate. This gives an overview about the state of knowledge on the addressed topic and serves as a lever for the investigation. The city of El-Oued that is representing the hot dry climate (desert) of Algeria was taken as a specific site for this study. Accordingly, the climate conditions in El-Oued were investigated based on climate data picked from the local weather station of Guemar. The study identifies the dominating bioclimatic design strategies for the predominating desert climate of El-Oued using Givoni's psychometric chart. Furthermore, a retrospective study defining the modalities of dwellings' production relating to the housing building sector in Algeria, as well as, the technical context (construction techniques, materials employed, etc.) was carried out.

The second step is analytical and includes two approaches: a qualitative investigation and a quantitative evaluation. The qualitative approach aims to identify and, then, to assess the passive cooling strategies used in the building's envelope as a response to the harsh climate conditions. This approach was based essentially on a fieldwork that was undertaken in the city of El-Oued. It induced site observations and field notes, used together with photo documentation and architectural surveys. After having carried out this preliminary work, it was possible to select two types of contemporary residential buildings representing the common public housing supply. These two significant buildings were used as case studies. They respectively illustrate a typical residential unit and a contemporary vernacular (neo-vernacular) building. The latter is designed according to cultural, social and, physical local context; as such, it embodies various climatic passive design strategies inspired from vernacular architecture. The selected housing types were thoroughly investigated in respect to their design and construction in order to determine the thermal performance of their envelope; the employed climatic design strategies and their effectiveness in ensuring human comfort were, also, highlighted. The quantitative approach was devoted to experimentation. It includes a campaign of in-situ measurements (temperature, humidity, etc.) that was carried out on the two selected residential building units. The collecting of hygro-thermal data will take place during the summer season. A thermal simulation will then be conducted using the DesignBuilder/EnergyPlus software to evaluate the thermal behavior of the building envelope throughout the whole summer period. In this last part of the research, the variability in the measurement conditions and the possibility of carrying out targeted parametric studies by isolating the influence of each element of the envelope has been exploited.

3 An overview of the case study

3.1 Climatic context

The two buildings investigated are located in El-Oued, capital of the Souf region. This Saharan city is situated in South-East of Algeria (Figure 1). It is characterized by a hot an arid (desert) climate with high temperature disparity between day and night as well as between summer and winter. Air temperature and solar radiation are rather high all year. The winter is quite soft but the temperature can drop below 0 °C while in summer it reaches 50 °C. Relative humidity is very low except for the winter months where 60% is common. The average rainfall varies between 80 and 100 mm/year (period from October to February) (Figures 2 & 3). The Sirocco (a hot dry wind) can blow throughout the year and it can cause very significant damage (drying, dehydration) (ANIREF n.d.). The thermal comfort zone (TCZ) for the hot and arid climate of Algeria as according to ASHRAE 55 standards is 18 °C < T < 30 °C (Semahi et al. 2019).

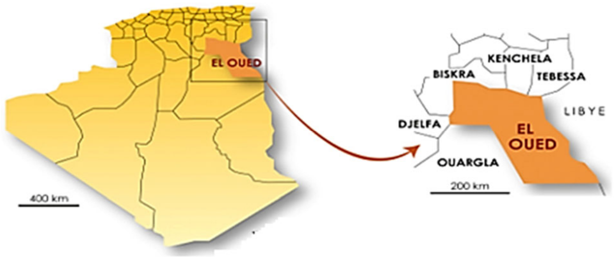


Fig. 1 El-Oued situation in Algeria

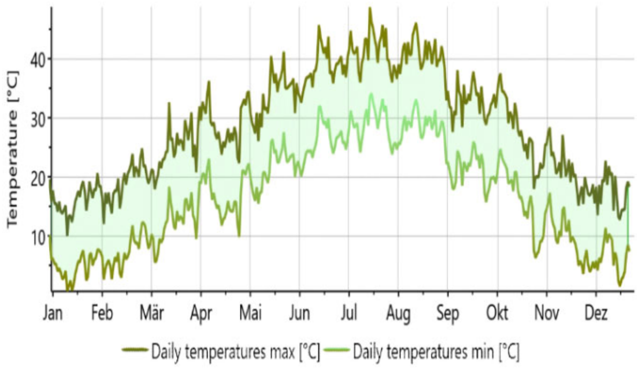


Fig. 2 Monthly temperature

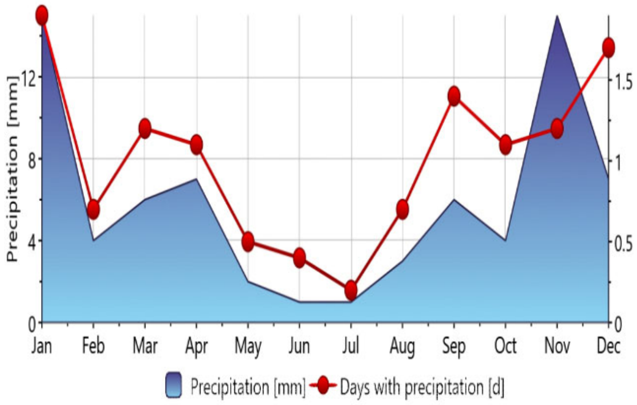


Fig. 3 Monthly precipitation

3.2 Bioclimatic analysis

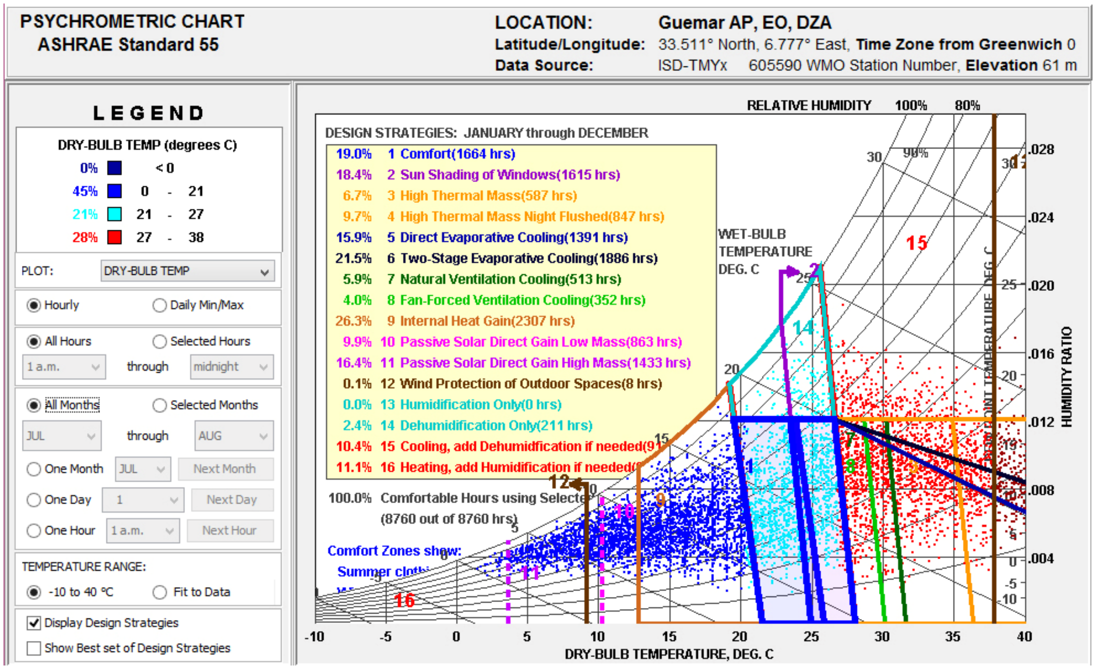
The climate conditions prevailing in the research site are investigated based on climate data picked from the local weather station of Guemar. Furthermore, the study identifies the dominating bioclimatic design strategies for the Saharan Souf region by using Givoni's bioclimatic chart. Based on a common psychometric diagram, this climatic analysis tool was developed by Givoni to represent the limits of comfortable environments. Givoni's chart predicts the comfort conditions within the building based on outside climate factor; the main characteristics of air humidity and temperature are reported on the psychrometric chart to evaluate the thermal sensation and comfort of the occupants (Givoni 1978). The combination of monthly temperature and relative humidity indicates the recommended passive design strategy for each month. The chart contains the comfort zone, marked by a solid line and several zones for passive design strategies, namely passive solar heating, humidification, evaporative cooling, natural ventilation, and high thermal mass (Bodach et al. 2014). By reporting the local climate data of El-Oued city on Givoni's bioclimatic chart the dominating bioclimatic design strategies for the site research are defined (Figure 4).

By examining the diagram, it possible to extract the following observations:

- The comfort zone (1) is defined by a central blue range with temperatures from 19 to 28 °C and bounded by comfortable relative humidity levels. The other ranges illustrate the best set of design strategies to apply in order to achieve to thermal comfort. According to the diagram indications, the months of April and October are considered comfortable.
- To the right of the comfort zone a period with very high temperatures and low relative humidity is defined. It corresponds to the summer season that covers a period of 4 months (May, June, July and August). The diagram indicates that radiation control, inertia by absorption with night ventilation, is required to achieve comfort conditions. Additionally, it is necessary to add an evaporative cooling system for the months of July and August (during the hottest period).
- The zone to the left of the comfort zone indicates the cool period characterized by low temperatures and relatively high humidity. It covers the zone of "additional heating" that spreads out during the months of December, January and February.

A fine reading of the diagram also reveals a percentage of average discomfort hours relating to the desert climate of El-Oued about 81%. Evaporative cooling is the most effective bioclimatic design strategy in the research site, accounting for more than 37% of the hours annually required due to extreme aridity of the desert climate. Passive solar heating accounting for 16.40% of the hours annually needed is the most effective bioclimatic design strategy in the cold season. This findings based on the bioclimatic analysis indicate that El-Oued can be classified as a cooling-dominated city (Semahi et al. 2019). In general, the above bioclimatic analysis shows that solar radiation is an important factor, given that the importance of its intensity. The wind factor is a constraint in winter, but it is also a positive element for night ventilation in summer. The results of the bioclimatic analysis, also, indicate that at the beginning of the summer the mass effect (high thermal mass) and night-time ventilation, are sufficient to restore indoors comfort conditions. However, during the overheating period (June, July and August) cooling systems by evaporation must be added to the previous techniques. In contrast, during the cold season, passive heating is recommended. To this purpose, solar direct gain combined with low thermal mass of the building can keep the indoor temperature at a comfortable level during the cold season. A good sizing and orientation of the openings would be effective. However, for days of extreme cold (in December and January), active solar or conventional heating might be partly needed.

By analyzing the climatic data of El-Oued accordingly to the Givoni's bioclimatic chart a set of recommended passive design strategies for both hot and cold seasons were given. To summarize, considering the prevailing climatic conditions in the studied region, the physiological comfort of the occupants can be achieved by applying two main



PSYCHROMETRIC CHART
ASHRAE Standard 55

LOCATION: **Guemar AP, EO, DZA**
Latitude/Longitude: 33.511° North, 6.777° East, **Time Zone from Greenwich** 0
Data Source: ISD-TMYx 605590 WMO Station Number, **Elevation** 61 m

LEGEND

DRY-BULB TEMP (degrees C)

0%	■	< 0
45%	■	0 - 21
21%	■	21 - 27
28%	■	27 - 38

PLOT: DRY-BULB TEMP

● Hourly ○ Daily Min/Max

● All Hours ○ Selected Hours
1 a.m. through midnight

● All Months ○ Selected Months
JUL through AUG
○ One Month JUL Next Month
○ One Day 1 Next Day
○ One Hour 1 a.m. Next Hour

TEMPERATURE RANGE:
● -10 to 40 °C ○ Fit to Data

☑ Display Design Strategies
☐ Show Best set of Design Strategies

DESIGN STRATEGIES: JANUARY through DECEMBER

19.0%	1 Comfort(1664 hrs)
18.4%	2 Sun Shading of Windows(1615 hrs)
6.7%	3 High Thermal Mass(587 hrs)
9.7%	4 High Thermal Mass Night Flushed(847 hrs)
15.9%	5 Direct Evaporative Cooling(1391 hrs)
21.5%	6 Two-Stage Evaporative Cooling(1886 hrs)
5.9%	7 Natural Ventilation Cooling(513 hrs)
4.0%	8 Fan-Forced Ventilation Cooling(352 hrs)
26.3%	9 Internal Heat Gain(2307 hrs)
9.9%	10 Passive Solar Direct Gain Low Mass(863 hrs)
16.4%	11 Passive Solar Direct Gain High Mass(1433 hrs)
0.1%	12 Wind Protection of Outdoor Spaces(8 hrs)
0.0%	13 Humidification Only(0 hrs)
2.4%	14 Dehumidification Only(211 hrs)
10.4%	15 Cooling, add Dehumidfication if needed(9
11.1%	16 Heating, add Humidification if needed(

100.0% Comfortable Hours using Selecte
(8760 out of 8760 hrs)

Comfort Zones show:
Summer clot

Fig. 4 Givoni's bioclimatic chart of El-Oued city for the whole year types of strategies: in summer, it is important to: reduce heat gain, protect the building from solar radiations, minimize the internal loads, dissipate excess heat and promote all means of natural cooling. In winter, the heat that is gained from solar radiation during the day must be captured, stored in the mass, preserved by insulating the building's envelope (especially the roof) and then to be distributed throughout the building to maintain living spaces at an acceptable level of thermal comfort. Finally, the results obtained show that it is possible to achieve thermal comfort conditions with no need for air-conditioning if relevant design strategies in the envelope and the structure are applied.

3.3 Case studies' presentation

The first case study is an apartment located in the upper floor of a multi-story residential building (Figure 5). This example is part of a recent project carried out by a state engineering office (the Land Agency in the South of Algeria). It was selected because it is representative of the public housing units produced in Algeria in terms of typology, size and building construction materials. Thus, this case study illustrates the contemporary architectural design practice for which the buildings climate performance is not a priority. The apartment consists of 4 rooms grouped around a central space that serves as a family stay room. It is about 70 m^2 area, has 3 facades respectively south, west and north and was constructed using standard manufactured materials (brick, concrete, cement, etc.)

The second case study that represents the neo-vernacular design is situated in the 400 Housing Units district. To allow the thermal evaluation and comparison of the two studied units, these had to be similar, or at least, they should resemble each other as much as possible. So, the neo-vernacular residential unit analyzed was equally an apartment located in upper floor of a multi-storey residential building.

The design of the 400 Housing Units project was the result of collaborative efforts between local authorities and El-Miniawy architects (Figure 6). These two Egyptian brothers are known to be disciples of Hassan Fathy. They shared his ideas about the transitional relationship between modern and vernacular architecture in a postmodern context and were considered to be strong advocates of the critical regionalism. Their approach involves the use of locally-sourced, natural materials to achieve context relevant designs. The housing project of the El-Miniawy brothers in El-Oued reflected their desire to create an urban fabric in a desert environment, and to respond to cultural, social, physical and economical context of the region. The project was carried out on the basis of social studies, surveys and a strong awareness of regional identity. In addition to social and cultural issues, climate was one of the most influential factors determining the design of the project. It was one of the few housing projects in Algeria that are designed according to bioclimatic architectural principles. The environmental design concept applied in the residential units adapted design elements and techniques inspired from local vernacular architecture which favored climate responsive solutions.

Fig. 5 First case study external view

Fig. 6 Second case study external view

4 Bioclimatic analysis of the selected residential units: the qualitative approach

By referring to a relevant literature and considering the bioclimatic analysis that was undertaken using Givoni's psychrometric chart, the two selected case studies were examined according to the following bioclimatic strategies: (1) protection against solar radiation, (2) high thermal mass, (3) use of solar radiation, (4) use of natural ventilation, (5) built form, and (6) urban scale planning.

4.1 Case study 1

- **Construction characteristics and thermal properties**

After identifying primary building bioclimatic strategies to be explored, the studied example was submitted to a concise analysis which highlighted its architectural and material characteristics. The qualitative investigation shows that:

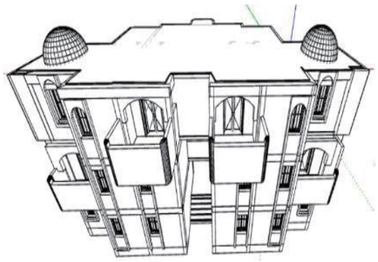
(1) the external walls are made up of 30 cm double walls of hollow bricks separated by an air gap (15 cm brick towards the outside + 5 cm air gap + 10 cm brick inwards the inside) with an external coating of cement mortar and plaster from the inside; (2) the interior partitions are simple hollow brick walls of 10 cm thick coated with plaster of 0.35 cm on each side; (3) the roof is composed of a hollow body slab and a concrete compression slab (16 + 4) cm; (4) exterior windows are with simple glazing with random protection of the openings; (5) the air space is used as a thermal insulation technique; (6) insulation is embedded at the roof structure; (7) the dome is superimposed with the flat roof (under the dome there is no gap) in this case, it is rather used for formal and aesthetic reasons.

* Climate responsive design strategies

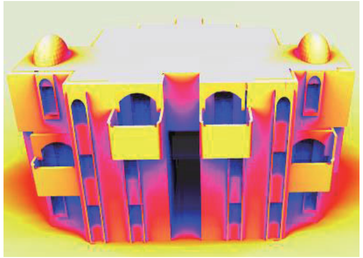
Given the design and constructive characteristics of the studied building, a bioclimatic analysis was carried out to assess the thermal performance deriving from constructive choices and conceptual decisions of designers. The qualitative investigation attempts to find the climate responsive features corresponding to the local environment; it shows that:

- The attention to climatic conditions in the architectural design process is essential in the choice of building's shape (Liébard and De Herde 2006). The choice of a simple parallelepiped shape with some triggering at the level of the balconies (Table 1, Figure A) was not the best choice in this case. It is true that the compact form is desirable to reduce the need for air conditioning, but a hyper-compact building is not desirable in terms of exposure to solar radiation during the summer period. In order to determine the exposure rate of the building's envelope and more precisely the south facade as the main facade is the most exposed to solar intensities, a simulation by the Archiwizard software was carried out. The results of the analysis show that almost all the main facade of the building (south facade) is exposed to intense solar radiation presented in the color scale with yellow and brick red with a high thermal accumulation or virtual heat quantity leading to overheating the facade (Table 1, Figure B).

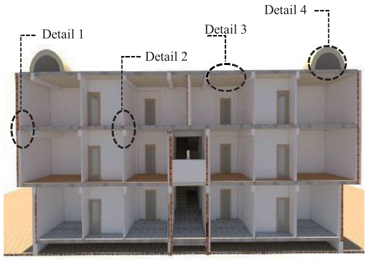
Table 1 First case study's envelope details



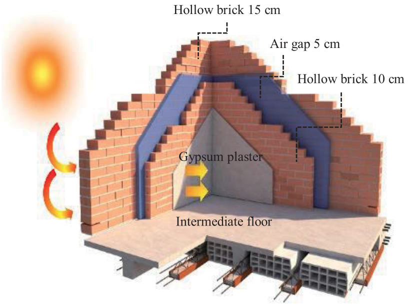
A. First case shape



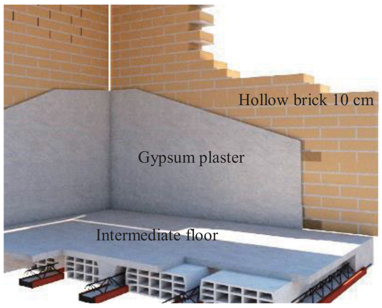
B. Sun exposure of the main facade



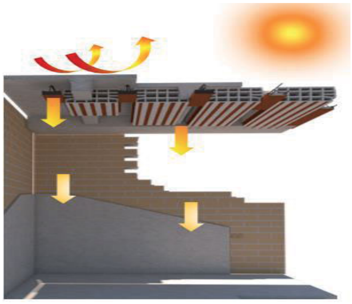
C. First case detailed section



D. External wall detailed section

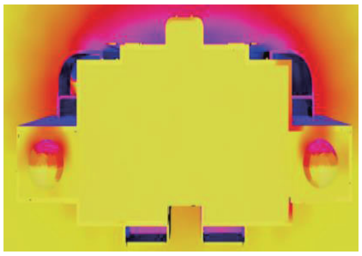


E. Internal wall detail

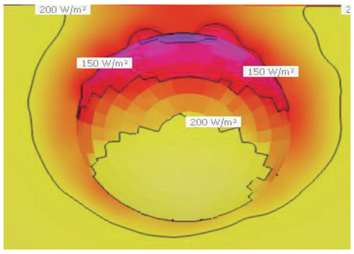


F. Flat roof detail

G. Dome's external view and detailed section



H. Roof's sun exposure



I. Dome's sun exposure

- In order to design buildings adapted to the climate, the choice of appropriate materials is crucial element and plays an important role in the subsequent thermal behavior of the building. In summer, every building stores and then transmits a large amount of heat by conduction; this amount is proportional to the thermal gradient and the coefficient of heat transmission, which is relating to the building materials and their thermo-physical characteristics. It is also relative to the surface and the position of the envelope determining also the resistance of the surfaces. The chosen materials (Table 1, Figures C & D) are imperfectly suitable because their thermophysical properties do not respond to hot and arid climate conditions (Table 2). The insulation of the walls by air gap that is used in most of the houses built in the last twenty years in Algeria allows a reduction in the cooling load compared to a house without insulation but it is not the best solution.
- The flat roof is the most common type of roofing used in hot and arid areas because of the scarcity of rain. It is also used by the inhabitants to carry out household activities and as a practical terrace to spend the nights under the stars (see Table1, Figure F). However, this kind of roofing could be not favorable in these areas considering most of the solar gain occurring the day is the result of direct solar radiation, so at sunrises the index angle is close to the normal incidence and the whole surface is subject to intense solar radiation (Konya 1980; Hadavand et al. 2008).
- The addition of the domes is done as a reference to the local identity of the city of El-Oued (considering the dome owns a symbolic meaning). Nevertheless, it continues to play partially its role in protecting the building against solar radiation (Table1, Figure G). On the contrary, the concave forms (domes) present a great capacity of reflection of the solar radiation. Given their thermal quality (Table 1, Figures H & I), these elements can be used and developed by the designers (Faghiha and Bahadori 2011).

4.2 Case study 2

- **Construction characteristics and thermal properties**

Salama (2001) wrote in a technical review report that the final design of the project was the result of a social survey conducted by the architects to understand better the cultural traditions, lifestyles and spatial needs of the people of the region. However, climate was the most influential factor in the design (Salama 2001).

The overall mass of the complex meets the socio-spatial needs of the inhabitants. Although the complex is a staggered mass of cubic/geometric volumes, the original heights, volumes, and colors of the exterior walls allowed the project to blend into the natural landscape of the region. This assumes that architectural forms should not compete with the natural environment but should complement it. In this context, the change of the exterior color to white could be seen as jarring as it produces glare in the sunny environment of El-Oued (Sghiouri et al. 2020).

In summary, a number of design features can be identified: (1) the use of *Tufla* bricks (a local material) in the complex is common to the architecture of the region;

Table 2 First case study's envelope materials

	Materials	Thermal conductivity λ (W/(m·K))	Thickness (m)
External wall	Cement plaster	1.4	0.015
	Hollow brick	0.5	0.15
	Air gap	0.31	0.05
	Hollow brick	0.5	0.1
	Gypsum plaster	0.35	0.015
Internal wall	Gypsum plaster	0.35	0.015
	Hollow brick	0.5	0.1
	Gypsum plaster	0.35	0.015
Low and intermediate floors	Gypsum plaster	0.35	0.015
	Hollow reinforced concrete slab	1.45	0.2
	Mortar	1.4	0.04
	Floor covering	2.1	0.06
Terrace floor	Gypsum plaster	0.35	0.015
	Hollow reinforced concrete slab	1.45	0.2
	Isolation	0.1	0.04
	Slope formation layer, washed gravel	1.15	0.04
	Waterproofing	0.04	0.03

(2) basement cellars have been constructed with openings on the sides to allow effective cross-ventilation of the low floor; (3) the staggered effect of volumes (juxtaposition of volumes and its impacts on shadow and light); (4) the minimal articulation of facades (compactness), coupled with the number of solid surfaces lead to a reduction in the number of facades beside the solid surfaces (horizontal ones); 5) the use of narrow openings; 6) the introduction of interior patios; 7) the use of outdoor stairs as a link between units; 8) the introduction of climate-adapted semi-urban fabric via shaded walkways and outdoor spaces; 9) the use of arches, arcades, vaults and domes; 10) the design of the project integrates traditional building techniques in a modern mode by using concrete skeleton and introducing domes and vaults of vernacular architecture.

*** Climate responsive design strategies**

As part of addressing the social and cultural needs of the Muslim inhabitants of "El-Oued" region and developing the design concepts for a the housing project, the architects attempted to develop a desert urban fabric with heavily shaded areas and direct ventilation to help reducing the summer heat (Ameur et al. 2020).

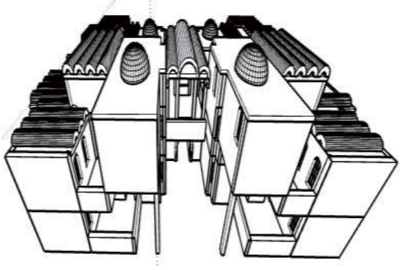
- A study by Dubois (2001) shows that knowing exactly how the sun propagates over a building allows for accurate calculation of the shade cast by neighboring buildings or the environment, and the ability to use the physical form of a building to control solar energy. It is confirmed that shading can reduce the cooling requirement of buildings by 23% to 89%, which in turn claims a thermal improvement of the space. From this point of view and with the objective of having a maximum of spaces and shaded areas protected from insulation, and studying the influence of climatic and thermal elements on different forms of construction, the square and simple cubic shape is not the optimal form to achieve the objective of the architects (Sami et al. 2019). From here comes the idea of the play of simple volumes to provide maximum shade in the second analyzed case study (Table 3, Figure A). The housing is a juxtaposition of several cubes with minimum facade surfaces and more shadow created with narrow window openings. This was remedied by assembling the housing masses and projecting the rooms on the upper floors to maximize shading (Table 3. Fig B) (Salama 2001).
- The particularity of this case study is that it integrates a socio-cultural aspect by considering the materials used in the architectural housing of the region in comparison with "modern" ones. The use of *tufla* bricks and *tafza* is common in the architecture of the region (Table 3, Figures D & E). This integration gives an impression of belonging to the tradition while reflecting the technology of the time. The technology and materials used correspond to the nature of a social housing project and reflect a good level of execution and supervision. Overall, the choice of materials and the technology are fundamental elements of the design and can be seen as part of an exploratory process leading to the affirmation of a local identity. They are among the most successful aspects of the project.

The choice of building materials is essentially determined by their local availability, so the nature of the soil and subsoil excludes the use of wood, ashlar and clay, as it only offers *tafza* (*lous*) and *tufla* as fully valued materials. The first is a very hard gypsum material that turns pink in free form hence the name *"Sand flower"*, but, in continuous sedimentation, it forms a very resistant and solid slab (Table 3, Figure F). The second material *"Tufla"* is a lighter but very reliable incrustation, which, once cured, forms a good plaster (Table 3, Figure G). As soon as it is dried, it becomes a very powerful binder.

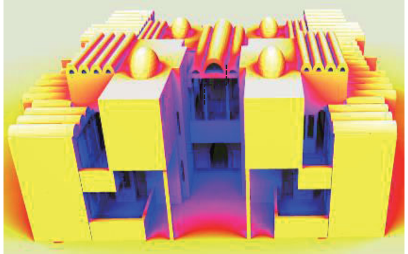
While designing with heavy materials, walls have a heat storage potential (thermal capacity) that can be used to improve the comfort of a building while lowering its energy consumption (Givoni 1978; Koch-Nielsen 2013; Leo Samuel 2017). The possibility of shifting phase of heat transfers through a masonry wall, for example, can delay the effect of daytime maximum temperatures until the evening. It is a technique particularly valuable in hot and dry climates, with large temperature variations between day and night. Therefore, it can be said that this integration ensures a sense of place in the project while reflecting the technique of the time (Table 4). The technique and materials used correspond to the climatic conditions of the region, which is essentially aimed at seeking greater climatic adaptability and which could contribute to improve indoor comfort (Bekkouche et al. 2014).

- By treating the basement (Table 3, Figure H), the goal was to seal and insulate the low floor and protect the house from rising damp and moisture infiltration. The low floor in this case is not in contact with the ground. The semi-buried void allows for natural cross ventilation by having openings facing the prevailing winds.
- As part of the design development of El-Oued housing project, El-Miniawy architects tried to ensure both social activities and climate adaptability public spaces. Therefore, they created shaded and ventilated spaces in urban design and enhanced social interaction through several types of urban spaces such as squares and pedestrian walkways. The architectural design consists of a series of building types characterized by arcades and interior spaces that take into consideration the traditions and culture of its Muslim inhabitants while separating public and private spaces (Table 3, Figure I). They create a space reserved for visitors in the front courtyard of the house and

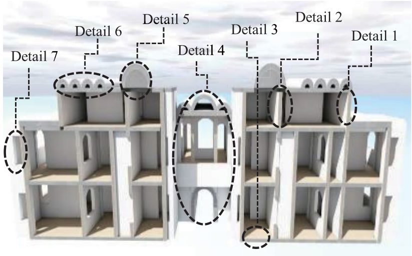
Table 3 Second case study's envelope details



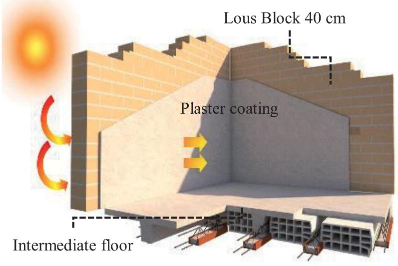
A. Second case shape



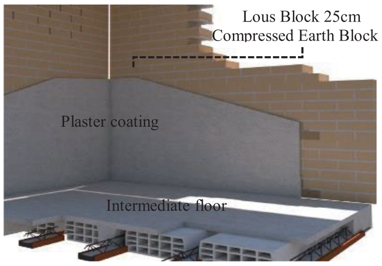
B. Main facade's sun exposure



C. Detailed section



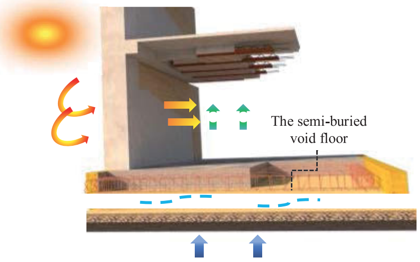
D. External wall detailed section



E. Internal wall detail

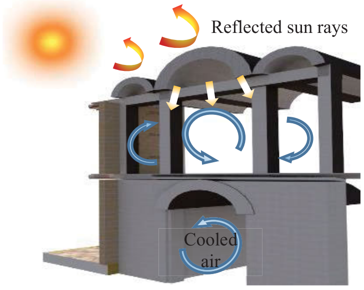
F. Tufla (sand flower)

G. Tafza gypsum

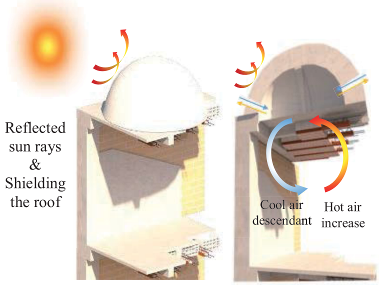


H. Underground floor ventilation detail

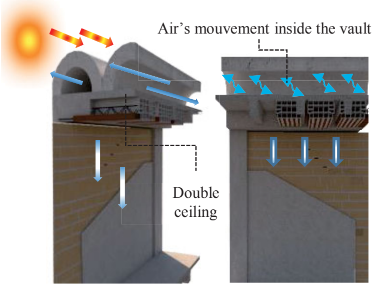
I. Central patio view



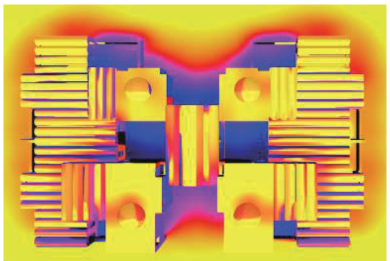
J. Central Patio ventilation schematic



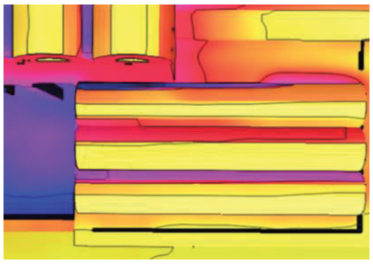
K. Dome's detailed section and external view



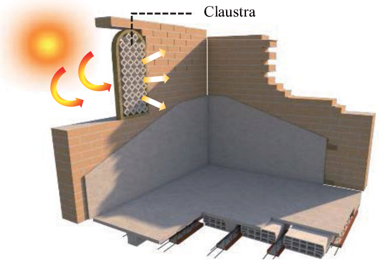
L. Vault transversal detailed section



M. Roof's sun exposure



N. Vault's sun exposure



O. Moucharabieh detail

Table 4 Second case study's envelope materials

Constructive element	Materials	Thermal conductivity λ (W/(m·K))	Thickness (m)
External wall	Gypsum + sand	0.22	0.02
	Compressed earth block	0.762	0.40
	Plaster coating	0.35	0.015
Internal wall	Plaster coating	0.35	0.015
	Compressed earth block	0.762	0.25
	Plaster coating	0.35	0.015
Low and intermediate floors	Tafza gypsum	0.35	0.015
	Hollow body + compression slab	1.45	0.2
	Mortar	1.4	0.04
	Flooring	2.1	0.06
Vault	Tafza gypsum	0.44	0.025
	Lous block	0.9	0.2
	Tafza gypsum	0.44	0.025
	Air gap	0.16	0.1
Dome	Tafza gypsum	0.44	0.025
	Lous block	0.9	0.2
	Tafza gypsum	0.4	0.025

separate it from the rest of the house by a different level, overlooking the central patio. One of the major advantages of the patio is the natural ventilation during the hot seasons (Table 3, Figure J). During the day, the air in the patio becomes warmer, rises, and escapes through the openings. Therefore, it allows good air circulation inside the building. During the night the process is reversed, fresh ambient air circulates in the patio and enters the adjacent spaces through the openings. This causes airflows and the refreshing air becomes warmer, then rises, and escapes through the openings on the upper floor. This ventilation helps to maintain the quality of the indoor air, replacing stale air with new air (air's renewal).

- El-Miniawy architects tried to draw inspiration from the construction techniques used in Souf region's vernacular architecture and apply them in the design of the project. This is achieved by using a concrete skeleton and a covering of domes (*gouba*) and vaults (*demsa*) which are two main typical components that expressly refer to the local vernacular architecture (Table 3, Figures K & L). According to Leo Samuel et al. (2017) the dome structured roofs when used in solar-intensive regions, aim to reduce the solar heat gain, as they provide self-shading and reduce the surface area to volume ratio. This shows that the use of domes and vaults at the roof level in hot and arid climate regions like El-Oued is a highly efficient solution to reduce the impact of heat gains due mainly to direct solar radiations. These architectural elements composed of curved or rounded planes operate passively and create shaded areas on the roof (Sadineni et al. 2006; Tang et al. 2006).

The concave shapes (domes and vaults) offer minimal surfaces with large volumes, as they have a high solar radiation reflection capacity. Designers can use and develop these elements, exploiting their thermal quality (Fathy 1973). During the day, the solar rays are diffused and reflected towards the celestial vault. The warm air is accumulated inside under the vacuum created by the dome and then released towards the outside through an opening located at the top or on the sides of the concave roof. During the night, these surfaces cool down by night-time radiation faster than horizontal surfaces.

By using vaults, the first ceiling is protected by direct sunlight and cooled by the moving air inside the vault (small vaults open on both sides allow natural cooling of the ceiling with natural through ventilation). The pressure difference between two facades, due to wind or differentiated sunlight, is the main driver of the indoor airflow. Of all natural ventilation driving forces, the effect of wind across the room is more efficient (Najafi and Yaghoubi 2015).

The thermal analysis of domes and vaults using the Archiwizard software shows that the solar power or the surface density of the flow arriving on the dome and vault is not homogeneous and there is a protected side presented by the blue and purple color and an exposed surface presented by the yellow color. Only a small part of its surface receives direct solar radiation, the rest is either protected by the element itself or receives a diffuse ray. The areas exposed to radiation change throughout the day depending on the orientation of the sun, but it is clearly noticeable that the east-west surfaces of the dome and the upper surface of the vault are the most exposed areas during the day (Table 3, Figures M & N).

- A Moucharabieh placed on the window performs as a shading device to reduce internal heat, strengthen the shadows inside, and diffuse sunlight into the space. Made of openwork masonry, the small holes filter out the sun's rays while avoiding glare (El Jaouhari et al. 2019). This device is often protruding to better capture the wind, which guarantees efficient ventilation (Table 3, Figure O).

5 In situ measurements

The main aim of this study was to measure hygrothermal parameters that define the outdoor climatic conditions and indoor thermal environment (air temperature, relative humidity and air velocity). Using a thermo-hygrometer sensor "Testo 480", measurements (thermal, humidity and ventilation) were collected from each case study during one week in July of summer 2019. Beforehand, the hottest week of the year has been determined according to the design-week method.

In addition, the measurements had to be carried out in the living area with the most severe thermal conditions (the warmest zone of the apartment). Accordingly, a room oriented south-west side was chosen to check the range of difference between the outside and the inside thermal environment conditions and to obtain quantitative information about the degree of comfort ensured in each case study. An analysis of the thermal behavior of the envelope of the two case studies was carried out according to the indoor temperature monitoring during the field measurement period and the thermal conditions obtained in the analyzed rooms.

5.1 The measurement's protocol

- **Time of temperature measurement:** the temperature and the relative humidity were measured in the month of July, with a bi-hourly protocol starting from 8:00 a.m. and all day long. The wind speed was negligible and almost equal to zero in the majority of the time.
- **Location**: the measurements were taken outside the buildings and inside in selected rooms at a height of 1.10 m as recommended by EN ISO 7726 (2001). The room was facing south-west and located in the upper level of the building. This choice was done to ensure not only the effect of the walls and floors but also that of the external roof, and to study the room with the most unfavorable conditions (the heat exchange between the interior space and the exterior environment that occur through the walls, floors and the exposed roof is maximized).
- **Measuring conditions:** the measurement of temperatures in the above-mentioned buildings was carried out under natural conditions, i.e. without the use of mechanical air-conditioning while opening the windows and blinds (usual living conditions). Other acting factors have been also considered such as the number of occupants and the influence of electric equipment. These factors influence of internal gains.
- **Measuring instruments**: the temperature was measured using a measuring instrument Testo 480 (Figure 7) with its various measuring probes (accuracy: ±0.3 °C + 0.1% of meas. val).

Fig. 7 The thermo-hygrometer sensor "Testo 480"

5.2 The monitoring data

A detailed analysis of the variations in indoor/outdoor temperatures and humidity was held to assess the thermal behavior of the two building's envelope. The period consisted of four complete daily cycles. A comparative reading of the measurements taken inside and outside the structures was represented in the form of graphs, which will allow comparison between the results obtained from the two cases.

The Figures 8 & 9 show that the air temperatures recorded inside the room of the first case study are high and very close to those monitored outside. Sometimes they decrease during the night and early morning. The maximum temperature reaches an average of 38.80 °C at 16:00 h and the minimum value is of 30.75 °C at 6:00 h with an average temperature difference of 8 °C, while the outside temperature reaches its maximum of 40.30 °C at 16:00 h and a minimum of 27.70 °C at 6:00 h with a difference of 12.60 °C. The internal humidity curve follows the evolution of the external one.

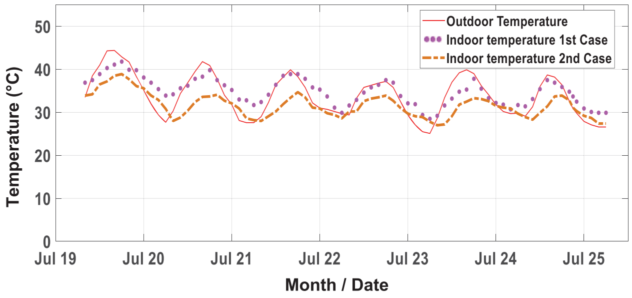


Fig. 8 Outdoor and indoor temperatures recorded

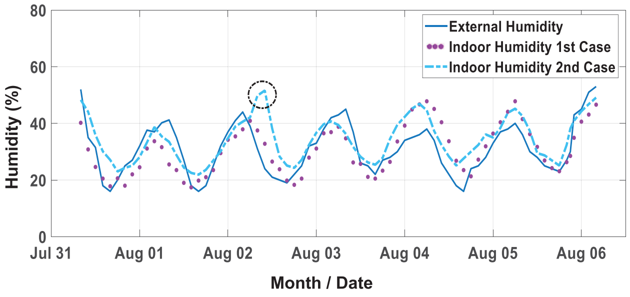


Fig. 9 Outdoor and indoor humidity recorded

The two humidity curves are almost parallel. The indoor humidity level and varies between 17% and 47%.

In such an inhospitable climate, the second case study succeeds to maintain interior temperatures lower than those of the first one with an average maximum temperature of 34.70 °C at 18:00 h and a minimum temperature of 27.90 °C at 8:00 h. The phase shift is of 2 hours when compared with the exterior values. The rate of interior humidity in this case varies between 23% and 49% with a spike of 52% in a day where low average humidity values were recorded. The spike that expresses a fluctuation of indoor humidity might be caused by occupants' activities (cooking, washing et cetera).

6 Simulation study

This part is devoted to the dynamic thermal simulation applied to the two selected case studies and the evaluation, verification and validation of the results obtained from the survey and site measurements. First, the tool chosen for the thermal simulation is DesignBuilder/EnergyPlus. This choice derives regarding several reasons, among which there is the capability offered by this tool both in terms of modeling and materialization and in data processing (Wasilowski and Reinhart 2009; Zhang 2014; Tindale 2015; Li et al. 2019).

6.1 Simulation protocol

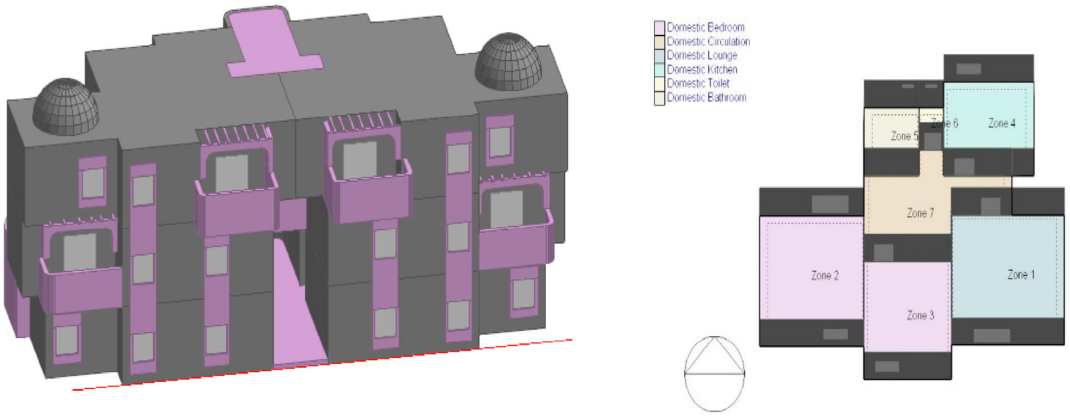
The city of El-Oued is located at 33.368° of latitude, 6.852° of longitude and 79 m of altitude. During the modeling phase of the buildings (Figures 10 & 11) (choice of: shapes, opaque and glazing materials, etc.), all the above mentioned characteristics of the studied examples were implemented.

The modeling process also included specific information related to household size (three persons) as well as their clothing considering summer period (0.4 clo). The studied zone is a living room, so, the occupants were in quiet seat activity with an estimated metabolism factor about 0.85 (man = 1.00, woman = 0.85, child = 0.75). This information was described as input data. After modeling, it was proceeded to free floating simulations to understand the envelope behavior. The simulation was based on the comparison of the conceptual and formal effects of the architectural and constructive aspects on its thermal performance.

6.2 Validation and simulation results

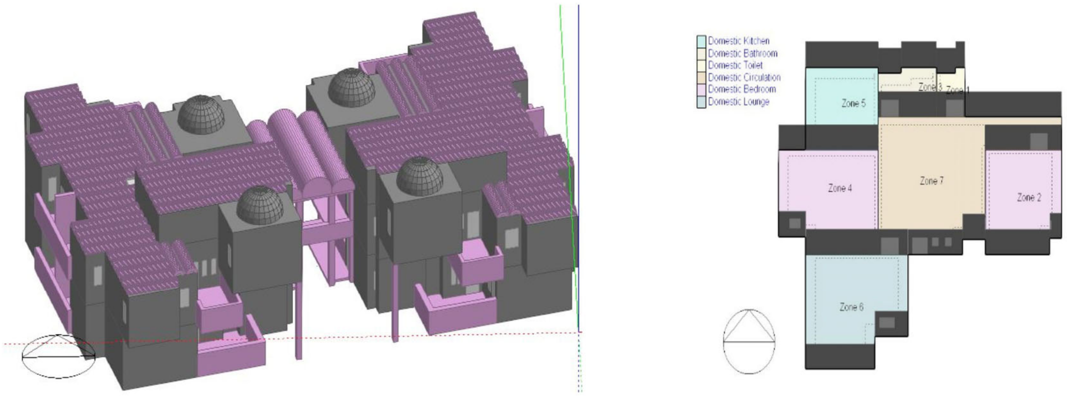
The validation process is a very important step to ensure calibrating of the simulation's results. The starting point for this process is a data graph containing the measured and simulated values of the same variable. The first step is to check the consistency between the temperatures in the weather file and those measured outside, and the second is to detect differences between the simulated data and the measured data in the considered study's period. Using a specific mathematical equation, error's rate calculations were performed (Hussain and Oosthuizen 2012; Benchekroun et al. 2019).

According to recent researches, the divergence between simulated and in-situ measurement's values is determined generally through a based simple difference percentage between those data. Therefore, this index that refers usually



(a) (b)

Fig. 10 (a) DesignBuilder model of the first case study; (b) first case spatial zoning



(a) (b)

Fig. 11 (a) DesignBuilder model of the second case study; (b) second case spatial zoning

to the instantaneous values average or integral value is required for validation's purposes. The "error's percentage" is most commonly used to compare measured and simulated values of total energy consumption, and is often used with temperature data. Thus, because of the simplicity and the ease of measurements, the model accuracy is widely used for a very first assessment (Huerto-Cardenas et al. 2020).

To calibrate simulation models correctly, the margin of errors must not exceed 5%. The compensation of errors can affect identifying building's problems because of the dynamic relationships between different parts of building. Therefore, the input parameters (input data configuration) of simulation must be modified to be within the errors' margins (5%) to calibrate the model correctly.

$$\text{Error Percentage}(\%) = \left|\frac{\text{Measured value} - \text{Simulated value}}{\text{Measured value}}\right| \times 100 \tag{1}$$

After this rapid check for the reliability of the simulation results (a percentage of errors is less than 5% (Maile et al. 2012)) occurs when compared to the data of in-situ measurements in the considered study's period (Table 5), a further step was applied to validate the simulated model.

The criteria and limit values set out in the ASHRAE Guideline 14-2014 (ANSI/ASHRAE 2014) which indicate that the monitoring of the variables and the analysis of the mean bias error (MBE) (Eq. (2)) and the coefficient of variation of the root mean square error (CV(RMSE)) (Eq. (3)) between the simulated and measured values defines the reliability of the thermal model. It is established as limit conditions for hourly values that MBE oscillates between −10% and + 10% and that CV(RMSE) is lower than 30%. All internal as well as external factors were tracked to validate the model. Figures 12, 13 & 14 show that the values obtained in both MBE and CV(RMSE) were lower than the limit values set in the ASHRAE Guideline, thus assuring the thermal model's validity (Mahar et al 2019; Bienvenido- Huertas et al 2020; Huang and Zhai 2020) .

$$\text{MBE} = \frac{\sum_{i=1}^{n}(y_i - x_i)}{n} \times 100[\%] \tag{2}$$

$$\text{CV(RMSE)} = \frac{1}{\bar{y}}\left[\frac{\sum_{i=1}^{n}(y_i - x_i)^2}{n}\right]^{1/2} \times 100[\%] \tag{3}$$

where: y_i is the measured value; x_i is the simulated value; n is the number of measures; $\bar{y}$ is the mean value of measured data.

In order to study the thermal behavior of the two buildings throughout the summer period, a correspondence between the experimental and simulated data, in terms of outdoor and indoor air temperature and outdoor humidity, was performed by the bias equation of the inequality coefficient (Williamson 1995; Stefanizzi et al. 2016) using

Table 5 Error's percentage calculation

	Measured average temperature (°C)	Simulated average temperature (°C)	Error (%)	Measured average humidity (%)	Simulated average humidity (%)	Error (%)
External	33.90	32.81	3.21	31.32		
1st case study	34.89	33.99	2.57	30.63	31.77	3.72
2nd case study	31.65	32.50	2.68	34.39	34.03	1.04

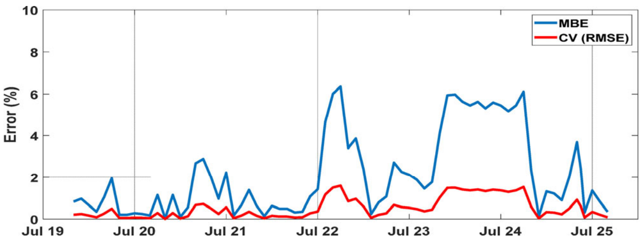


Fig. 12 Outdoor temperature error

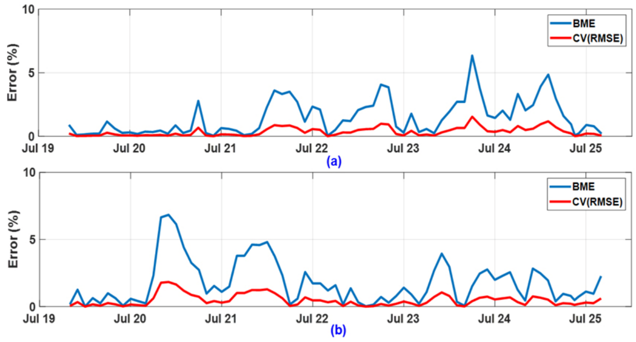


Fig. 13 Indoor temperature error: (a) 1st case; (b) 2nd case

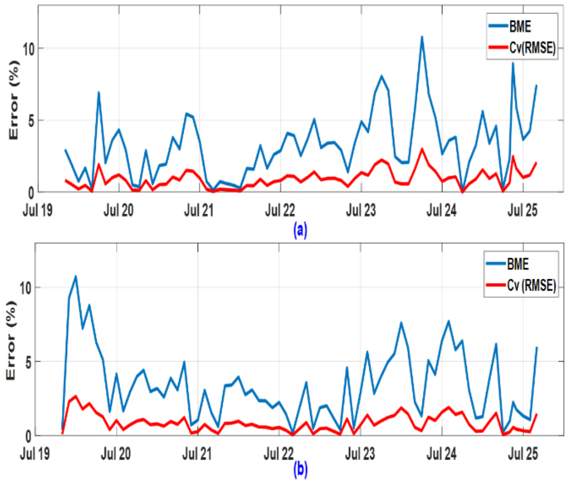


Fig. 14 Indoor humidity error: (a) 1st case; (b) 2nd case

the numerical calculation software Matlab:

$$\mathrm{IC} = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(Y-X)^2}}{\sqrt{\frac{1}{N}\sum_{i=1}^{N}X^2}+\sqrt{\frac{1}{N}\sum_{i=1}^{N}Y^2}} \tag{4}$$

where: X is the measured internal value; Y is the simulated internal value, N is the number of time steps.

The inequality coefficient (IC) determines the accuracy of models used in thermal performance. IC is based on three factors: unequal tendency (mean), unequal variation (variance) and imperfect co-variation (co-variance), (Eq. (4)). The value of IC can be varied from 0 to 1, showing that 0 is perfect match value and 1 showing no match result. So, when the values get close to 0, it means that it assures a good match in inequality (for example 0.1). On the contrary, bad match occurs when the values vary between 0.9 to 1 (Born et al. 2001).

An average value of the inequality coefficient (IC) for each indicator was calculated (Table 6), and used to adjust the simulation results. Figures 15 & 16 show the adjustment of the measured temperature and humidity compared to those simulated.

Table 6 Inequality coefficient (IC) calculation

	External temp.	1st case indoor temp.	1st case indoor RH	2nd case indoor temp.	2nd case indoor RH
IC 1	0.0043	0.0016	0.0141	0.0016	0.0603
IC 2	0.0092	0.0020	0.0153	0.0020	0.0485
IC 3	0.0118	0.0104	0.0178	0.0104	0.0502
IC 4	0.0142	0.0122	0.0296	0.0122	0.0430
IC 5	0.0292	0.0156	0.0339	0.0156	0.0523
IC 6	0.0270	0.0155	0.0311	0.0155	0.0471
IC average	**0.0160**	**0.0095**	**0.0236**	**0.0095**	**0.0502**

7 Results and discussion

After measurements validation, the simulation was carried out over a longer period to study the behavior of the buildings throughout the whole summer period (Figures 15 & 16). The graphs show that the temperature in the second case study does not exceed 40°C, whereas the temperature in the first case study can exceed 40°C in several days, especially from the last week of July until mid-August. The fluctuations of the interior temperature in the second case are not very high; this is due to the envelope's materials and its form, which prevents the direct reception of solar rays either for the treatment of the roof or the judicious choice of windows' locations. On the other hand, the increase in temperature in the first case, especially in the afternoon, is due to the restitution of heat stored by the wall of the facades exposed to direct rays in addition to the solar gains entering through the windows. The radiation process affects both air and surfaces temperatures. The emission and absorption of radiation has a very important role in the heat exchanges that occur in the external surface. With the ineffectiveness of solar protection on the different facades, the degree of exposure to solar radiation increases as the sunshine intensity.

On hot summer days, the humidity level of the ambient air is a very important factor in the feeling of well-being or discomfort. In hot and arid climates, the humidity level outside is generally lower than inside, so ventilation of the rooms by opening doors and windows will not have a great

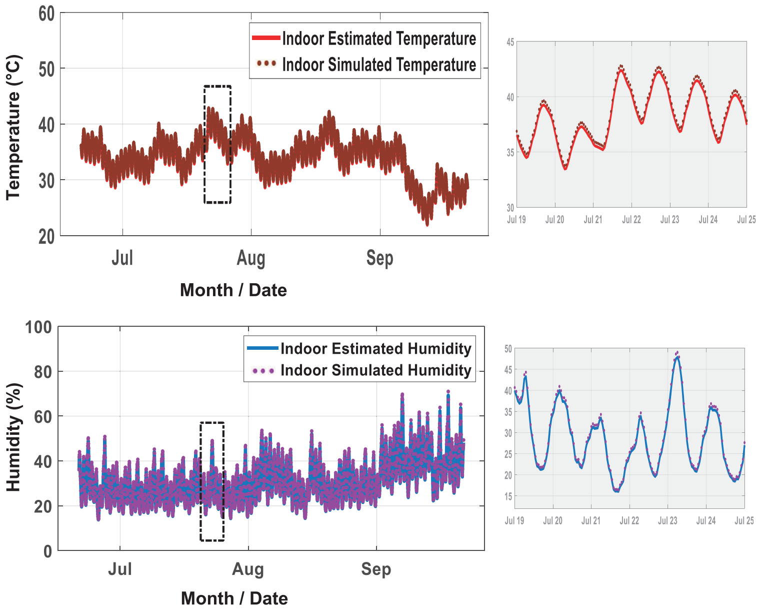


Fig. 15 First case simulated and measured indoor air temperature and humidity

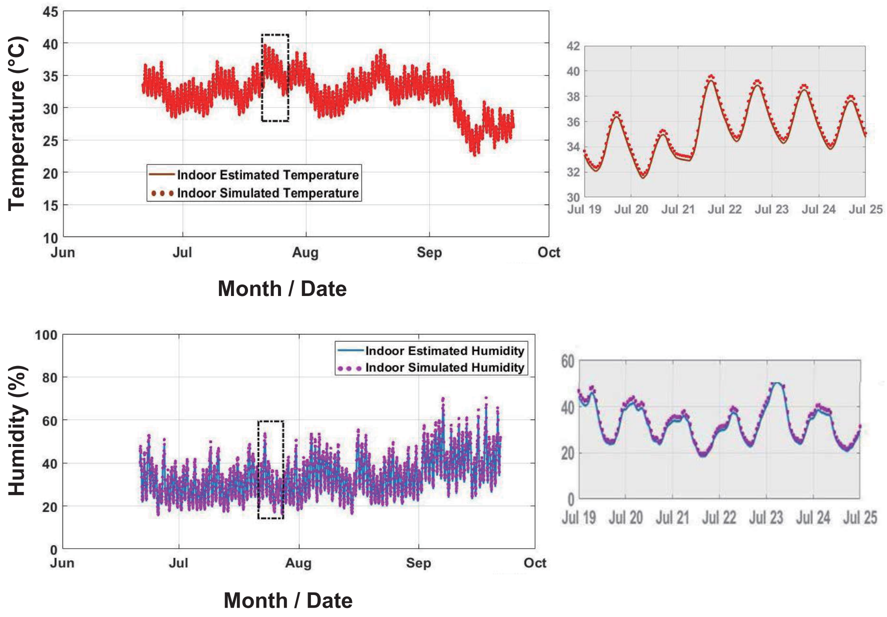


Fig. 16 Second case simulated and measured indoor air temperature and humidity

effect on the humidity level. The pattern of the humidity curve is almost stable in both cases, varying between 20% and 60% during most of the summer.

The fluctuation of air temperature and relative humidity profiles, indoors and outdoors, carried out during the hottest period of the year in the two cases are in Figures 15 & 16. The analysis on recorded data gives more clarification on how the architectural envelope's features (formal-conceptual and material choices) impact buildings' climate performance and occupants' thermal comfort in hot and arid climate zones.

By referring Figure 17 a comparison between outdoor and indoor air temperatures simulated during the summer period (June 21–September 21) is done. A general reading of the temperatures graphs shows that the internal temperatures in the second case study are lower than in the first one. As it shows, there is a large difference between the outside temperatures and the temperatures measured in the second building while the first building suffers from high temperatures mimicking those outside.

From Figure 17 and Table 7, it can be seen that the outdoor temperatures for the summer period vary between

17.50 °C and 45.50 °C with a temperature difference of 28.50 °C and an average temperature of 32.75 °C. For the first case study, as illustrated in Figures 17 & 18, indoor air temperature varies between 21.90 °C and 42.20 °C with an average value of 33.77 °C and a minimum humidity level of 13.70%, maximum of 69% and average of 30.90%. Such an important observation regarding temperature reveals that it is almost like the one outside.

The thermal environment in the second case study seems to be more adapted to its surroundings; the temperatures are more moderate varying between 22.80 °C and 36.10 °C with an average temperature value of 28.90 °C. As far as humidity is concerned, it varies between 17.80% and 56.60%. The analysis shows that the use of appropriate bioclimatic strategies in architectural design can contribute to a significant reducing of indoor temperatures, thus significantly reducing the need for air conditioning and consequently reducing energy consumption for air conditioning loads.

The detailed section (Figure 17) represents the most unfavorable week of the summer with daily outdoor temperatures exceeding 45 °C. The graph of the second case (the neo-vernacular building) is characterized by rather stable values; the daily thermal peak during the worst conditions in summer was decreased from 45.50 °C (outdoor) to 36.10 °C (indoor) while indoor mean temperature reaches only 28.50 °C. The apartment in this case is close

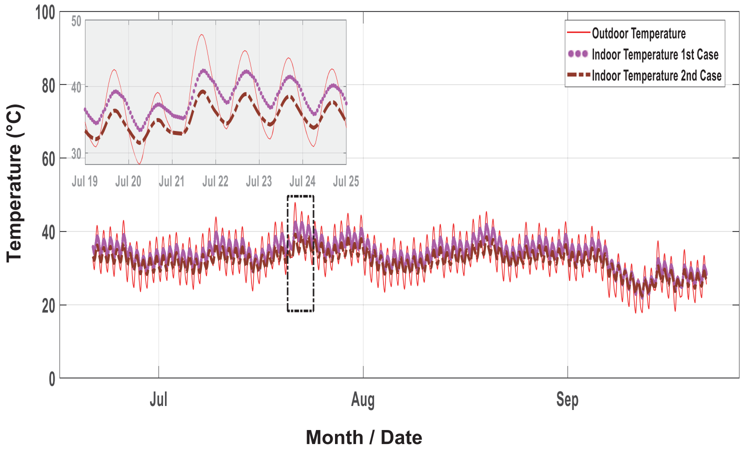


Fig. 17 Outdoor and indoor studied cases air temperature

Table 7 Comparison of outdoors and indoors air temperature and relative humidity values

	Temperature (°C)			Relative humidity (%)		
	Outdoor	Indoor case study 1	Indoor case study 2	Outdoor	Indoor case study 1	Indoor case study 2
Mean	32.75	33.77	28.90	43	30.90	32.73
Maximum	45.50	42.20	36.10	60	69	56.60
Minimum	17.50	21.90	22.80	20	13.70	17.80

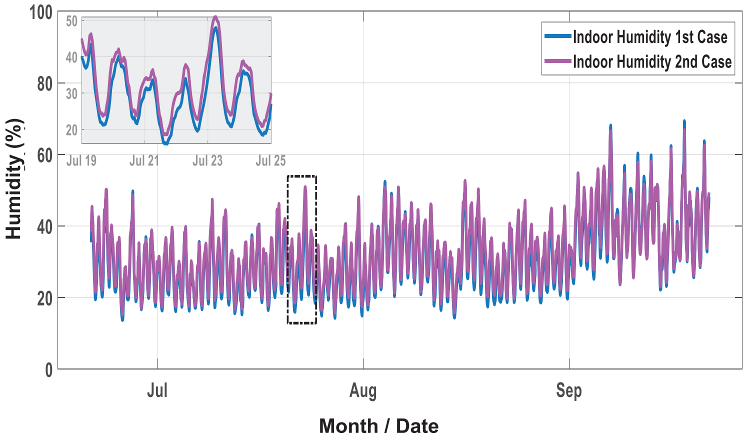


Fig. 18 Indoor studied cases relative humidity

to being comfortable when compared with the comfort temperature zone in this area, which ranges between 19 °C and 28 °C according to Givoni's bioclimatic chart. The low diffusivity of the materials and the strategies used are minimizing the heat restitution time. The thermal protection by roof vaults and domes and the compactness of the facades, as well as, the relative protection of the windows have prevented overheating, induced by direct sunlight. In contrast, the typical residential unit (1st case study) decreased the daily thermal peak only from 45.50 °C (outdoor) to 42.20 °C (indoor). The insufficient thermal comfort conditions recorded in the first case depend closely on the architectural envelope's features, since both buildings have the same orientation and are submitted to similar climatic conditions.

8 Conclusion

Climate considerations are essential dimensions in providing thermal performance and indoor comfort in residential buildings. This seems to be a common sense, but in practice, especially in emerging countries like Algeria where standards and regulations on energy saving are still lacking, the thermal performance of the building is not considered during the design and construction phase. This results in buildings that are strongly dependent on mechanical air-conditioning systems to control the indoor climate. Paradoxically, vernacular architecture, especially in hot and arid regions, is considered to be a model for sustainability and climate responsive design; it embodies a range of design principles, features and techniques that are actually known as green strategies. The relevance of these vernacular features is still valid today being now the basis of sustainable building design.

Using in-situ measurements and computational simulations, the research demonstrated that the neo-vernacular building better responds to local climate constraints and, consequently, provided better thermal comfort conditions. Thermal performance enhancements potential from improving building envelope performance is considerable: the maximum air temperature during the summer was decreased from 45.50 °C (outdoor) to 36.10 °C (indoor).

The results presented in this research support the arguments that integrating climate-responsive strategies developed in vernacular dwellings is not only feasible for contemporary constructions, but also efficient. Furthermore, the findings suggest that considering traditions performed in ancient vernacular architecture as an approach to improve climatic performance can lead to an optimum adaptation of contemporary buildings to climate and environment and provide alternative solutions to reduce energy consumption without sacrificing occupants' comfort quality.

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