

PROSTOR

34 [2026] 1 [71]

A SCHOLARLY JOURNAL OF ARCHITECTURE AND URBAN PLANNING
ZNASTVENI ČASOPIS ZA ARHITEKTURU I URBANIZAM

UNIVERSITY
OF ZAGREB
FACULTY OF
ARCHITECTURE
SVEUČILIŠTE
U ZAGREBU
ARHITEKTONSKI
FAKULTET

ISSN 1330-0652
[https://doi.org/
10.31522/p](https://doi.org/10.31522/p)
CODEN PORREV
UDC 71/72
34 [2026] 1 [71]
1-146
1-6 [2026]

109-119 **SAMIRA SOUKANE
MOHAMED DAHLI**

IMPROVING THE ENERGY PERFORMANCE OF FRENCH COLONIAL BUILDINGS
IN ALGERIA: BALANCING HERITAGE VALUES AND ENERGY CHALLENGES

PRELIMINARY COMMUNICATION
[https://doi.org/10.31522/p.34.1\(71\).9](https://doi.org/10.31522/p.34.1(71).9)
UDC 72.03:697 (652.11) "1830/1930"



Af

SAMIRA SOUKANE^{1,2}, MOHAMED DAHLI³

¹ DEPARTMENT OF ARCHITECTURE, FACULTY OF SCIENCE AND TECHNOLOGY, MOHAMED KHIDER UNIVERSITY, BISKRA, ALGERIA

² DEPARTMENT OF ARCHITECTURE, FACULTY OF TECHNOLOGY, UNIVERSITY ABDERRAHMANE MIRA, BEJAIA, ALGERIA

 [HTTPS://ORCID.ORG/0009-0006-3210-309X](https://orcid.org/0009-0006-3210-309X)

³ DEPARTMENT OF ARCHITECTURE, FACULTY OF CONSTRUCTION ENGINEERING, MOULOUD MAMMERI UNIVERSITY, TIZI-OUZOU

 [HTTPS://ORCID.ORG/0009-0001-4984-148X](https://orcid.org/0009-0001-4984-148X)

samira.soukane@univ-bejaia.dz
mohamed.dahli@ummto.dz

PRELIMINARY COMMUNICATION

[HTTPS://DOI.ORG/10.31522/P.34.1\(71\).9](https://doi.org/10.31522/p.34.1(71).9)

UDC 72.03:697 (652.11) "1830/1930"

ARTICLE RECEIVED / REVISED / ACCEPTED: 16. 12. 2025. / 2. 2. 2026. / 11. 5. 2026.

IMPROVING THE ENERGY PERFORMANCE OF FRENCH COLONIAL BUILDINGS IN ALGERIA: BALANCING HERITAGE VALUES AND ENERGY CHALLENGES

KEYWORDS

ALGIERS
BIO-BASED THERMAL INSULATION
COLONIAL BUILDINGS
ENERGY EFFICIENCY
HERITAGE VALUES

ABSTRACT

Algeria inherited a substantial building stock of significant heritage value, particularly concentrated in the historic center of Algiers, notably within the Larbi Ben M'hidi district from the French colonial period (1830-1962). However, these buildings generally exhibit poor energy performance and high levels of energy consumption. This study investigates how the preservation of heritage values can be reconciled with improving the energy efficiency of colonial-era residential buildings in the Larbi Ben M'hidi district of Algiers. A thermal diagnostic based on infrared thermography was conducted on several buildings, leading to the selection of the building located at 39 Rue Larbi Ben M'hidi as the

case study. Subsequently, dynamic thermal simulations were carried out using ArchiWIZARD, based on the EnergyPlus calculation engine, in order to evaluate four energy retrofitting scenarios. In parallel, a bio-based thermal insulation material composed of cork waste and cellulose was developed and thermally characterized. The optimal formulation (75% cork) exhibited a thermal conductivity of $\lambda = 0.048$ W/m·K and a specific heat capacity of $C_p = 1285$ J/kg·°C. When integrated into the simulation model, this insulation material enabled a reduction in energy demand of 54.44% for heating and 22.64% for cooling, while preserving the architectural integrity of the heritage façades.

INTRODUCTION

A large part of the architectural heritage from the French colonial period in Algeria embodies undeniable heritage values and represents a living testimony to the country's urban and cultural history. These buildings are distinguished by their richly decorated façades, generous volumes, and construction techniques adapted to the climate, which still contribute today to the identity of city centers with colonial cores (Mohdeb, Attar and Saraoui, 2023). In Algiers, colonial architecture (1830-1930) illustrates a dual approach: the assertion of colonial authority through monumental public buildings, ordered façades, continuous balconies, and Haussmannian cornices, and adaptation to local context through Neo-Moorish and Art Deco styles incorporating arches, patios, and ornamental motifs (Béguin, 1983; Chaouche, 2013). This coexistence has produced a hybrid urban fabric that forms the basis of Algiers's architectural identity. However, these buildings exhibit significant thermal losses, lack thermal insulation, and suffer from material aging, leading to high energy consumption. Their thermal rehabilitation therefore raises both technical and cultural challenges: how can historic heritage be adapted to modern energy requirements without altering its architectural authenticity?

Among available solutions, internal thermal insulation (IT) is often preferred for heritage buildings, as it allows the preservation of the

exterior appearance while improving energy performance (Zagorskis et al, 2014). Bio-based materials, in particular, offer a sustainable alternative compatible with historical masonry and characterized by low environmental impact (Claude, 2018). ITI combined with roof insulation and the rational replacement of joinery can reduce energy consumption by 43 to 56% depending on the climatic context (Galatioto et al, 2019), and may exceed 50% when high-performance systems such as heat pumps are implemented (Qu et al, 2021; Cho et al, 2020; Jiang, Lucchi, and Del Curto, 2023; González-Prieto et al, 2023). Hybrid approaches integrating insulation, system modernization, and renewable energy technologies make it possible to approach near-nZEB or Net Zero Energy standards (Franco et al, 2015; Sugár et al, 2020; Caro and Sendra, 2020; Ahmad et al, 2021). In Mediterranean contexts, the combination of insulation, mechanical ventilation, and heat recovery ensures a balance between energy performance and indoor air quality (Coelho and Henriques, 2021; Blázquez et al, 2019).

In the Algerian context, the energy rehabilitation of colonial buildings goes beyond the single objective of improving energy efficiency. It is part of a broader heritage conservation approach aimed at extending the lifespan of these buildings while respecting their architectural identity. This study therefore aims to:

- Characterize the thermal behavior of colonial buildings in Algiers through infrared thermography and in situ measurements;
- Evaluate the performance of a new bio-based insulation material composed of cork waste and cellulose;
- Simulate different dynamic thermal scenarios to estimate potential energy savings and their compatibility with heritage preservation.

The Larbi Ben M'hidi district is characterized by a high concentration of French colonial-era buildings, featuring construction systems and façades emblematic of the historic center of Algiers. This urban fabric therefore provides a particularly relevant context for analyzing energy rehabilitation strategies while safeguarding architectural and heritage values.

MATERIALS AND METHODS

This study aims to evaluate and improve the energy performance of residential buildings from the French colonial period in Algeria (1830-1930) while preserving their architectural and heritage values. First, eight buildings in the Larbi Ben M'hidi district were selected according to the Vitruvian triad: *Firmitas*, *Utilitas*, *Venustas* (Choay, 2001; Baba Ahmed et al,

2013; Hadjilah and Zerouala, 2018), and were subsequently subjected to a thermal assessment using infrared thermography (Paoletti et al, 2013; Ascione et al, 2015).

The combined analysis of these investigations led to the selection of the building located at 39 Rue Larbi Ben M'hidi as the case study, for which in situ measurements and dynamic thermal simulations were carried out. In parallel, a bio-based insulation material made from cork waste and cellulose was developed and experimentally characterized using the transient hot-wire method. Finally, the impact of this insulation material on the building's thermal behavior was evaluated through dynamic thermal simulations using ARCHIWizard/EnergyPlus (Ascione et al, 2015; 2016; Khadraoui and Sriti, 2017).

THERMAL DIAGNOSIS OF BUILDINGS WITH HIGH HERITAGE VALUES

Criteria for selecting buildings

The urban landscape of Algiers is strongly marked by buildings inherited from the French colonial period, constructed between 1830 and 1930. The Larbi Ben M'hidi district (formerly Isly) represents the first planned extension of the colonial city beyond the former Ottoman ramparts (Oukaci and Kassab, 2021; Oukaci, 2022) and constitutes one of the most emblematic examples of this period (Petruccioli, 1992; Belouchrani, 2012). Predominantly residential in character, it contains remarkable buildings distinguished by an eclectic architecture combining European and local influences, ranging from Neoclassicism to Art Deco, including Art Nouveau and Neo-Moorish styles (Chérif, 2017). The high concentration of buildings with significant heritage value, particularly along the structuring axes of Larbi Ben M'hidi, Ali Boumendjel, and Abane Ramdane (Fig. 2), constituted a decisive factor in defining the study area.

At the end of this initial assessment, eight representative buildings were selected, as shown in Table 1.

A thermal assessment using infrared thermography was conducted for eight selected buildings within the study area.

Thermography protocol for eight selected buildings

The thermographic measurement campaign of eight selected residential buildings was conducted on 9 February 2021, between 8:00 a.m. and 11:00 a.m., during the winter period. The main façades investigated were predominantly oriented east (80%), while the remaining 20% were oriented west (Fig. 2). All the buildings are equipped with central heat-



FIG. 1 REPRESENTATIVE BUILDINGS WITHIN THE LARBI BEN M'HIDI DISTRICT, ALGIERS. (SOURCE: AUTHORS, 2025)

ing, and the indoor temperatures measured in residential apartments were within the thermal comfort range (22-25 °C) (AFNOR, 2019; Liébard and De Herde, 2005).

Measurements were carried out exclusively in residential spaces, with the commercial premises on the ground floor excluded, in order to calibrate the thermal model to reflect the actual residential occupancy of the building. Internal heat gains from occupants and household appliances were considered negligible, as most apartments were unoccupied at the time of the measurements. Thermographic measurements were performed in accordance with the ISO 6781:2015 standard (ISO, 2015), under favorable weather conditions (overcast sky to minimize the influence of solar radiation, low wind speed, and an indoor-outdoor temperature difference greater than 10 °C) (Pajani, 2014; Ascione et al, 2015). Outdoor temperatures ranged from 10 °C at 8:00 a.m. to 12 °C at 11:00 a.m. An infrared thermal cam-

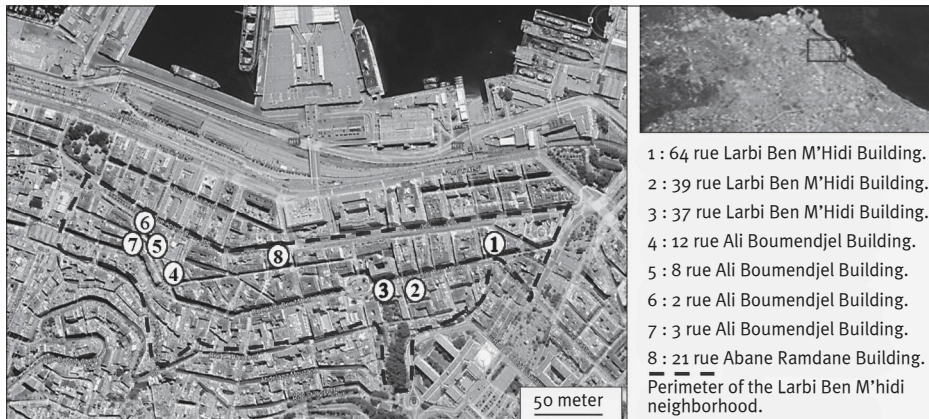


FIG. 2 IDENTIFICATION OF THE CASE-STUDY BUILDINGS IN THE LARBI BEN M'HIDI DISTRICT OF ALGIERS. (SOURCE: GOOGLE EARTH, PROCESSED BY THE AUTHORS)

era (Flir i7), calibrated between 9 and 38 °C with an emissivity of 0.93 corresponding to that of stone, was used. Its operating temperature range is between 0 and 50 °C, with a spectral band between 7.5 and 13.5 μm .

The heritage assessment, based on the Vitruvian triad (excellent habitability, very good state of preservation, high heritage value), combined with the results of the infrared thermography presented in the Results section (Fig. 7), guided the selection of the building at 39 Rue Larbi Ben M'hidi for indoor temperature measurements and dynamic thermal simulation

AMBIENT TEMPERATURE STUDY OF BUILDING 39 RUE LARBI BEN M'HIDI

Presentation of the building

The study focuses on the building located at 39 Rue Larbi Ben M'hidi, in the historic center of Algiers, constructed between 1905 and 1906 by architect L. Bourgarel (Daoudi, 2013). The building has a compact layout organized around an atrium that provides zenithal daylight and natural ventilation for the interior

spaces (Fig. 3 C-D). It consists of a ground floor topped by five upper floors (G+5).

The structural system is based on load-bearing stone walls with a thickness of 55 cm (Fig. 3 F) and floors composed of vault infill blocks supported by steel beams (IPN). The external joinery is made of wood with single glazing (4 mm), presenting a thermal transmittance coefficient of $U = 5.7 \text{ W/m}^2\cdot\text{K}$.

Protocol for recording indoor/outdoor ambient temperatures

To select an optimal day for temperature measurements, several criteria were considered, including building access and the availability of co-owners. The mid-season day of 28 September 2022 was selected, ensuring natural conditions without the use of heating or air conditioning, in order to obtain measurements representative of the building's actual thermal behavior.

The measurements were carried out in the living room of an apartment located on the 4th floor of the building at 39 Rue Larbi Ben M'hidi, oriented toward the east façade, where thermographic photographs were also taken (Fig. 4 A). This intermediate floor was chosen to limit the influence of thermal gains from the roof and the lower levels. The living room was selected due to its primary function and its thermal representativeness of the apartment. Measurements were taken at two-hour intervals between 8:00 a.m. and 6:00 p.m., at a height of 1.2 m, both indoors and outdoors on the balcony. The recorded parameters were:

- Indoor ambient temperature (T_{ind});
- Outdoor ambient temperature (T_{out}).

All measurements were performed using a multifunction Testo 480 anemometer, ensuring accurate temperature recording. The evolution of indoor and outdoor temperatures provides information on the energy efficiency of the building envelope and openings. The T_{int} values will be used for the validation of the thermal simulation model.

Central Algiers is located at 36°41' N and 3°12' E, at an altitude of 25 m, and is characterized by a temperate Mediterranean climate, with hot, dry summers and mild, humid winters. Average temperatures in September range from 18 and 29 °C, illustrating typical mid-season conditions (Meteonorm V8, data 2012-2022, Fig. 4 B).

The main boundary conditions for the thermographic and ambient temperature measurements at the building located at 39 Rue Larbi Ben M'hidi are presented in Table II.

Following the thermal diagnostic phase, the methodological approach continues with the development of a bio-based insulating material.

TABLE I SUMMARY OF THE MOST REPRESENTATIVE BUILDINGS IN THE LARBI BEN M'HIDI DISTRICT ACCORDING TO THE VITRUVIAN TRIAD. (SOURCE: AUTHORS, 2021).

N°	Buildings	State of preservation (<i>firmitas</i>)	Habitability (<i>utilitas</i>)	Heritage values (<i>venustas</i>)
1	64 Rue Larbi Ben M'hidi	Good state of preservation	Excellent habitability	High heritage value
2	39 Rue Larbi Ben M'hidi	Very good state of preservation	Excellent habitability	
3	37 Rue Larbi Ben M'hidi	Good state of preservation	Good habitability	
4	12 Rue Ali Boumendjel	Good state of preservation	Good habitability	High heritage value
5	8 Rue Ali Boumendjel	Good state of preservation	Good habitability	
6	2 Rue Ali Boumendjel	Good state of preservation	Excellent habitability	
7	3 Rue Ali Boumendjel	Good state of preservation	Good habitability	
8	21 rue Abane Ramdane	Good state of preservation	Excellent habitability	High heritage values

DEVELOPMENT OF THE CORK/CELLULOSE COMPOSITE MATERIAL

Materials used: cork and paper waste

This study uses cork waste and paper waste (cellulose) as raw materials to develop a bio-based thermal insulation composite. The cork was obtained from industrial waste generated during the manufacture of discs and stoppers and collected from the public company EPE Béjaïa Liège, supplied by several forest conservations offices (Jijel, Souk-Ahras, Sétif and Tizi Ouzou). The recovered cork aggregates have a particle size ranging from 2.5 to 8 mm. Cork is widely used as a thermal insulation material, either in expanded panels or in composites such as cork-gypsum, cork-wood, cork-clay or cork concrete (Kellati et al, 2010; Cherki et al, 2014; Limam et al, 2016; Mounir et al, 2014; Ziregue et al, 2016; Tedjiti et al, 2020). However, these composites often present relatively high thermal conductivity (0.1-0.4 W/m²·°C) due to the density of the mineral matrices used to bind the aggregates (Fino, Tadeu and Simões, 2018).

To overcome this limitation, a cellulose matrix derived from paper waste was used. The cellulose was obtained from discarded newspapers and cardboard. After cutting into small pieces, the material was treated with a 7% sodium hypochlorite solution, washed with potable water, and dried to constant mass to eliminate microorganisms and bleach the pulp (Bentchikou et al, 2012). The dried material was then finely ground to facilitate volumetric dosing. The combination of cork aggregates with recycled cellulose enables the development of a bio-based cork/cellulose insulation material, while simultaneously recovering waste and contributing to circular economy and energy transition.

Preparation of specimens

Proportioning, mixing of constituents, and molding of specimens

The cork-paper mixtures were prepared according to volumetric proportions of 75%, 50%, and 25% (Dahli and Toubal, 2010). The volumes of the constituents were measured using a graduated container. Mixing was carried out using a 5 L mixer in accordance with the EN 196-1 (ECS, 2016) standard, for 3 minutes: 90 s at 140 rpm followed by 90 s at 285 rpm, with an intermediate pause to scrape the mixing bowl.

The specimens (15 × 10 × 3 cm) were then molded according to the NF EN 993-15 (Afnor, 2005) standard in two layers with slight compaction in order to eliminate entrapped air and improve cohesion. They were air-dried for three days and subsequently demolded.



Drying and surface finishing of specimens

In order to limit the influence of moisture on the thermal properties, the specimens were dried at 103 °C in an oven (Fig. 5) to constant mass was reached, and then polished to ensure better thermal characterization. The experimental measurements were carried out on these dry and smooth samples according to three series of tests.

Thermo-Physical characterization of specimens

Measurement of the apparent density ρ of the composites

Density corresponds to the mass of a material per unit volume. The specimens with different cork/cellulose compositions were weighed using a precision balance to determine their mass M . Their volume V corresponds to the

FIG. 3 A: LOCATION OF THE BUILDING IN THE LARBI BEN M'HIDI DISTRICT; B : MAIN FAÇADE OF THE BUILDING; C : ATRIUM OF THE BUILDING; D : ZENITHAL LIGHTING OF THE ATRIUM; E : STAIRCASE WITH INTEGRATED ELEVATOR F : WALL COMPOSITION OF THE BUILDING. (SOURCE: AUTHORS, 2021).

FIG. 4 A: SPACE SELECTED FOR INDOOR TEMPERATURE MEASUREMENTS; B: MONTHLY TEMPERATURES OF THE CITY OF ALGIERS FOR THE PERIOD 2012-2022. (SOURCE: AUTHORS, 2023; METEONORM V8)

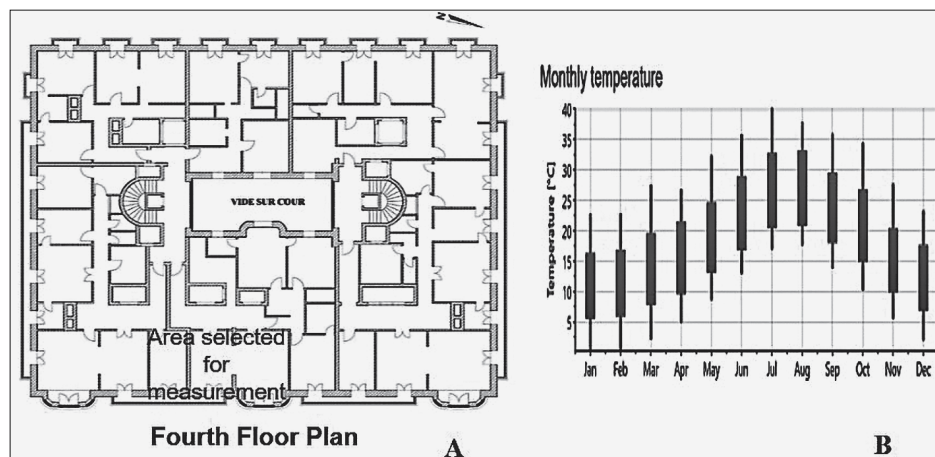


TABLE II BOUNDARY CONDITIONS OF THE THERMOGRAPHIC SURVEY AND INDOOR-OUTDOOR TEMPERATURE MEASUREMENTS AT 39 RUE LARBI BEN M'HIDI. (SOURCE: AUTHORS, 2022).

Parameter	Thermographic survey of eight buildings	Ambient measurements – 39 Rue Larbi Ben M'hidi
Date	09/02/2021 (winter)	28/09/2022 (mid-season)
Time range	8 h – 11 h	8 h – 18 h (bi-hourly)
Outdoor temperature (°C)	10 – 12	22.8 – 24
Indoor temperature (°C)	22 – 25	19 – 21
Cloud cover	Overcast	Partly cloudy
Internal gains (occupants, appliances)	Negligible (mostly unoccupied apartments)	Negligible
Emissivity	0.93	/

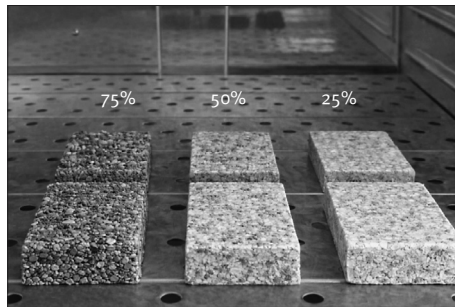


FIG. 5 CURING OF CORK/CELLULOSE COMPOSITE SPECIMENS. (SOURCE: AUTHORS, 2022)



FIG. 6 EXPERIMENTAL SETUP FOR MEASURING THERMAL CONDUCTIVITY AND SPECIFIC HEAT (TC-METER). (SOURCE: AUTHORS, 2022)

dimensions $0.15 \times 0.10 \times 0.03 \text{ m}^3$. The apparent density was calculated using Equation (1), and the results are presented in Table IV.

$$\rho \text{ Kg} / \text{m}^3 = \frac{M}{V} \quad 1$$

Measurement of thermal conductivity λ and specific heat capacity C_p of the composites

The thermal conductivity and specific heat capacity of the cork-cellulose composite were determined using the transient hot-wire method (Dahli and Toubal, 2010; Liu et al, 2019; Tedjdit et al, 2020). The experimental setup consists of a thermal probe placed between two identical samples and connected to a data acquisition unit (CT-meter) developed by the CSTB, in accordance with the EN ISO 8894-2:2007 standard (ISO, 2007) (Fig. 6). The principle of the method is to induce localized heating in the material and then measure the temperature rise over a short period of time.

DYNAMIC THERMAL SIMULATION

Presentation of the simulation tool

Dynamic thermal simulations were carried out using the software ArchiWIZARD (v7), based on the EnergyPlus (v8) calculation engine, selected for its ability to accurately evaluate energy performance while accounting for climatic, geometric, and material parameters. A climate file specific to Algiers was

generated in EPW format using Meteonorm (v8.2) to ensure representativeness of local conditions.

The geometric modeling of the building located at 39 Rue Larbi Ben M'hidi was performed using ArchiCAD (v22). The resulting digital model, exported in SKP format, faithfully represents the current state of the building without any modification, and was used both for model validation and for comparison with the energy optimization scenarios. The thermo-physical properties of the materials composing the building envelope are detailed in Table III.

Dynamic thermal simulation protocol

The dynamic thermal simulation was performed on the building located at 39 Rue Larbi Ben M'hidi, excluding the ground floor, top floor, and attic to limit the influence of heat transfer with the ground and the roof. The simulation was conducted over a one-year period with an hourly time step, ensuring numerical stability of the calculations (avoiding initialization errors) and enabling the characterization of the building's thermal behavior during both winter and summer periods. The simulations were carried out using fixed setpoints (heating at $20 \text{ }^\circ\text{C}$ and cooling at $25 \text{ }^\circ\text{C}$), simplified occupancy profiles, a constant air renewal rate, and an infiltration rate of 0.7 vol/h , representative of the existing building conditions.

Four dynamic thermal simulation scenarios were developed to examine the impact of the thermal characteristics of glazed and opaque surfaces on the building's energy consumption. The first scenario represents the reference model, corresponding to the actual thermal performance of the building. The second scenario evaluates the impact of argon-filled double glazing ($U = 1.1 \text{ W/m}^2\cdot\text{K}$). The third scenario analyzes the effect of a 15 cm internal bio-based cork-cellulose insulation layer ($\lambda = 0.048 \text{ W/m}\cdot\text{K}$; $C_p = 1285 \text{ J/kg}\cdot\text{K}$; $\rho = 32.4 \text{ kg/m}^3$). Finally, the fourth scenario corresponds to an optimized model, combining the improvement of glazing and the thermal performance of the external opaque walls.

RESULTS DISCUSSION

RESULTS DISCUSSION OF THE THERMOGRAPHY OF THE EIGHT BUILDINGS

The thermographic results reveal significant heat losses at the openings of the eight buildings studied (Fig. 7). All of them are equipped with 4 mm single glazing, presenting a thermal transmittance coefficient of $U = 5.7 \text{ W/m}^2\cdot\text{K}$, which explains their poor energy per-

TABLE III THERMO-PHYSICAL CHARACTERISTICS OF THE BUILDING ENVELOPE MATERIALS IN THE 39 RUE LARBI BEN M'HIDI BUILDING. (SOURCE: DTR, 1997; ISO, 2007).

Materials	Thermal Conductivity coefficient λ (W/m K)	Specific heat c_p (J/kg °C)	Apparent density ρ (kg/m ³)	Thickness cm
Exterior rendering (s lime)	0,87	1080	1800	2,5
Blue stone	1,75	950	2400	50
Interior gypsum plaster	0,3	936	900	2,5
	thermal transmittance $U \text{ W/m}^2\cdot\text{K}$			thickness cm
Single-glazed	5,7			4

formance. The integration of double or triple glazing therefore appears necessary to improve energy efficiency; this solution shall be evaluated in the section dedicated to numerical simulation.

The façades also exhibit variable thermal losses, ranging from low to very high levels. These losses are mainly due to the massive, uninsulated load-bearing stone walls. In addition, the junctions between façades and floor slabs with balconies constitute sensitive areas because of the presence of thermal bridges. In this context, internal thermal insulation is recommended in order to improve energy performance while preserving the heritage values of the façades.

RESULTS AND DISCUSSION OF MEASURED INDOOR AND OUTDOOR AMBIENT TEMPERATURES

The temperature measurements carried out on 28 September 2022 (Fig. 8) confirm the results observed during the thermographic diagnosis. The difference between indoor and outdoor temperatures remains low between 10:00 a.m. and 4:00 p.m. (ff 1°C), indicating significant thermal exchanges through the building envelope. A slight time lag of about one hour between the peaks of outdoor and indoor temperatures also highlights the limited thermal inertia of the building.



FIG. 7 THERMOGRAPHY RESULTS OF THE 8 BUILDINGS. (SOURCE: AUTHORS, 2021)

FIG. 8 HOURLY VARIATION OF OUTDOOR AND INDOOR TEMPERATURES MEASURED ON SEPTEMBER 28, 2022, AT 39 RUE LARBI BEN M'HIDI. (SOURCE: AUTHORS, 2022)

FIG. 9 MEASURED AND SIMULATED INDOOR TEMPERATURES ON SEPTEMBER 28. (SOURCE: AUTHORS, 2023)

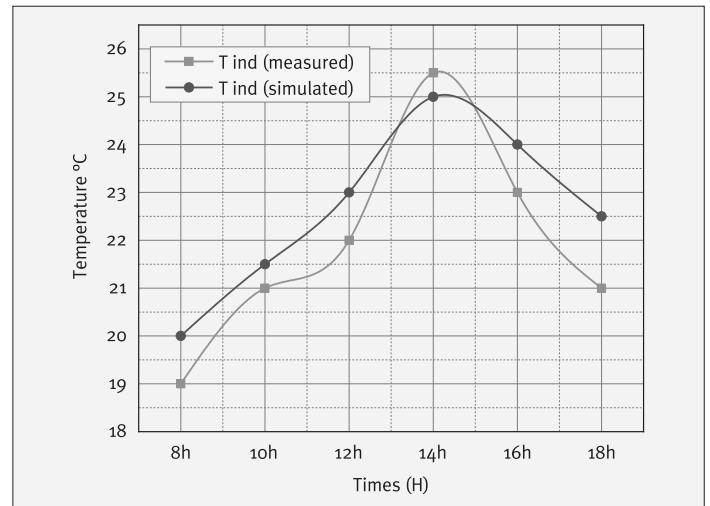
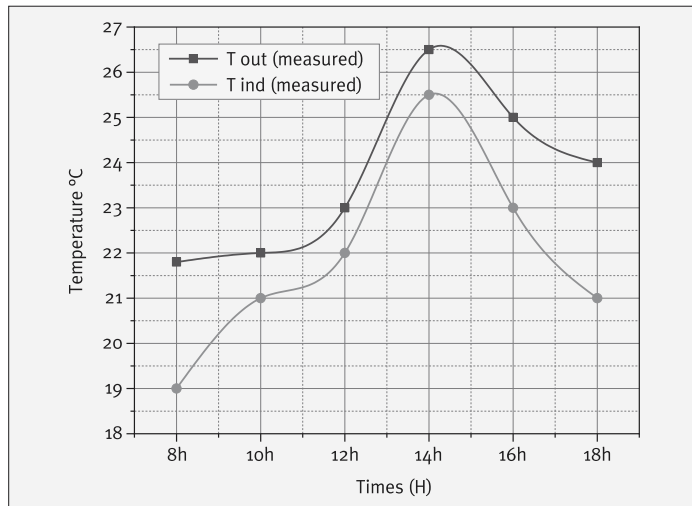


TABLE IV SUMMARY OF THE THERMO-PHYSICAL PROPERTIES OF CORK/CELLULOSE COMPOSITES (SOURCE: AUTHORS, 2022).

Specimens	Thermal characteristics		Physical characteristic
	Thermal conductivity λ (W/m·°C)	Specific heat Cp (J/kg·°C)	Apparent bulk density (kg/m³) I
Group 1 (75% cork)	0,048	1285	32,4
Group 2 (50% cork)	0,064	1244	71,1
Group 3 (25% cork)	0,08	1211	112

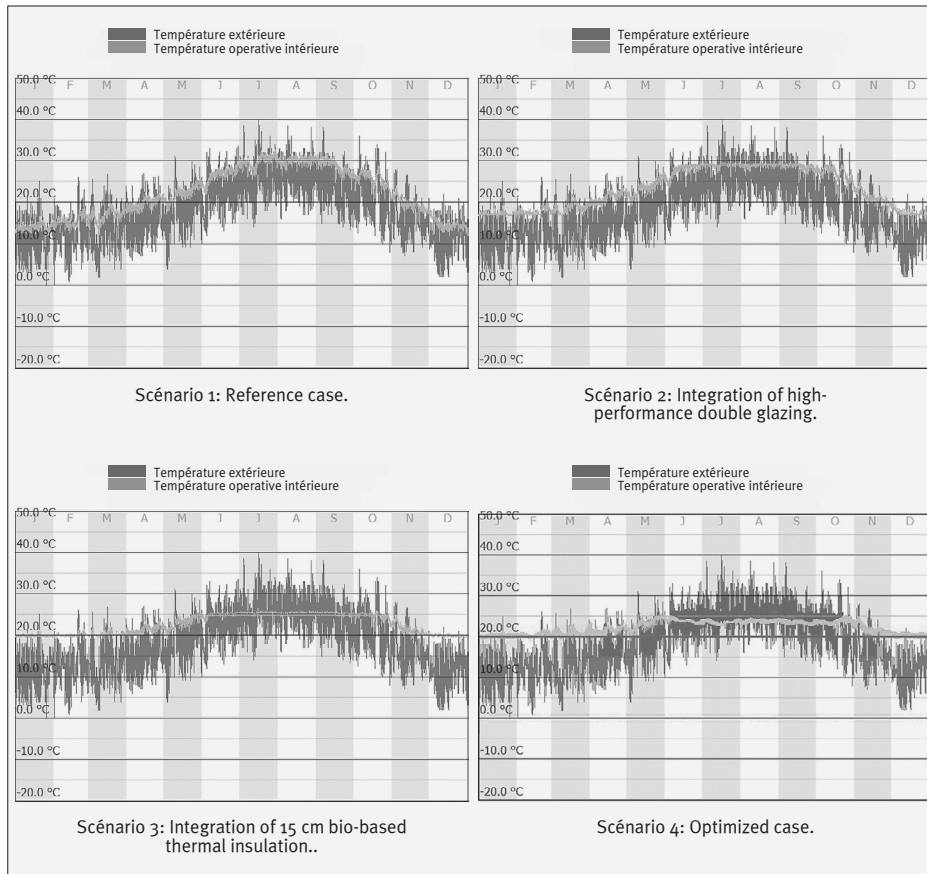


FIG. 10 RESULTS OF THE DYNAMIC THERMAL SIMULATION OF INDOOR TEMPERATURES UNDER FOUR SCENARIOS. (SOURCE: AUTHORS, 2023)

This action is mainly explained by the low thermal performance of the envelope, related to the absence of wall insulation, the presence of single glazing, the influence of variable solar gains associated with the building's orientation promoting rapid heat transfer, as well as the absence of significant internal gains. This therefore indicates a strong dependence of indoor thermal conditions on external climatic variations.

RESULTS AND DISCUSSION OF THE THERMO-PHYSICAL CHARACTERISTICS OF CORK/CELLULOSE COMPOSITES

The average values of the thermo-physical properties are presented in Table IV. The results show that Group 1 (75% cork / 25% cellulose) provides the best energy performance, with a thermal conductivity of 0.048 W/m·K and an apparent density of 32.4 kg/m³, owing to the high porosity of the cork aggregates. As the proportion of cork decreases in favor of denser cellulose, both thermal conductivity and apparent density increase.

The specific heat capacity varies only slightly across compositions (1211-1285 J/kg·°C) and

remains higher than that of concrete or natural stone, which represents an advantage for heat storage and release during thermal retrofitting operations. Based on these findings, the Group 1 composite was selected for numerical simulations.

NUMERICAL SIMULATION RESULTS

Validation of the numerical model

The numerical model was validated by comparing the measured and simulated indoor temperatures on 28 September (Fig. 9). The curves follow a similar trend with minimal deviations. Statistical indicators (Zhou et al, 2023) confirm this agreement: RMSE \approx 1.2 °C, MAE < 1 °C, and Pearson correlation coefficient R \approx 0.90. These results confirm the model's reliability for simulating thermal retrofitting scenarios.

Results discussion of simulated indoor temperatures

The results of the dynamic thermal simulation (Fig. 10) show that, in the reference scenario, indoor temperatures closely follow outdoor temperatures, ranging from 10-20 °C in winter and 25-32 °C in summer, resulting in a high demand for heating and cooling. This poor energy performance of the building at 39 Rue Larbi Ben M'Hidi is mainly due to the absence of low-emissivity glazing and thermal insulation on external walls. The integration of low-emissivity double glazing (Scenario 2) slightly improves indoor temperatures, reaching approximately 18 °C in winter and 30 °C in summer, with a minor flattening of thermal curves. However, its effect remains limited, as a large portion of thermal exchanges between the building and the exterior occurs through the façades. The addition of the bio-based thermal insulation (Scenario 3) significantly improves indoor temperatures, stabilizing at around 20 °C in winter and 25 °C in summer. These improvements are explained by the thermal properties of the material, notably its low thermal conductivity (0.048 W/m·K) and high specific heat capacity (1285 J/kg·K). The combination of low-emissivity double glazing and bio-based insulation strongly reduces thermal exchanges. Indoor temperatures reach 20-23 °C in winter and just below 25 °C in summer, enhancing both thermal comfort and the overall energy performance of the building compared to the previous scenarios.

The choice of internal thermal insulation preserves the aesthetic integrity of the façades, a major concern for heritage buildings. Al-

though conventional materials such as polyurethane offer higher performance, their hygrothermal and environmental incompatibility justifies their exclusion. The cork/cellulose bio-based composite was therefore preferred for its durability and compatibility with existing walls, confirming the relevance of an approach that balances energy efficiency and heritage preservation (Ascione et al, 2015; De Berardinis, Rotilio, and Marchionni, 2014; Claude, 2018).

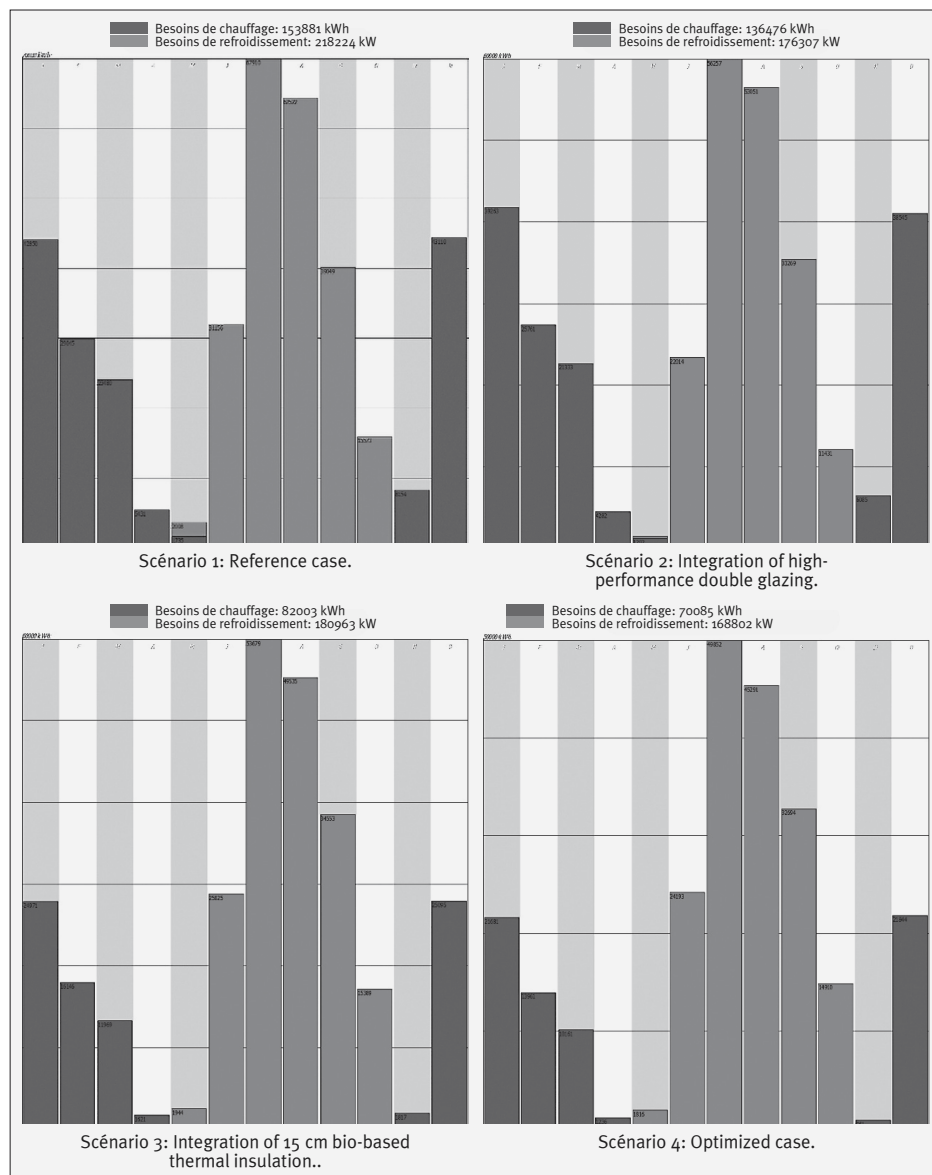
Energy consumption results discussion

Figure 11 presents the annual heating and cooling demands for four scenarios. Double glazing (Scenario 2) reduces consumption by 11.31% for heating and 19.20% for cooling. Insulation alone (Scenario 3) achieves a reduction of 46.71% for heating and 17% for cooling. The combination of insulation with double glazing (Scenario 4) delivers the best performance, with 54.44% savings for heating and 22.64% for cooling, demonstrating the effectiveness of these interventions in improving the energy performance of residential buildings from the French colonial period in Algeria.

CONCLUSION

The study of the buildings at 39 Rue Larbi Ben M'hidi highlights the energy vulnerability of French colonial constructions in Algeria, despite significant heritage value. These buildings, representative of the Larbi Ben M'hidi district, exhibit high energy consumption due to a thermally deficient envelope: massive, uninsulated walls and single glazing. Infrared thermography confirmed significant heat losses through façades and openings. To address these shortcomings, two interventions were simulated using ARCHIWizard: the integration of low-emissivity double glazing and the application of a bio-based cork-cellulose insulation on the interior walls ($\lambda = 0.048 \text{ W/m}\cdot\text{K}$; $C_p \text{ ff } 1285 \text{ J/kg}\cdot\text{°C}$ for the 75% cork formulation).

The results show that the combination of internal thermal insulation (ITI) and double glazing is most effective, reducing heat losses, stabilizing indoor temperatures between 20 and 25 °C, and decreasing energy consumption by over 50% for heating and 20% for cooling, while preserving the architectural integrity of the façades. Although focused on a single building, its characteristics; massive masonry, lack of insulation, single glazing, and typical interior layout, allow these findings to be extended to other colonial residen-



tial ensembles in Algeria. Limitations include a simplified numerical model that does not fully capture the hygrothermal complexity of historic walls. Hygrothermal analyses, including vapor migration, condensation risk, and the long-term conduct, as well as studies on other colonial typologies, would strengthen the scope of the results. Despite these limitations, the bio-based cork-cellulose insulation emerges as a promising solution, adaptable to diverse Algerian climates and other built environments.

This study proposes an approach that reconciles energy efficiency, thermal comfort, and heritage preservation, contributing to the wider discourse on the thermal rehabilitation of colonial buildings in Algeria.

FIG. 11 HEATING AND COOLING DEMANDS ACCORDING TO 4 SCENARIOS. (SOURCE: AUTHORS, 2023)

BIBLIOGRAPHY

1. AFNOR (2005). *Méthodes d'essai pour produits réfractaires façonnés denses-Partie 15 : détermination de la conductivité thermique par la méthode du fil chaud (parallèle)*. NF EN 993-15. Paris, 18 p.
2. AFNOR (2019). *Performance énergétique des bâtiments-Paramètres d'ambiance intérieure pour la conception et l'évaluation de la performance énergétique des bâtiments*. NF EN 16798-1. Paris, 89 p.
3. AHMAD, R.M., EL-SAYED, Z., TAHA, D., SHOKRY, H. and MAHMOUD, H. (2021) "An approach to select an energy-efficient shading device for the south-oriented façades in heritage buildings in Alexandria, Egypt", *Energy Reports*, 7, pp. 133-137. <https://doi.org/10.1016/j.egypr.2021.06.024>
4. ASCIONE, F., BIANCO, N., DE MASI, R.F., DE ROSSI, F. and VANOLI, G.P. (2015) "Energy retrofit of an educational building in the ancient center of Benevento: feasibility study of energy savings and respect of the historical value", *Energy and Buildings*, 95, pp. 172-183. <https://doi.org/10.1016/j.enbuild.2014.10.072>
5. ASCIONE, F., DE MASI, R.F., DE ROSSI, F., RUGGIERO, S. and VANOLI, G.P. (2016) "Optimization of building envelope design for nZEBs in Mediterranean climate: Performance analysis of residential case study", *Applied Energy*, 183, pp. 938-957. <https://doi.org/10.1016/j.apenergy.2016.09.027>
6. BABA AHMED, T., CHÉRIF, N., MOYA, L. and FERNANDEZ-SALGADO, C. (2013) *Méthode de réhabilitation d'un centre historique : diagnostic du quartier Ben M'hidi – Alger*. Alger : Alternatives Urbaines.
7. BÉGUIN, F. (1983) *Arabesances : décor architectural et tracé urbain en Afrique du Nord (1830-1950)*. Paris : Dunod.
8. BELOUCHRANI, W. (2012) "Lecture morphologique du système de façade de l'immeuble de rapport algérois : définition du corpus", *Architectonics : Mind, Land and Society*, 24, pp. 73-85.
9. BENTCHIKOU, M., GUIDOUM, A., SCRIVENER, K., SILHADI, K. and HANINI, S. (2012) "Effect of recycled cellulose fibres on the properties of lightweight cement composite matrix", *Construction and Building Materials*, 34, pp. 451-456. <https://doi.org/10.1016/j.conbuildmat.2012.02.097>
10. BLÁZQUEZ, T., FERRARI, S., SUÁREZ, R. and SENDRA, J.J. (2019) "Adaptive approach-based assessment of a heritage residential complex in southern Spain for improving comfort and energy efficiency through passive strategies", *Energy*, 181, pp. 504-520. <https://doi.org/10.1016/j.energy.2019.05.160>
11. CARO, R. and SENDRA, J.J. (2020) "Evaluation of indoor environment and energy performance of dwellings in heritage buildings. The case of hot summers in historic cities in Mediterranean Europe", *Sustainable Cities and Society*, 52, p. 101798. <https://doi.org/10.1016/j.scs.2019.101798>
12. European Committee for Standardization ECS (2016). *Methods of testing cement – Part 1: Determination of strength*. EN 196-1. Brussels, 32 p.
13. CHAOUCHE, S. (2013) "L'impact de l'urbanisme colonial sur la fabrique de la ville algérienne", *Sciences et Technologie D*, 37, pp. 39-50.
14. CHÉRIF, N. (2017) "Alger, 1830-1980 : chronique d'une historiographie en construction", *Perspective*, 2, pp. 131-152. <https://doi.org/10.4000/perspective.7596>
15. CHERKI, A., REMY, B., KHABBAZI, A., JANNOT, Y. and BAILLIS, D. (2014) "Experimental thermal properties characterization of insulating cork-gypsum composite", *Construction and Building Materials*, 54, pp. 202-209. <https://doi.org/10.1016/j.conbuildmat.2013.12.076>
16. CHO, H.M., YUN, B.Y., YANG, S., WI, S., CHANG, S.J. and KIM, S. (2020) "Optimal energy retrofit plan for conservation and sustainable use of historic campus building", *Applied Energy*, 275, 115313. <https://doi.org/10.1016/j.apenergy.2020.115313>
17. CHOAY, F. (2001) *L'Allégorie du patrimoine*. Paris : Éditions du Seuil.
18. CLAUDE, S. (2018) *Étude expérimentale et numérique de solutions basées sur les éco-matériaux pour la rénovation thermique du patrimoine bâti urbain*. PhD thesis. Toulouse: INSA Toulouse.
19. COELHO, G.B. and HENRIQUES, F.M. (2021) "Performance of passive retrofit measures for historic buildings that house artefacts", *Sustainable Cities and Society*, 71, 102982. <https://doi.org/10.1016/j.scs.2021.102982>
20. DAHLI, M. and TOUBAL, R. (2010) "Matériau isolant thermique à base de déchets ménagers et oléicoles", *Revue des Énergies Renouvelables*, 13(2), pp. 339-346.
21. DAOUDI, N.S. (2013) *Bilan et perspectives de la démarche interdisciplinaire appliquée à la caractérisation des ambiances : cas d'un édifice à atrium colonial d'Alger*. PhD thesis. Alger: EPAU.
22. DE BERARDINIS, P., ROTILIO, M. and MARCHIONNI, C. (2014) "Improving the energy efficiency of historic masonry buildings", *Energy and Buildings*, 80, pp. 415-423. <https://doi.org/10.1016/j.enbuild.2014.05.047>
23. FINO, R., TADEU, A. and SIMÕES, N. (2018) "Influence of a period of wet weather on the heat transfer across a wall covered with uncoated medium-density expanded cork", *Energy and Buildings*, 165, pp. 118-131. <https://doi.org/10.1016/j.enbuild.2018.01.020>
24. FRANCO, G., MAGRINI, A., CARTESEGNA, M. and GUERRINI, M. (2015) "Towards a systematic approach for energy refurbishment of historical buildings: the case study of Albergo dei Poveri in Genoa, Italy", *Energy and Buildings*, 95, pp. 153-159. <https://doi.org/10.1016/j.enbuild.2014.10.051>
25. GALATIOTO, A., RICCIU, R., SALEM, T. and KINAB, E. (2019) "Energy and economic analysis on retrofit actions for Italian public historic buildings", *Energy*, 176, pp. 58-66. <https://doi.org/10.1016/j.energy.2019.03.167>

AUTHORS' BIOGRAPHIES AND CONTRIBUTIONS

26. GONZÁLEZ-PRIETO, D., FERNÁNDEZ-NAVA, Y., MEGIDO, L. and PRIETO, M.M. (2023) "Economic and environmental prioritisation of potential retrofitting interventions in electricity decarbonisation scenarios: application to a heritage building used as offices", *Journal of Building Engineering*, 72, 106561. <https://doi.org/10.1016/j.jobe.2023.106561>
27. HADJILAH, A. and ZEROUALA, I. (2018) La réhabilitation du centre historique d'Alger. Pathologies et diagnostic des constructions en maçonnerie datant de la période coloniale, In : 1^{ère} Conférence internationale sur la vulnérabilité et la réhabilitation des structures (VUREST 2018), USTHB, Alger, 7-8 May 2018. Alger : Laboratoire d'Environnement, d'Eau, de Géomécanique et Ouvrages (LEEGO).
28. ISO (2007) *Refractory materials – Determination of thermal conductivity – Part 2: Hot-wire method (parallel)*. ISO 8894-2:2007. Geneva, 13 p.
29. ISO (2015) *Detection of heat, air and moisture irregularities in buildings by infrared methods – Part 3. ISO 6781-3*. Geneva, 18 p.
30. JIANG, L., LUCCHI, E. and DEL CURTO, D. (2023) "Adaptive reuse and energy transition of built heritage and historic gardens: the sustainable conservation of Casa Jelinek in Trieste (Italy)", *Sustainable Cities and Society*, 97, 104767. <https://doi.org/10.1016/j.scs.2023.104767>
31. KELLATI, N.E., EL BOUARDI, A., AIZOUL, T., TYOURI, M. and EZBAKHE, H. (2010) "Valorisation énergétique du matériau liège", *Afrique Science*, 6(2), pp. 108-116.
32. KHADRAOUI, M.A. and SRITI, L. (2017) "Facades thermal behavior of the office buildings in a hot and arid climate", *Algerian Journal of Engineering, Architecture and Urbanism*, 1(2), pp. 28-38.
33. LIÉBARD, A. and DE HERDE, A. (2005) *Traité d'architecture et d'urbanisme bioclimatiques : concevoir, édifier et aménager avec le développement durable*. Paris: Observ'ER.
34. LIMAM, A., ZERIZER, A., QUENARD, D., SALLEE, H. and CHENAK, A. (2016) "Experimental thermal characterization of bio-based materials (Aleppo pine wood, cork, and their composites) for building insulation", *Energy and Buildings*, 116, pp. 89-95. <https://doi.org/10.1016/j.enbuild.2016.01.007>
35. LIU, L., ZOU, S., LI, H., DENG, L., BAI, C., ZHANG, X., WANG, S. and LI, N. (2019) "Experimental physical properties of an eco-friendly bio-insulation material based on wheat straw for buildings", *Energy and Buildings*, 201, pp. 19-36. <https://doi.org/10.1016/j.enbuild.2019.07.037>
36. DTR C 3-2 (1997) *Réglementation thermique des bâtiments d'habitation – Règles de calcul des déperditions calorifiques, Fascicule 1*. Alger: Ministère de l'Habitat et de l'Urbanisme, 72 p.
37. MOHDEB, R., ATTAR, A. and SARAoui, S. (2023) "Forging the city image during the French colonial period (1883-1962) in the case of Jijel (Algeria)", *Prostor*, 31(1(65)), pp. 96-111. [https://doi.org/10.31522/p.31.1\(65\).9](https://doi.org/10.31522/p.31.1(65).9)
38. MOUNIR, S., MAALOUFA, Y., CHERKI, A.B. and Khabbazi, A. (2014) "Thermal properties of the composite material clay/granular cork", *Construction and Building Materials*, 70, pp. 183-190. <https://doi.org/10.1016/j.conbuildmat.2014.07.108>
39. OUKACI, A. (2022) "L'analyse parcellaire comme source de l'histoire urbaine et architecturale", *Historia Urbana*, 30(30), pp. 147-171.
40. OUKACI, A. and KASSAB, T.B.A. (2021) "Construction du quartier d'Isly au XIX^e siècle : naissance et formation de la première ville française fondée à Alger (1840-1900)", *Historia Urbana*, 29, pp. 149-176.
41. PAJANI, D. (2014) *Thermographie du bâtiment : diagnostic et applications*. Paris: Techniques de l'Ingénieur.
42. PAOLETTI, D., AMBROSINI, D., SFARRA, S. and BISEGNA, F. (2013) "Preventive thermographic diagnosis of historical buildings", *Journal of Cultural Heritage*, 14(1), pp. 116-121. <https://doi.org/10.1016/j.culher.2012.05.005>
43. PETRUCCIOLI, A. (1992) "Alger 1830-1930 : pour une lecture typologique des immeubles d'habitation", *Environmental Design Journal*, 1-2, pp. 104-117.
44. QU, K., CHEN, X., WANG, Y., CALAUTIT, J., RIFFAT, S. and Cui, X. (2021) "Comprehensive energy, economic and thermal comfort assessments for the passive energy retrofit of historical buildings: a case study of a late nineteenth-century Victorian house renovation in the UK", *Energy*, 220, 119646. <https://doi.org/10.1016/j.energy.2020.119646>
45. SUGÁR, V., TALAMON, A., HORKAI, A. and KITA, M. (2020) "Energy saving retrofit in a heritage district: the case of Budapest", *Journal of Building Engineering*, 27, 100982. <https://doi.org/10.1016/j.jobe.2019.100982>
46. TEDJITI, A.K., GHOMARI, F., TALEB, O., BELARBI, B. and BOUHRAOUA, R.T. (2020) "Potential of using virgin cork as aggregates in the development of new lightweight concrete", *Construction and Building Materials*, 265, 120734. <https://doi.org/10.1016/j.conbuildmat.2020.120734>
47. ZAGORSKAS, J., ZAVADSKAS, E.K., TURSKIS, Z., BURINSKIENĖ, M., BLUMBERGA, A. and BLUMBERGA, D. (2014) "Thermal insulation alternatives of historic brick buildings in the Baltic Sea region", *Energy and Buildings*, 78, pp. 35-42. <https://doi.org/10.1016/j.enbuild.2014.04.010>
48. ZHOU, X., LIU, R., TIAN, S., ZHANG, Y. and WANG, Y. (2023) "A review of validation methods for building energy modeling programs", *Building Simulation*, 16(11), pp. 2027-2047. <https://doi.org/10.1007/s12273-023-1050-0>
49. ZIREGUE, A., KHENFER, M., QUÉNEUDEC-T'KINT, M. and MONTRELAY, N. (2016) "Developmental potentiality of insulating lightweight concrete based on cork and calcareous", *Journal of Adhesion Science and Technology*, 30(9), pp. 934-946. <https://doi.org/10.1080/01694243.2015.1129882>

SAMIRA SOUKANE is an architect, holding a master's degree in architecture, with experience in the structural rehabilitation of colonial heritage buildings in Algeria. She currently holds the position of Assistant Professor in the Department of Architecture at Abderrahmane Mira University.

MOHAMED DAHLI holds a Ph.D. in Concrete and Climate from Ukraine, with research interests focusing on architectural environments, energy efficiency in buildings, and thermal insulation materials, particularly bio-based solutions. His work also extends to the study and enhancement of architectural heritage from the colonial period. He is currently a lecturer in the Department of Architecture, at Mouloud Mammeri University of Tizi-Ouzou.

Conceptualization: S.S. and M.D.; Methodology: S.S. and M.D.; Software: S.S.; Validation: M.D.; Resources: S.S.; Data Curation: S.S.; Writing-Original Draft: S.S.; Investigation: S.S.; Writing-Review and Editing: M.D.; Visualization: S.S. All authors have read and agreed to the published version of the manuscript.

ACKNOWLEDGMENTS

During the preparation of this work, the author did not use ChatGPT to refine the language.

COPYRIGHT

© 2026 The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution 4.0 International License (CC-BY 4.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited. See <https://creativecommons.org/licenses/by/4.0/>. Prostor is a peer-reviewed open access journal published by University of Zagreb Faculty of Architecture.

