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ALGERIAN 3D PANEL SYSTEMS: IMPROVING THERMAL COMFORT AND ENERGY EFFICIENCY IN A RANGE OF CLIMATES

SISTEMAS DE PAINÉIS 3D DA ARGÉLIA: MELHORANDO O CONFORTO TÉRMICO E A EFICIÊNCIA ENERGÉTICA EM UMA VARIEDADE DE CLIMAS

SISTEMAS DE PANELES 3D ARGELINOS: MEJORA DEL CONFORT TÉRMICO Y LA EFICIENCIA ENERGÉTICA EN UNA VARIEDAD DE CLIMAS

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ABSTRACT

This study evaluates thermal comfort and energy efficiency in residential buildings in Oran and Béchar, Algeria—regions with contrasting climates. Using TRNSYS dynamic simulation, it examines how three types of building envelopes affect temperature stability and energy demands for heating and cooling. Findings highlight that building envelope design and material choice significantly impacts energy efficiency. Advanced 3D panel technology demonstrated notable energy savings, reducing consumption by up to 29% compared to traditional materials, while also maintaining thermal comfort in both climates. The study further investigates the energy performance of 3D panels, double-brick walls, and insulated double walls, showing that 3D panel systems consistently lower energy consumption by reducing heating and cooling needs. These results underscore the value of climate-responsive designs and passive cooling strategies, positioning 3D panel technology as a promising solution for enhancing thermal comfort and reducing energy use in Algeria's residential sector.

RESUMO

Este estudo avalia o conforto térmico e a eficiência energética em edifícios residenciais em Oran e Béchar, Argélia — regiões com climas contrastantes. Usando a simulação dinâmica TRNSYS, ele examina como três tipos de envoltórios de edifícios afetam a estabilidade da temperatura e as demandas de energia para aquecimento e resfriamento. As descobertas destacam que o design do envoltório do edifício e a escolha do material impactam significativamente a eficiência energética. A tecnologia avançada de painéis 3D demonstrou economia de energia notável, reduzindo o consumo em até 29% em comparação com materiais tradicionais, ao mesmo tempo em que manteve o conforto térmico em ambos os climas. O estudo investiga ainda mais o desempenho energético de painéis 3D, paredes duplas de tijolos e paredes duplas isoladas, mostrando que os sistemas de painéis 3D reduzem consistentemente o consumo de energia ao reduzir as necessidades de aquecimento e resfriamento. Esses resultados ressaltam o valor de projetos responsivos ao clima e estratégias de resfriamento passivo, posicionando a tecnologia de painéis 3D como uma solução promissora para aumentar o conforto térmico e reduzir o uso de energia no setor residencial da Argélia.

RESUMEN

Este estudio evalúa el confort térmico y la eficiencia energética en edificios residenciales en Orán y Béchar, Argelia, dos regiones con climas contrastantes. Utilizando la simulación dinámica TRNSYS, se examina cómo tres tipos de envolventes de edificios afectan la estabilidad de la temperatura y las demandas energéticas para calefacción y refrigeración. Los hallazgos destacan que el diseño de la envolvente del edificio y la elección de materiales tienen un impacto significativo en la eficiencia energética. La tecnología avanzada de paneles 3D, en particular, demostró un ahorro energético notable, reduciendo el consumo hasta en un 29 % en comparación con los materiales tradicionales, manteniendo al mismo tiempo el confort térmico en ambos climas. El estudio investiga además el rendimiento energético de los paneles 3D, las paredes de ladrillo y las paredes dobles aisladas, mostrando que los sistemas de paneles 3D reducen consistentemente el consumo de energía al disminuir las necesidades de calefacción y refrigeración. Estos resultados subrayan el valor de los diseños adaptados al clima y las estrategias de refrigeración pasiva, posicionando la tecnología de paneles 3D como una solución prometedora para mejorar el confort térmico y reducir el uso de energía en el sector residencial de Argelia.

INTRODUCTION

In a rapidly expanding world, where production is intensifying, and population growth continues unabated, natural resources—especially fossil fuels—are being consumed at unsustainable rates. These resources are depleting faster than they can regenerate, leading to increased scarcity. Combined with the environmental degradation and rising operational costs associated with fossil fuel use, this has prompted a strong focus on improving energy efficiency (Cao et al., 2016; Agrawal et al., 2018).

Approximately 40% of the world's energy consumption is attributed to buildings, making them pivotal in the energy landscape. Projections indicate that energy demand in buildings will continue to rise in the coming decades (Nejat et al., 2015). In Algeria, the move towards housing industrialization has been embraced as a fast and cost-effective method of construction. The widespread use of cement, concrete, and prefabricated materials has led to a standardization of housing across the country. However, this has also made the construction sector one of the most energy-intensive, consuming 43.3% of Algeria's total energy supply (Soumia et al., 2022; Ghedamsi et al., 2016; Stambouli, 2011). Given these pressing challenges, a critical question arises: how can energy efficiency in the building sector be optimized? An energy-efficient building would minimize energy use while still providing maximum comfort to its occupants (Blomqvist et al., 2022).

Over the past few decades, significant advancements have been made in the field of energy efficiency in the building industry (Papadakis & Katsaprakakis, 2023). Numerous studies have highlighted the critical importance of optimizing a building's thermal performance to reduce energy consumption while ensuring occupant comfort (Nasrollahzadeh, 2021). The selection of construction materials and the adoption of advanced thermal insulation technologies play a pivotal role in achieving this goal. Among the most promising solutions are high-performance insulating materials, such as external thermal insulation (ETI), and energy-efficient systems, including double and triple glazing (ALQahtani et al., 2023). These technologies are particularly relevant in regions with diverse climates, such as Algeria, where extreme temperatures and fluctuating weather patterns demand customized solutions.

Thermal insulation remains one of the most extensively researched areas in energy efficiency. Numerous studies have demonstrated that enhancing the thermal performance of a building's envelope can significantly reduce energy consumption, particularly for heating and cooling (Akbari et al., 2009; Taherian et al., 2023). In Algeria, where energy demand is high for both cooling in desert regions and heating in the northern areas, the adoption of high-performance insulation solutions is crucial to meet the country's growing energy needs (Mokrani et al., 2023).

In addition to conventional insulation methods, passive technologies such as green roofs and phase-change materials (PCMs) have emerged as promising solutions to further improve thermal performance and reduce energy consumption (Basyouni & Mahmoud, 2024). These technologies, which are the subject of ongoing research, offer substantial potential to optimize energy efficiency in buildings, especially in climates like Algeria's, where they are being increasingly considered as viable alternatives, despite still being in the experimental phase in some areas.

Regarding thermal comfort, several studies have underscored the importance of maintaining stable indoor conditions and precise thermal regulation to ensure occupant well-being (Rane et al., 2023). However, while significant progress has been made in understanding the materials and technologies aimed at improving energy efficiency, research specifically focused on thermal comfort in environments with extreme temperature variations, such as Algeria, remains relatively scarce (Hamlili, 2024). Many existing studies prioritize energy performance, often overlooking the delicate balance between minimizing energy consumption and maintaining optimal comfort for occupants (D'Oca et al., 2018).

Algeria, with its diverse climates—ranging from Mediterranean regions to the Saharan desert—faces significant challenges in managing energy for heating and cooling, with energy needs varying greatly across regions. Solar energy, due to its global availability, is one of the most promising solutions to this challenge. Algeria enjoys considerable solar potential, with annual sunshine ranging between 2650 and 3500 hours, and solar energy received ranging from 1700 to 2650 kWh/m² per year (Boulkedra & Lakhal, 2021; Boubou, 2017; Hebri, 2018). Studies indicate that Algeria's total energy consumption, which stood at 73.23 TWh in 2008, is expected to increase to 179.78 TWh by 2040. Notably, Zone 7, accounting for 73% of the nation's energy usage, is projected to experience the highest demand. In the residential sector, the bulk of energy consumption is driven by cooking, heating, and hot water needs (Ghedamsi et al., 2016).

To meet these energy challenges, construction methods and materials, such as triple glazing and enhanced insulation, must evolve. Furthermore, advanced calculation tools are required to accurately model the complex thermal dynamics of buildings (Bosu et al., 2023). The integration of energy-efficient solutions is now more urgent than ever. While local studies have focused on the energy efficiency of thermal insulation for buildings, they have largely overlooked the crucial factor of indoor thermal comfort.

This study aims to assess and evaluate the thermal comfort of residential buildings equipped with different insulation systems across various regions in Algeria. By utilizing the dynamic thermal simulation tool TRNSYS, the research will explore ways to optimize building envelopes to balance heating and cooling efficiency (Mohammed et al., 2011).

Ultimately, this study seeks to propose strategies that enhance thermal comfort while reducing energy consumption, all while accounting for Algeria's unique climatic conditions and the energy demands of its buildings. Forecasting building energy demand is vital for a range of applications, including informing early design decisions, improving building energy performance, optimizing building systems, and planning urban energy infrastructure (Papachristos, 2015).

MATERIALS AND METHODS

Description Of Climate Sites

To assess the thermal performance of the multi-zone house, two distinct climate sites in Algeria were selected: Oran (Climate Zone E1) and Béchar (Climate Zone E3 in summer and H3a in winter). These regions present contrasting climatic conditions, providing an opportunity to test the resilience of energy solutions in extreme environments (Mokhtara et al., 2019; 2020).

Oran (Climate Zone E1) and Béchar (Climate Zones E3 in summer and H3a in winter) exhibit markedly different climatic conditions that influence their respective energy efficiency strategies. Oran experiences a Mediterranean climate, which is marked by hot, dry summers and mild, wet winters (Table 1, Figure 1, Figure 2). Solar radiation remains relatively constant throughout the year, averaging 1,700 kWh/m², which positions it as an ideal location for solar energy exploitation (Jayakumar, 2009). Precipitation levels are low, averaging approximately 420 mm per year over 72.9 days, defining a dry climate conducive to the construction of energy-efficient buildings that incorporate natural ventilation strategies and thermal insulation (Sadineni et al., 2011) (Table 1). Summer maximum temperatures can reach up to 35°C, while winter temperatures rarely fall below 5°C, effectively reducing heating requirements (Figure 3, Table 1). This Mediterranean climate supports the adoption of passive thermal regulation solutions, such as south-facing windows and materials with high thermal mass (Makhloufi & Louafi, 2022).

Table 1. Outdoor temperature ranges (minimum and maximum) and precipitation levels in the cities of Oran and Béchar (2014)

Month	Oran				Béchar			
	T Min average	T avg.	T Max average	P	T Min average	T average	T Max average	P
	(°C)			(mm)	(°C)			(mm)
Jan	5	10	15	60	1	8	15	0
Feb	7	12	16	50	4	11	18	0
Mar	8	13	18	30	8	15	22	10
Apr	10	15	20	30	12	19	26	0
May	13	18	22	20	16	23	30	0
Jun	17	21	26	0	21	28	35	0
Jul	17	24	29	0	25	32	40	0
Aug	20	25	30	0	25	31	38	0
Sep	17	23	28	10	20	26	33	0
Oct	13	18	23	30	13	20	27	10
Nov	9	15	20	60	7	13	20	10
Dec	7	12	16	70	2	9	16	0
Year	12	17	22	420	13	20	27	80

Figure 1. Summer and winter temperatures in Oran

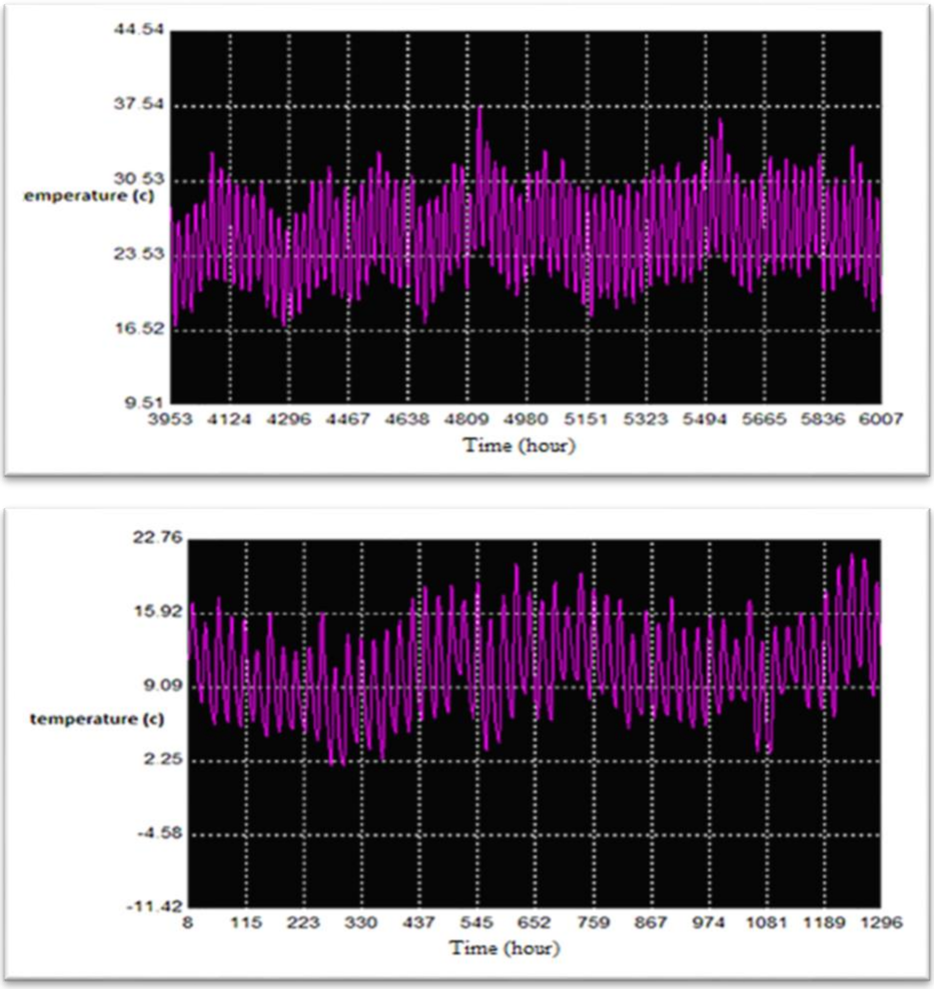
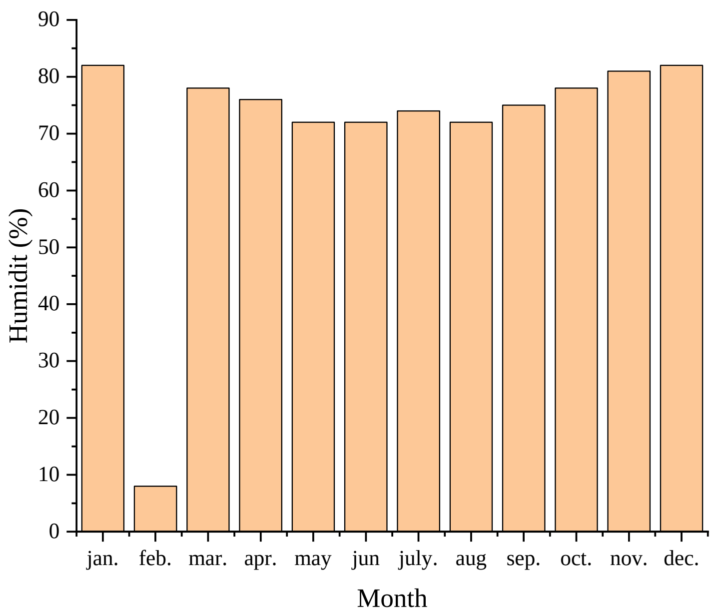


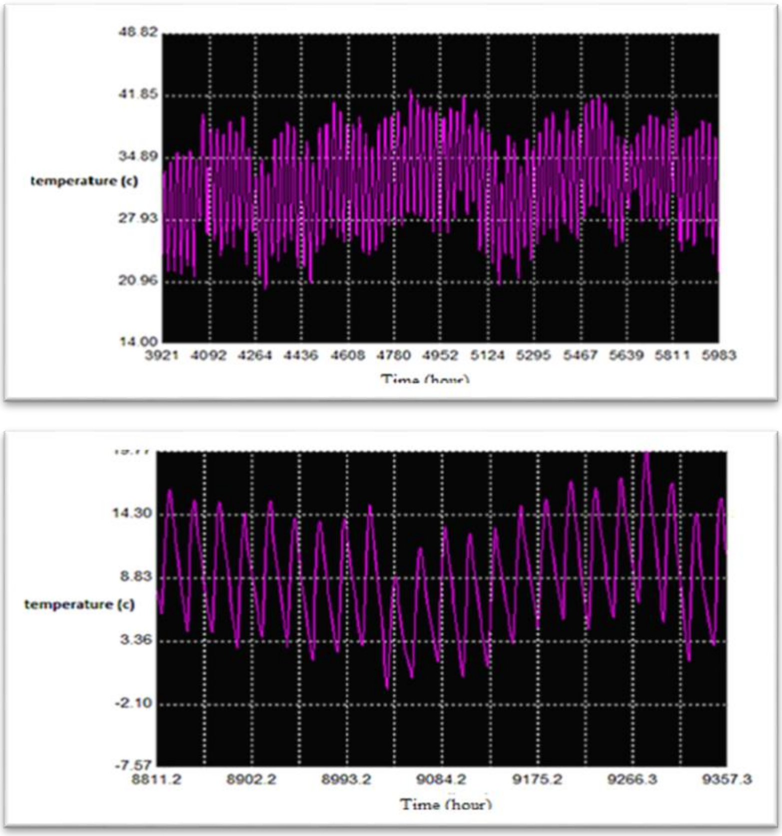
Figure 2. Annual Humidity of the City of Oran (Year 2014)



In contrast, Béchar's desert climate is characterized by extreme temperature fluctuations, with long, hot, and dry summers often exceeding 40°C and mild winters where nighttime temperatures can drop to -5°C (Table 1). The region experiences exceptionally high solar radiation, reaching up to 800 W/m² on a horizontal plane, making it highly suitable for harnessing both solar thermal and photovoltaic energy (Pan et al., 2019). However, the harsh climatic conditions necessitate a more rigorous approach to passive cooling and insulation to ensure optimal thermal comfort (Sadineni et al., 2011). During summer, daytime temperatures frequently soar to 45°C with very low relative humidity, approximately 27%, while winter nights can see temperatures plummet to -5°C. This stark contrast between Oran's milder Mediterranean climate and Béchar's extreme desert conditions highlights the need for tailored energy efficiency strategies that address each location's unique thermal and climatic challenges.

Under these conditions, it is crucial to adopt both active and passive heat management strategies, such as reflective roofing, night ventilation systems, and high thermal inertia materials (Lin et al., 2022; Ling et al., 2024). The climatic differences between Oran and Béchar provide an opportunity to assess the thermal performance of the multizone house in diverse environments. In Oran, heating needs are minimal and can be largely offset by proper thermal insulation and optimal building orientation. In contrast, Béchar's extreme summer temperatures demand effective cooling strategies, particularly using materials with high thermal storage capacity and the integration of photovoltaic and thermal solar systems for energy production and passive cooling (Makhloufi & Louafi, 2022) (Figure 3).

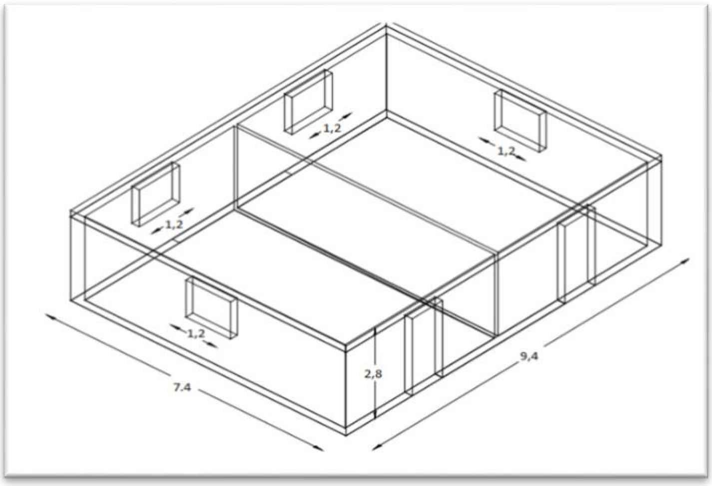
Figure 3. Summer and Winter Temperatures in Béchar



STUDY OF A MULTIZONE RESIDENTIAL BUILDING

The focus of this study is a multizone residential house located in two distinct climatic environments, aimed at evaluating the impact of climate variations on energy and thermal performance. The house's design characteristics are as follows (Figure 4): Orientation: South-facing, maximizing solar exposure in winter and reducing heating needs (Biyik et al., 2017), in line with recommendations from studies on building energy efficiency in Mediterranean climates (Good et al., 2015; Vermeulen, 2014). Total Area: 69.56 m². Dimensions: 9.4 m x 7.4 m x 2.8 m, representing a small dwelling with a surface-to-volume ratio favorable for energy optimization. Windows: 4 windows of 1.2 m², with two facing south, one east, and one west. The use of single glazing could result in significant thermal losses, especially in colder climates (Sadineni et al., 2011). Type of Glazing: Single glazing, which offers less thermal insulation compared to double glazing (Good et al., 2015).

Figure 4. 3D Visualization of the Residential House for Analysis



The configuration of the windows, primarily oriented to the south, is strategically designed to capture passive solar radiation during winter, in line with the principles of bioclimatic design (Pan et al., 2019). However, single glazing can present challenges in terms of thermal performance, particularly in regions with significant temperature variations. The configuration of the windows, primarily oriented to the south, is strategically designed to capture passive solar radiation during winter, in line with the principles of bioclimatic design (Pan et al., 2019). However, single glazing can present challenges in terms of thermal performance, particularly in regions with significant temperature variations.

SIMULATION PROCESS

The simulation process using TRNSYS.16 is carried out in two key steps. The first step involves inputting the climate data for the two regions, Oran and Béchar, using the Weather Data type (Figure 5, Figure 6). Accurate climate data is essential to ensure the reliability of the simulations. To ensure reliability, three replicates were performed for each test scenario. The standard deviation of temperature measurements was ±0.71 and 1.0 °C. Incorporating local climate data significantly enhances the accuracy of energy simulation models, allowing for more precise assessments of buildings' thermal performance (Silvero et al., 2019).

Figure 5. Simulation in TRNSYS Studio

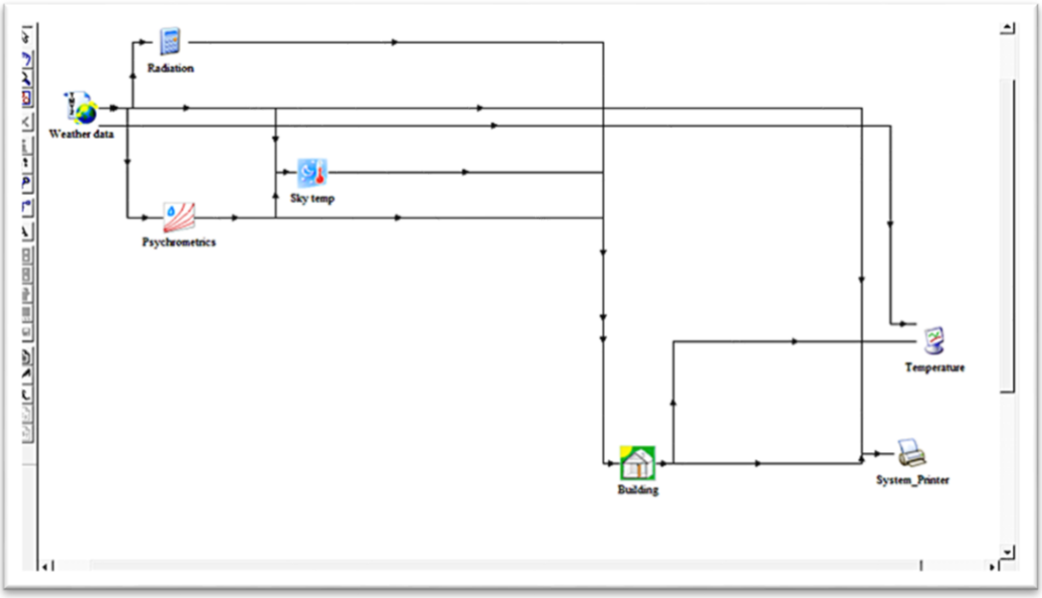


Figure 6. Reinforced concrete block with expanded polystyrene insulation (sprayed micro-concrete + galvanized welded mesh)

The second step involves a detailed description of the building using the TRNBUILD files. This includes parameters such as the thickness, thermal conductivity, heat capacity of materials, and orientation. The test cell has been designed as an insulated structure. The vertical walls and the floors (upper and lower) are represented in Tables 2 and 3.

Table 2. Thermal properties of building materials for energy efficiency (case 1 and 2)

Composition	Materials		Conductivity (λ (Wm⁻¹K⁻¹))	Density (kg m⁻³)	Specific Heat Capacity (J kg⁻¹ k⁻¹)	Thickness (m)
Vertical Wall	Cement Render		1.5	1500	1000	0.01
	Brick		1.08	1650	1000	0.1
	Insulation	Case 1	0.038	20	1450	0.04
		Case 2	0.094	1		
Lower Floor	Gerflex Coating		0.31	1190	1046	0.003
	Insulation	Case 1	0.038	20	1450	0.04
		Case 2	1.75	2450	920	0.1
	Concrete		1.75	2450	920	0.1
	Waterproofing		0.04	1150	1000	0.03
Upper Floor	Sloped Form		1.75	2450	1000	0.05
	Insulation (Menhoudj et al., 2018)		0.038	20	1450	0.04
	Slab (Menhoudj et al., 2018)		1.75	2300	1000	0.04
	Hollow Core (Menhoudj et al., 2018)		1.14	1850	1000	0.16
	Cement Render		1.5	1500	1000	0.01
Window	Single Glazing (Menhoudj et al., 2018)		1.2	2750	830	0.004

Table 3. Thermal properties of building materials for energy efficiency (case 3)

Composition	Materials	Conductivity (λ(Wm⁻¹K⁻¹))	Density (kg m⁻³)	Specific Heat Capacity (J kg⁻¹ k⁻¹)	Thickness (m)
Vertical Wall	Concrete	1.75	2400	1000	0.04
	Insulation	0.038	20	1450	0.06
Lower Floor	Gerflex Coating (Menhoudj et al., 2018)	0.31	1190	1000	0.003
	Concrete (Menhoudj et al., 2018)	1.75	2400	1000	0.04
	Insulation (Menhoudj et al., 2018)	0.038	20	1450	0.06
	Waterproofing	0.04	1150	1000	0.03
Upper Floor	Sloped Form	1.75	2450	1000	0.05
	Concrete	1.75	2400	1000	0.04
	Insulation	0.038	20	1450	0.06
Window	Single Glazing	1.2	2750	830	0.004

RESULTS

Temperature Discrepancies And Energy Consumption Trends For Heating And Cooling In Oran And Béchar

For the first case, the following charts display the indoor and outdoor temperatures over a 48-hour period in winter and summer for Case 01. It is observed that the temperature in both rooms significantly deviates from the set point temperature of 18 °C, with a minimum difference of 10 °C. This highlights the need for a heating system. Optimizing heating systems is essential for maintaining thermal comfort in buildings (Vonžudaitė et al., 2023).

In the city of Oran, the temperature in both rooms is significantly different from the set point of 18 °C, with a minimum deviation of 10 °C (Figure 7). This situation highlights the importance of an adequate heating system, not only for the comfort of the occupants but also for their health. Recent studies have established a clear link between indoor temperatures below 18 °C and adverse health outcomes, particularly affecting the respiratory and cardiovascular systems. For instance, a 2023 study found that indoor temperatures under 18 °C are associated with negative health effects, though the evidence was insufficient to determine specific temperature thresholds for different population groups (Janssen et al., 2023). Furthermore, a 2022 study highlighted the increased risk of cardiovascular diseases associated with indoor temperatures below 18 °C and estimated the potential health benefits of eliminating indoor cold exposure (Singh et al., 2022).

These findings underscore the importance of maintaining indoor temperatures above 18 °C to protect health, especially among vulnerable populations.

The temperatures observed in both rooms are close to the set point of 25 °C, with a maximum difference of 12 °C (Figure 8). This indicates that the cooling system may be slightly overused, particularly during periods of moderate heat. Therefore, it would be advisable to consider the implementation of an artificial ventilation system or a low-intensity cooling system, which could be sufficient to maintain acceptable thermal comfort. Natural ventilation can reduce energy consumption while providing optimal comfort (Ali et al., 2023; Sakhri et al., 2023).

Figure 7. Winter indoor-outdoor temperature of Oran city in free-standing conditions: case study 1

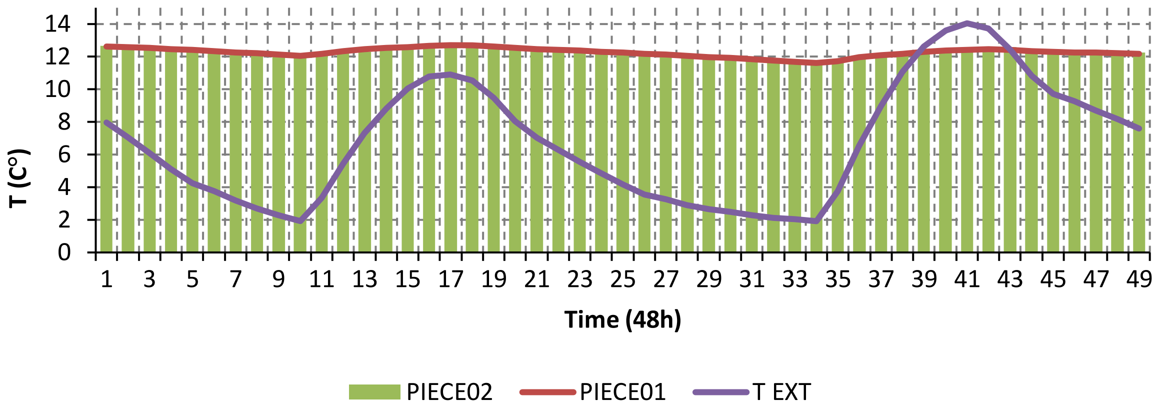
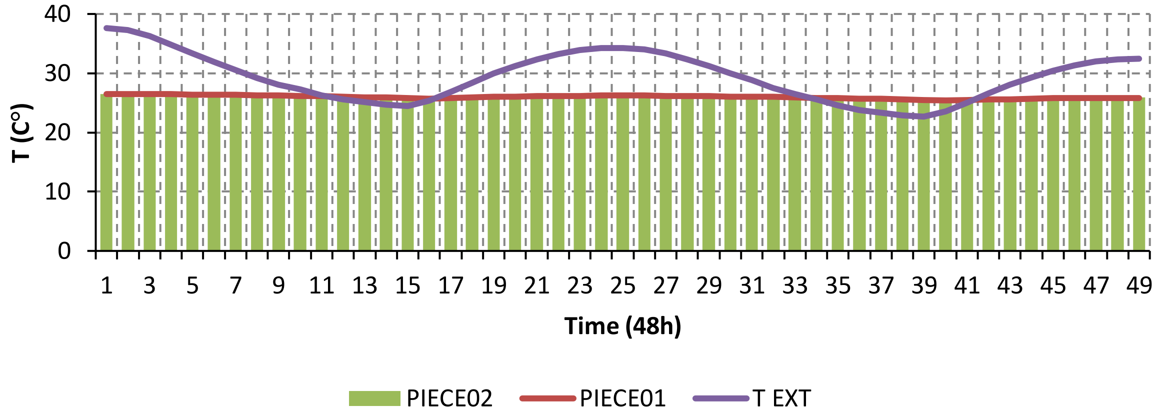
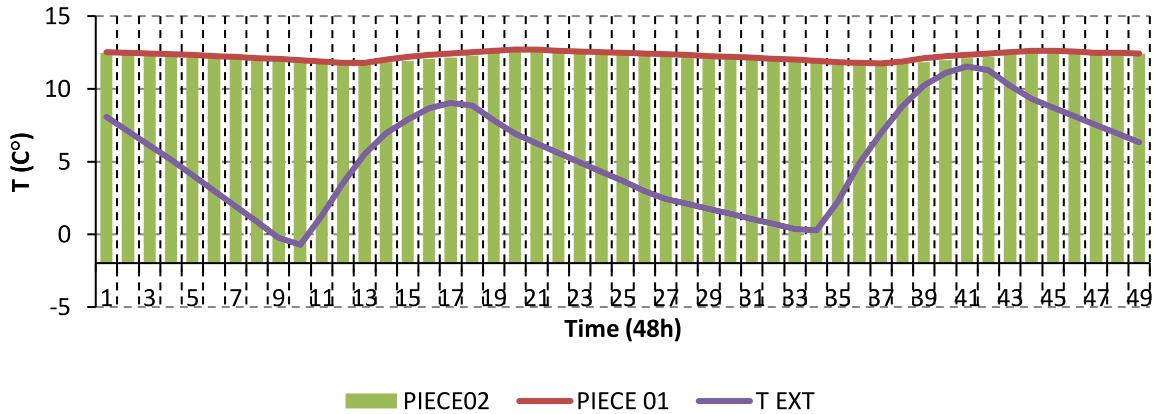


Figure 8. Summer indoor-outdoor temperature difference of Oran city in free-standing conditions: case study 1



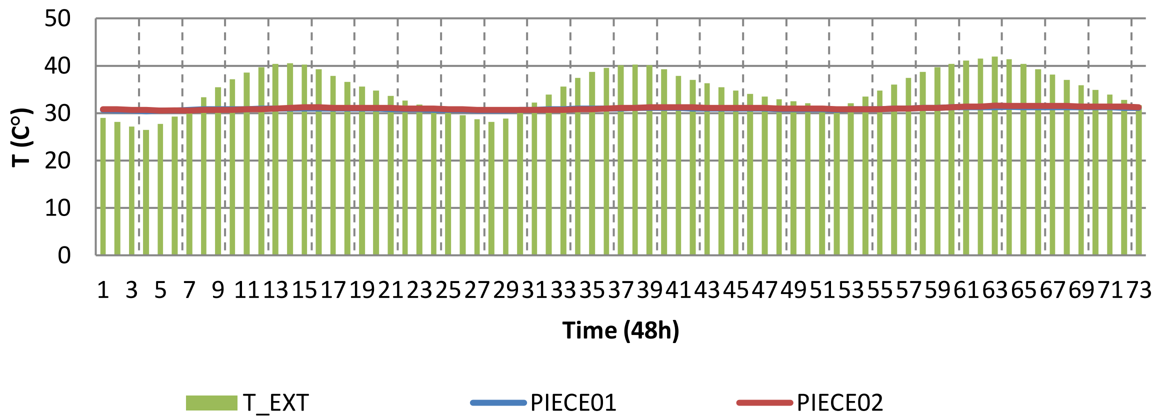
Regarding the city of Béchar, the temperatures in both rooms are significantly below the set point, with a minimum temperature difference of 14 °C (Figure 9). A study conducted by the National Institute of Public Health in Algeria found that excessively low indoor temperatures increase the risk of cold-related illnesses (Ben Youssef et al., 2021). This underscores the necessity for a heating system to achieve a comfortable temperature of 18 °C (VanHoof et al., 2010). The use of efficient heating systems is also crucial for ensuring a healthy and comfortable living environment, especially in regions where winters can be particularly harsh (Pressman, 1996).

Figure 9. winter indoor-outdoor temperature difference of béchar city in free-standing conditions: case study 1



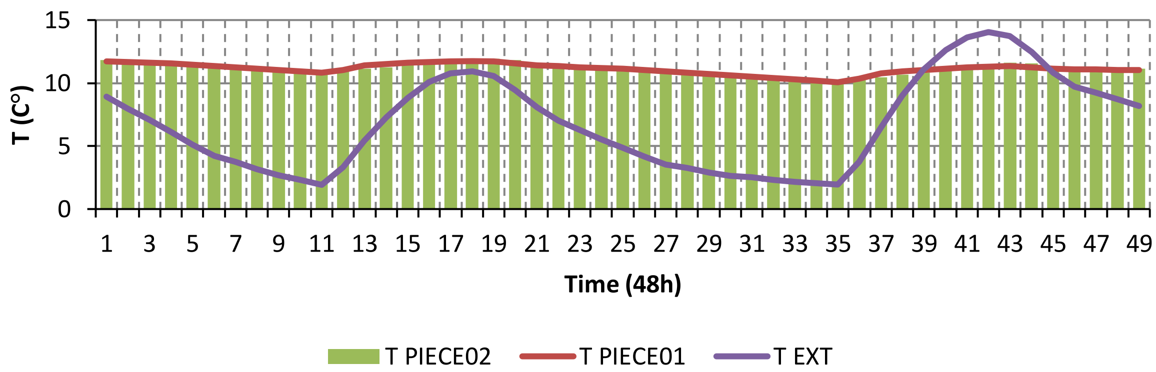
According to research by Yang et al. (2014), integrating passive design strategies with air conditioning systems can significantly reduce energy consumption while ensuring adequate thermal comfort. This approach combines cutting-edge technological innovations with energy-efficient architectural design principles. For example, the cooling load of buildings can be greatly reduced by using passive techniques such as thermal insulation, materials with high thermal inertia, or strategically placed openings for natural ventilation. In such cases, the addition of air conditioning systems helps meet comfort requirements when passive technologies alone are insufficient to maintain optimal conditions. However, it would be valuable to explore several areas to better understand and leverage this synergy. These include potential technical or practical limitations, installation and operational costs, and the impact of this combination across different climatic zones. A thorough analysis of these factors would demonstrate the feasibility and long-term benefits of this approach, encouraging its broader adoption in both residential and commercial sectors (Figure 10).

Figure 10. Summer indoor-outdoor temperature difference of Béchar city in free-standing conditions: case study 1



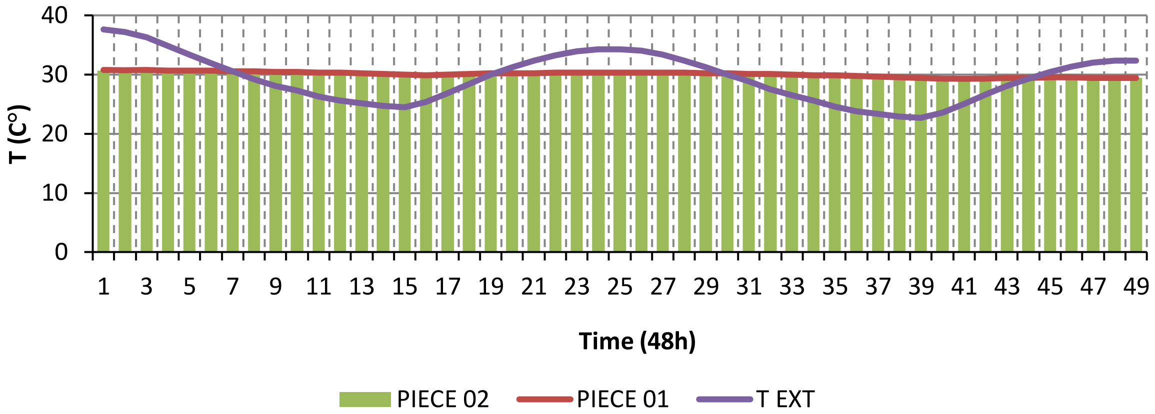
In the second case, for the city of Oran, the temperatures recorded in both rooms are significantly lower than the recommended set point of 18 °C, showing a minimum difference of 9 °C (Figure 11). This situation underscores the importance of an efficient heating system to maintain a comfortable indoor environment, especially during the colder months. Recent studies emphasize that inadequate indoor temperatures can negatively impact the well-being and productivity of occupants (Seppänen & Fisk, 2006; Zhang et al., 2010; Alhorr et al., 2016).

Figure 11. Winter indoor-outdoor temperature difference of Oran city in free-standing conditions: case study 2



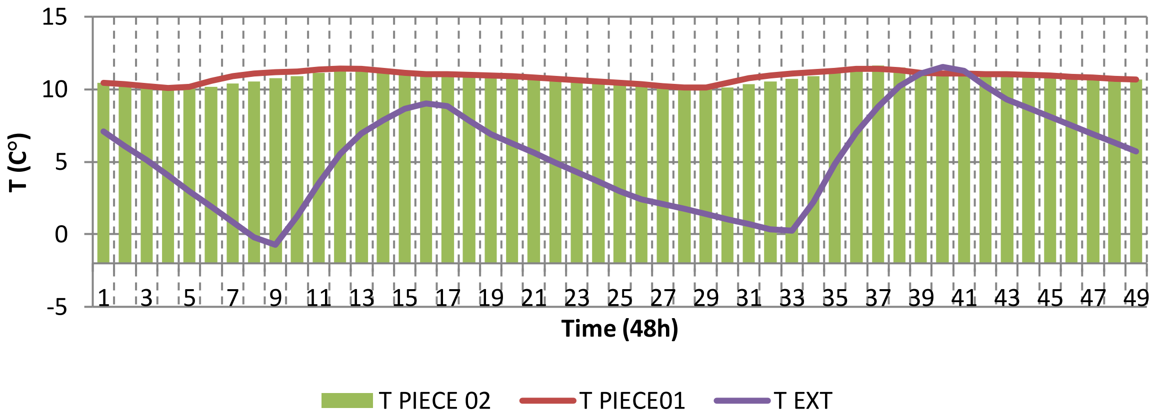
The temperatures measured in the two studied rooms significantly deviate from the set temperature of 25°C. In fact, we observed a maximum difference of 7°C, indicating an indoor temperature of 32°C (Figure 12). This situation underscores the urgent need to implement an effective cooling system. Heat waves and high temperatures in the coastal regions of Algeria are increasing alarmingly, necessitating tailored solutions to ensure the thermal comfort of occupants (Faci et al., 2018).

Figure 12. Summer indoor-outdoor temperature difference of Oran city in free-standing conditions: case study 2



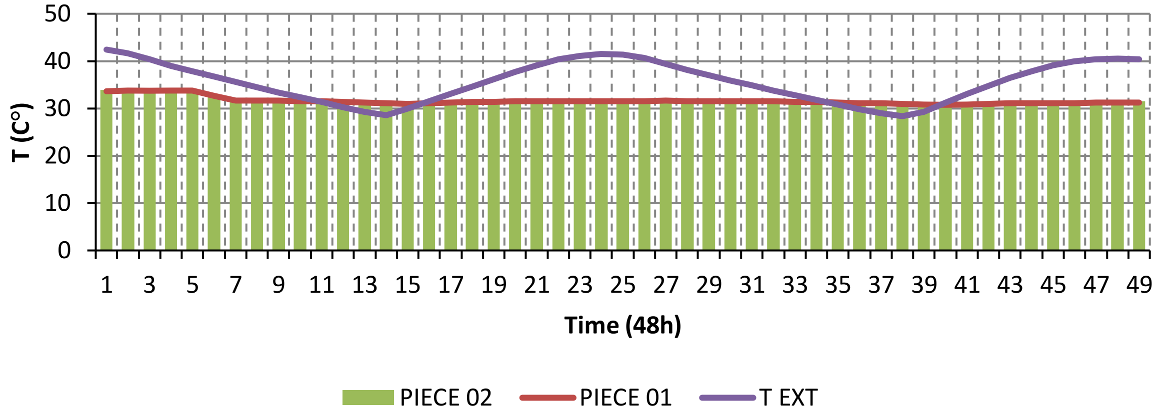
Similarly, in the city of Béchar, the temperatures in both rooms are significantly below the standard of 18 °C, with a difference of up to 13 °C (Figure 13). This critical situation further underscores the need for an adequate heating system to ensure acceptable thermal comfort. Inadequate heating can lead to health issues, including respiratory diseases, which are exacerbated by extreme climatic conditions (D'Amato et al., 2014).

Figure 13. Winter indoor-outdoor temperature difference of Béchar city in free-standing conditions: case study 2



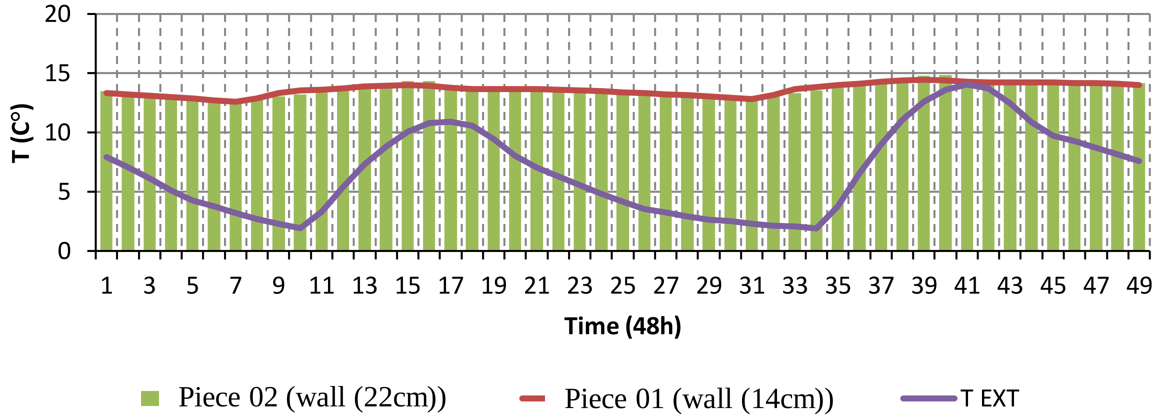
The temperatures recorded in both rooms deviate significantly from the standard of 25°C, showing a maximum difference of 9°C, which corresponds to temperatures reaching 34°C (Figure 14). This critical situation makes the adoption of a cooling system essential. Extreme temperatures, exacerbated by climate change, can have detrimental effects on the health and well-being of populations, thereby underscoring the importance of appropriate interventions (Lin et al., 2022; Liu et al., 2024).

Figure 14. Summer indoor-outdoor temperature difference of Béchar city in free-standing conditions: case study 2



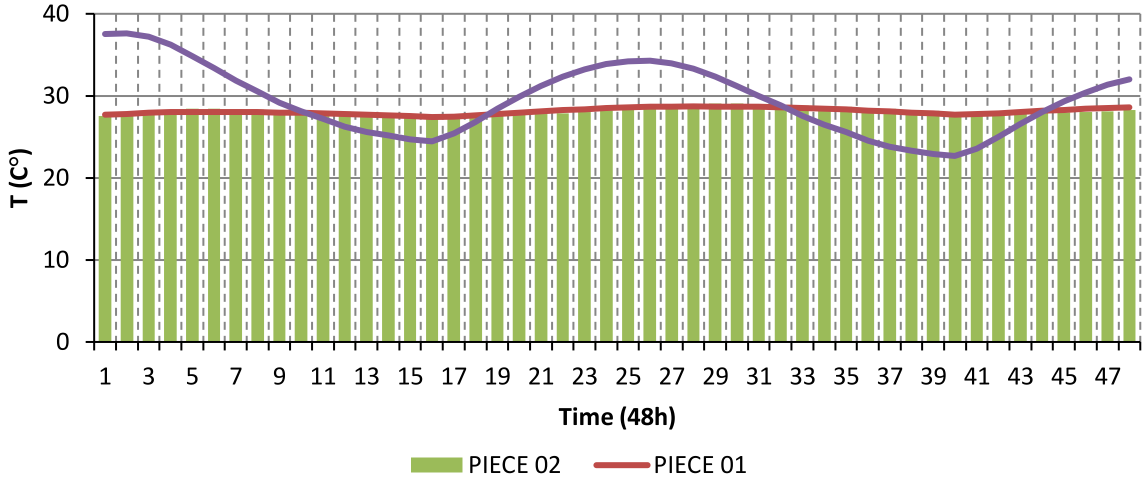
For the third case, in Oran, the temperature in the two studied rooms is relatively close to the set point of 18 °C during certain hours of the day. However, there is a significant difference of 11 °C during the coldest periods (Figure 15). This situation indicates the need for a heating system, albeit one that may operate at low intensity to maintain adequate thermal comfort. Recent studies show that low-energy heating systems can reduce energy consumption while keeping indoor temperatures comfortable, thereby contributing to the energy sustainability of buildings (Harkouss et al., 2018; Xiang et al., 2023).

Figure 15. Winter indoor-outdoor temperature difference of Oran city in free-standing conditions: case study 3



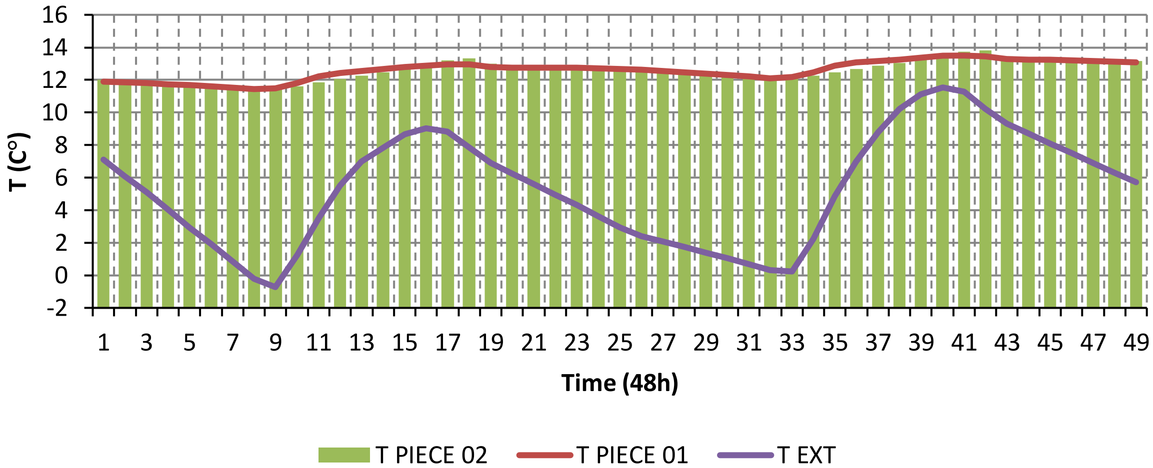
In the city of Oran, temperature measurements in two rooms indicate a close alignment with the set point temperature of 25 °C (Figure 16). In fact, the maximum recorded temperature deviates by only 11 °C from this value. This slight deviation suggests that the use of an active cooling system could potentially be overlooked. However, it is advisable to consider implementing an artificial ventilation system to ensure optimal thermal comfort, especially during periods of extreme heat. The use of both natural and artificial ventilation systems can significantly reduce energy consumption while maintaining thermal comfort (Silvero et al., 2019).

Figure 16. Summer indoor-outdoor temperature difference of Oran city in free-standing conditions: case study 3



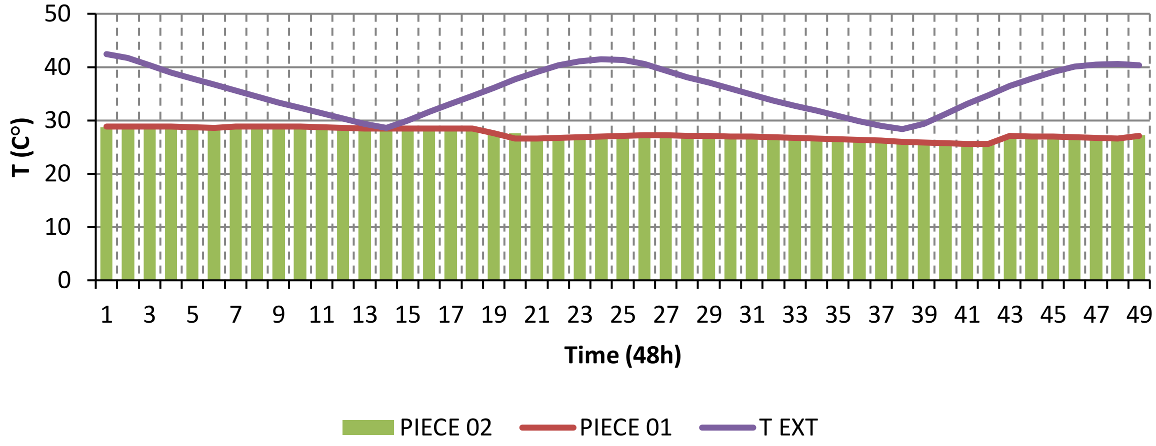
In contrast, in Béchar, the temperatures in both rooms significantly deviate from the set point of 18 °C, with differences reaching up to 13 °C during the coldest periods (Figure 17). This highlights the importance of implementing an appropriate heating system to meet the increased thermal demand. According to research conducted by the National Institute for Energy and Environmental Research, adopting modern and efficient heating technologies could help mitigate energy costs and reduce environmental impact (Mancini & Basso, 2020).

Figure 17. Winter indoor-outdoor temperature difference of Béchar city in free-standing conditions: case study 3



Regarding Béchar, the results indicate that the temperatures in both rooms are relatively close to the set point temperature of 25 °C, with a maximum difference of 14 °C (Figure 18). In this context, it becomes imperative to implement a cooling system, albeit one of low intensity. A moderate cooling approach allows for the maintenance of comfortable indoor conditions without incurring excessive energy consumption. A recent study has shown that using passive cooling solutions in conjunction with efficient air conditioning systems can reduce energy costs while enhancing occupant comfort in arid regions (Faci et al., 2018).

Figure 18. Summer indoor-outdoor temperature difference of Béchar city in free-standing conditions: case study 3



Comparative Analysis Of Heating And Cooling Energy Demand

In the first case, it is essential to highlight that energy demands in Oran are considerably higher during the heating period compared to the cooling period (Figure 19). Data reveal that the heating energy requirements total 1533 kWh, whereas cooling needs are only 766 kWh. This discrepancy underscores the necessity for effective energy management, especially in a context where temperatures can fluctuate dramatically between winter and summer (Mellah et al., 2019).

Figure 19. The demand for both heating and cooling systems is essential throughout the entire year (Oran city)

Conversely, the situation in Béchar differs from that in Oran. Here, energy needs during the cooling period surpass those of the heating period (Figure 20). Heating requirements amount to 1633 kWh, while cooling demands reach 2005 kWh. This trend can be attributed to the region's higher summer temperatures, which lead to increased air conditioning usage (Morlet & Keirstead, 2013). It is essential to highlight that, despite the elevated cooling requirements, overall energy consumption in this region remains substantial (Benzaama et al., 2021).

Figure 20. The demand for both heating and cooling systems is essential throughout the entire year (Béchar city)

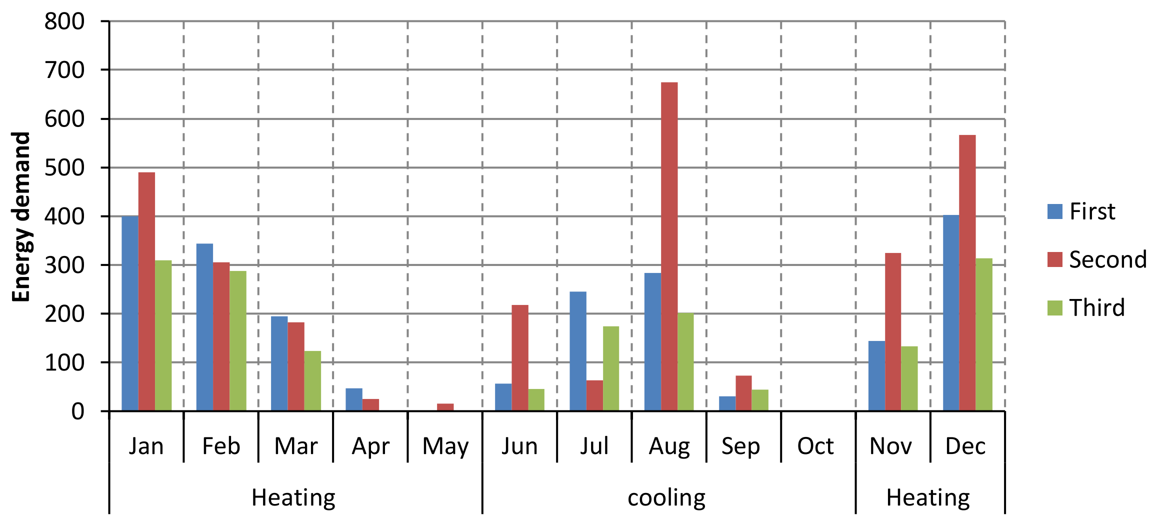


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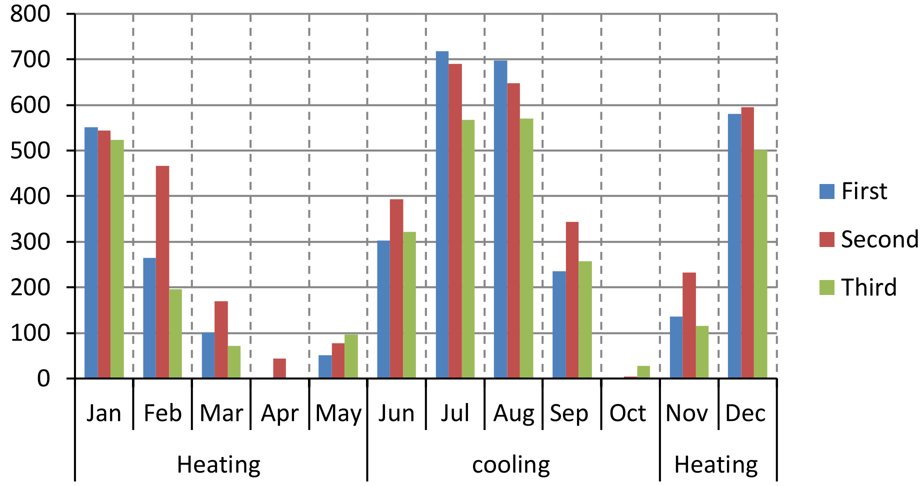
Figure 20. The demand for both heating and cooling systems is essential throughout the entire year (Béchar city)



The evolution of energy needs in these two cities highlights the importance of adopting tailored energy strategies that consider local climatic conditions and seasonal variations. Recommendations include optimizing heating and cooling systems, as well as integrating renewable energy solutions to reduce reliance on conventional energy sources (Bouraiou et al., 2020).

In the second case, focusing on the city of Oran, energy demands during heating and cooling periods are notably high. The energy requirements for heating reach 1909 kWh, while cooling demands amount to 1606 kWh. Figure 19 underscores the necessity of developing effective energy strategies to address the growing demand driven by climatic variations. Periods of extreme heat and severe cold lead to increased energy consumption, making it essential to adopt sustainable solutions that optimize energy efficiency in the Oran region. Integrating renewable energy sources, such as solar power, presents a viable alternative for reducing energy dependence.

Similarly, in the city of Béchar, energy needs are also substantial and are relatively balanced between cooling and heating periods. The energy requirements for heating are 2052 kWh, while cooling demands reach 2157 kWh. The importance of energy planning in a region where climatic extremes can significantly affect energy consumption (Figure 19). Rising summer temperatures and colder winters further intensify the need to enhance energy infrastructure in Béchar. Therefore, optimizing heating and cooling systems, along with embracing innovative technologies, is crucial to meeting this growing energy demand while fulfilling environmental commitments (Mohammed et al., 2011).

In the third case, focusing on the city of Oran, energy needs during the heating season are relatively modest, while they remain negligible throughout the cooling period. The recorded energy data for this region indicates heating energy requirements of 1204 kWh and cooling energy needs of 565 kWh. Figure 19 illustrates that although there is some demand for heating, it is not excessive, likely due to the Mediterranean climate characterized by mild winters and hot summers. Energy consumption in Oran aligns with national trends, where heating demand is generally low in the northern part of the country.

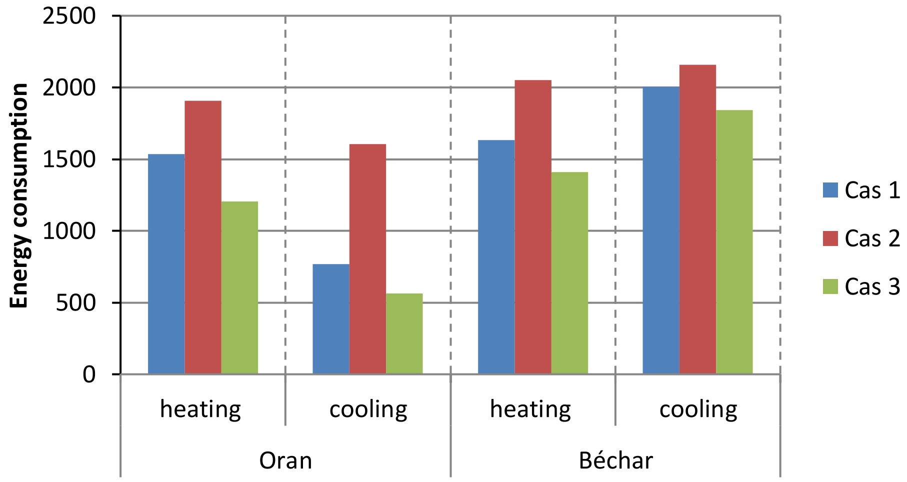
In contrast, the city of Béchar exhibits significantly higher energy demands during the cooling period compared to the heating period. The energy balance for these two seasons reveals substantial differences: heating energy needs amount to 1409 kWh, while cooling energy requirements peak at 1841 kWh. This discrepancy underscores the arid climate of Béchar, where summer temperatures can soar to extreme levels, leading to an increased demand for cooling energy.

Enhancing Building Envelope Efficiency In Oran And Béchar For Climate Adaptation (Figure 21)

This study evaluates three distinct types of building envelopes—referred to as Envelope 1, Envelope 2, and Envelope 3—analyzed annually in the cities of Oran and Béchar. For each envelope configuration, we closely monitored and recorded energy consumption for both heating and cooling requirements. The envelopes differ in material composition and structural design, with Envelope 3 incorporating advanced 3D panel technology.

To determine energy efficiency, we compared the seasonal and annual energy performance of each envelope. Efficiency rates were calculated by measuring each envelope's energy usage relative to the baseline established by Envelope 2 (Figure 21).

Figure 21. Energy Consumption Across Three Scenarios



To compare the three envelope types used in Oran (Figure 21): Envelope 1, with a total energy consumption of 2299 kWh, demonstrates significantly better energy efficiency than Envelope 2, which consumes 3515 kWh, resulting in a 55% improvement. Envelope 3 performs even better, with a total consumption of just 1769 kWh, leveraging advanced 3D panel technology to achieve remarkable energy savings. Compared to Envelope 2, Envelope 3 shows a 98% improvement in energy efficiency and outperforms Envelope 1 by 69%.

In Oran's climate, Envelope 1 excels in cooling efficiency, indicating it is particularly suited for cooling demands, though its overall annual consumption remains relatively low. Similarly, Envelope 2 performs marginally better in cooling than in heating but shows high annual energy consumption and a significant energy balance. Envelope 3 also shows enhanced cooling performance over heating in Oran, making it especially effective during cooling periods. With notably low annual energy consumption, Envelope 3 operates efficiently, requiring minimal reliance on heating and cooling systems.

To compare the energy performance of the three envelope options for Béchar (Figure 21): Envelope 1, with a total energy consumption of 3638 kWh, is 16% more efficient than Case 2, which consumes 4209 kWh. Envelope 1 performs especially well during the heating season, indicating higher efficiency in colder months, though it maintains a relatively low annual energy consumption overall. Envelope 2 offers a balanced performance across both the cooling and heating seasons; however, its total annual consumption and energy balance remain comparatively high. Envelope 3 (the 3D panel option) has a total consumption of 3252 kWh, making it 29% more efficient than Case 2 and 12% more efficient than Envelope 1. It performs best during the cooling season, suggesting enhanced effectiveness in warmer periods. Overall, Envelope 3 demonstrates the lowest annual energy consumption among the options.

Optimization Of The Building Envelope (3D Panels)

In comparing three wall configurations—double-brick walls with an air gap, double-wall structures with internal insulation, and a 3D panel envelope—our goal is to identify a cost-effective solution balancing energy efficiency and thermal comfort. This section presents the numerical findings derived from optimizing the 3D panel envelope.

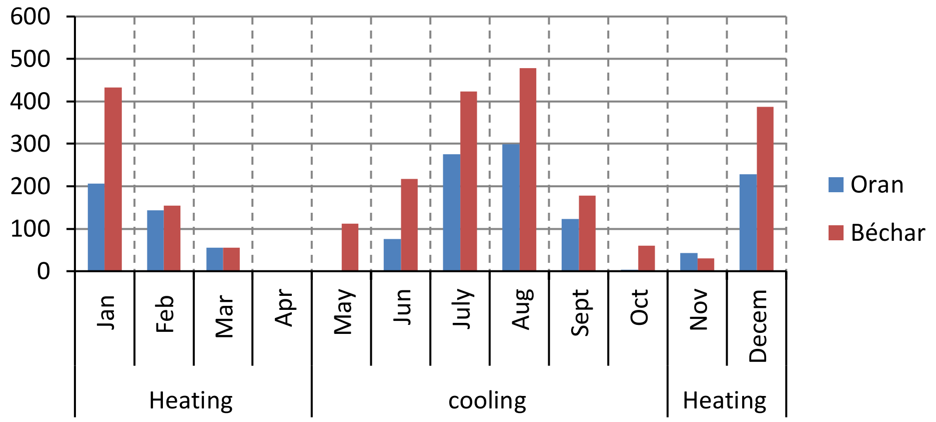
We start by emphasizing results that showcase the impact of insulation thickness and concrete layer on overall performance. Following this, we analyze the simulation and optimization processes applied to both the envelope and windows. Comparing the thickness and energy consumption across the three configurations reveals that the 3D panel requires significantly less material thickness than the other cases. Consequently, we can consider increasing the panel's thickness to determine if this enhances energy performance. To aid in the envelope optimization process (Table 4).

Table 4. outlines the specific characteristics and thicknesses of each envelope type

Composition	Materials	Conductivity (λ(Wm^{-1}K^{-1}))	Density (kg m^{-3})	Specific Heat Capacity (J kg^{-1} k^{-1})	Thickness (m)
Vertical Wall	Concrete	1.75	2400	1000	0.06
	Insulation	0.038	20	1450	0.10
LowerFloor	Gerflex Coating (Menhoudj et al., 2018)	0.31	1190	1000	0.003
	Concrete (Menhoudj et al., 2018)	1.75	2400	1000	0.06
	Insulation (Menhoudj et al., 2018)	0.038	20	1450	0.10
	Waterproofing	0.04	1150	1000	0.03
UpperFloor	SlopedForm	1.75	2450	1000	0.05
	Concrete	1.75	2400	1000	0.06
	Insulation	0.038	20	1450	0.10
Window	Single Glazing	1.2	2750	830	0.004

Energy consumption in Oran has experienced a significant decline, with an overall decrease of 1371 units. Specifically, heating usage accounted for 577 kWh, while cooling accounted for 794 kWh. This reduction underscores the city's transition toward more energy-efficient practices. Key factors contributing to this trend include advancements in building energy efficiency and a heightened awareness among residents regarding sustainable energy management (Figure 22). Similarly, in Béchar, energy consumption during the heating and cooling seasons has also decreased significantly, with recorded usage of 1061 kWh and 1471 kWh, respectively. This represents a total reduction of 2532 consumption units compared to previous years. This decline can be partly attributed to rising regional temperatures and the adoption of more sustainable energy solutions (Figure 22).

Figure 22. The energy requirements for heating and cooling throughout the year



In Oran, the 14 cm 3D panel demonstrates a 29% reduction in energy consumption compared to the 22 cm panel. Similarly, in Béchar, the 14 cm panel also achieves a 29% decrease in energy use. To illustrate the performance differences between the two panels in an unconfined environment (Figure 23), it was observed that during the minimum temperature scenario, the indoor temperature with the 3D panel at 22 cm was closer to the target temperature of 18°C, showing only a 3°C difference between the 22 cm and 14 cm 3D panels. In contrast, during the maximum temperature scenario, the indoor temperature with the 3D panel at 22 cm approached the target temperature of 25°C, with a similar 3°C difference between the 22 cm and 14 cm panels (Figure 24).

Figure 23. The difference between the indoor and outdoor temperatures of a single room with a 3D panel measuring 14 cm in thickness and one measuring 22 cm in free-standing conditions winter period in Oran

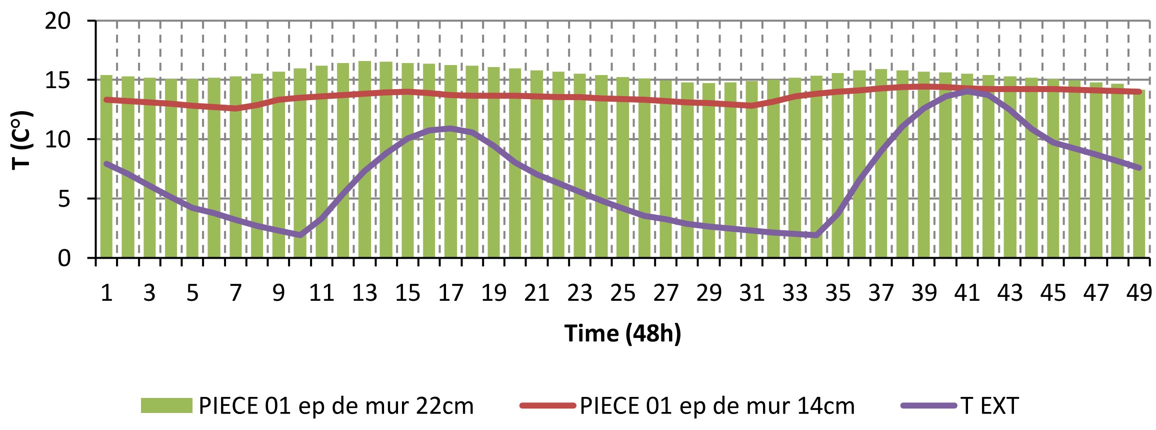
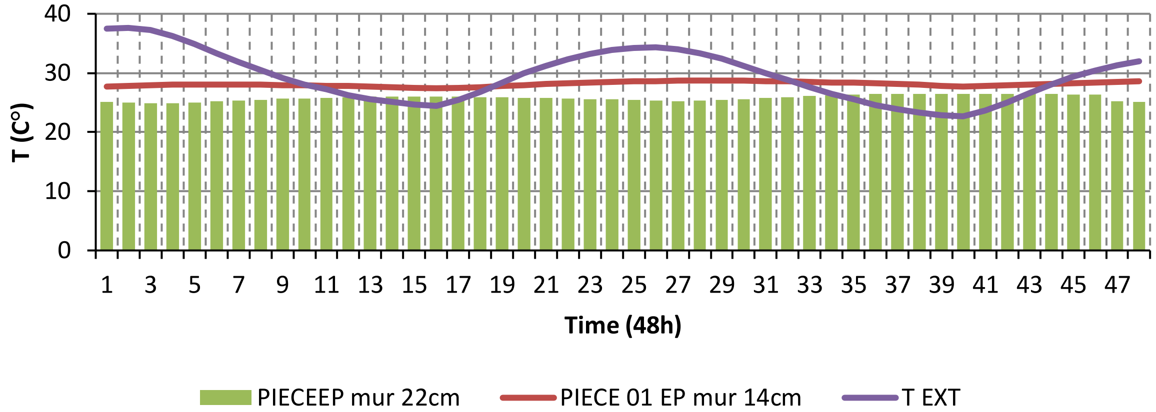


Figure 24. The difference between the indoor and outdoor temperatures of a single room with a 3D panel measuring 14 cm in thickness and one measuring 22 cm in free-standing conditions summer period in Oran



The indoor temperature of the room with the 3D panel at 22 cm closely approached the setpoint temperature of 18°C, exhibiting a difference of 3°C compared to the case with the 14 cm panel, under minimum temperature conditions (Figure 25). Similarly, for maximum temperature conditions, the indoor temperature with the 3D panel at 22 cm aligned closely with the setpoint temperature of 25°C, again showing a 3°C difference between the 22 cm and 14 cm panel cases (Figure 26).

Figure 25. The difference between the indoor and outdoor temperatures of a single room with a 3D panel measuring 14 cm in thickness and one measuring 22 cm in free-standing conditions winter period in Béchar

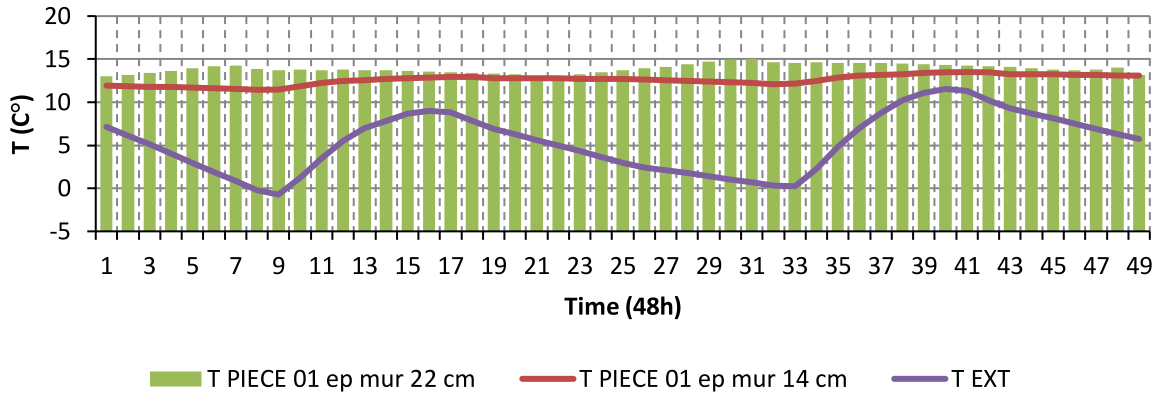
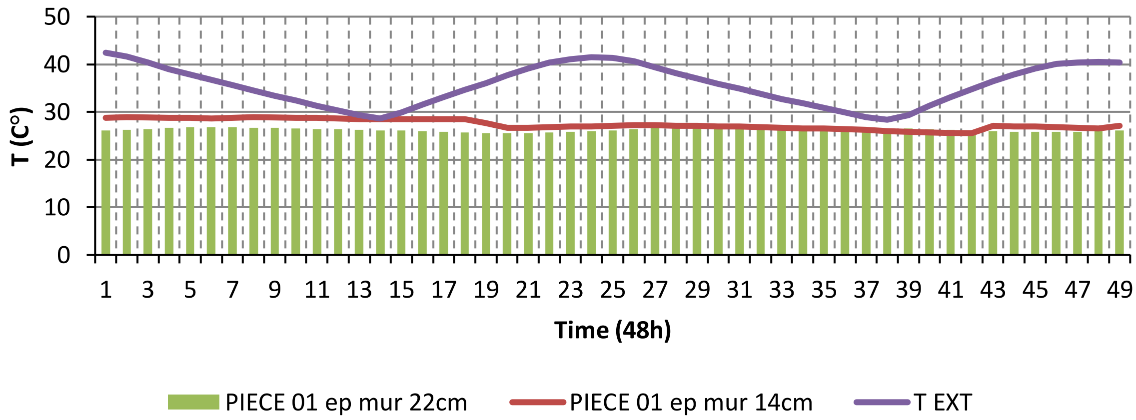


Figure 26. The difference between the indoor and outdoor temperatures of a single room with a 3D panel measuring 14 cm in thickness and one measuring 22 cm in free-standing conditions summer period in Béchar



CONCLUSION

The findings of this study underscore the significant impact that advanced building envelope materials and innovative designs have on enhancing thermal comfort and reducing energy consumption in residential buildings across Algeria's varied climate zones. Through a detailed comparative analysis, the study demonstrates that novel solutions, particularly 3D panel systems, provide considerable energy savings while maintaining stable indoor comfort.

The analysis further reveals that 3D panel systems surpass conventional materials in delivering thermal stability and energy efficiency, thanks to their superior thermal properties and adaptable design. The adoption of these advanced technologies could empower Algeria's construction sector to better address the challenges posed by its diverse climates, decrease dependence on non-renewable energy, and foster sustainable building practices. Future research may explore the integration of hybrid passive-active systems with renewable energy sources, potentially enhancing environmental sustainability and energy efficiency in residential buildings throughout Algeria's climate zones.

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