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From static metrics to multi-objective parametric optimization: enhancing the performance of semi-arid residential buildings through the Hourly Thermal Comfort Index

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Abstract:
Energy consumption and thermal comfort remain pivotal global challenges that directly impact the quality of residential life and habitat sustainability. This research develops a numerical model to predict the thermal behavior of residential buildings through a comprehensive parametric analysis, focusing on windows as critical elements in energy exchange. A wide range of variables was evaluated, including insulation deficiencies, material properties, glazing types, window-to-wall ratio (WWR), solar shading devices, floor levels, and operational factors such as family size and lighting loads. The study was conducted on a residential facade in Batna, Algeria – a warm, semi-arid climate. Thermal comfort was assessed by monitoring ambient temperatures and correlating them with the Hourly Thermal Comfort Index (HTCI) in accordance with ASHRAE 55 standards. To ensure objective accuracy, the study focused on a field-based sample of five residents living in southwest-oriented units. The findings, which maximize thermal performance using the "Galapagos" evolutionary algorithm, show that single glazing significantly degrades comfort levels. In contrast, advanced configurations – combining double or triple low-E glazing with horizontal shading – increased the comfort index from a baseline of 55.54% to over 77% for the southwest orientation. By providing a precise hourly analysis (HTCI) that captures instantaneous thermal fluctuations, this study addresses the limitations of traditional static assessments. These findings establish a framework for future research that integrates in situ measurements with occupant surveys, effectively bridging the gap between objective performance and subjective experience to achieve a holistic understanding of thermal challenges in real-world residential environments.

Keywords:
thermal comfort, multi-objective optimization, parametric approach, hourly thermal comfort index, residential building

1. Introduction

In a context marked by climate challenges and rising energy prices, the systematic optimization of buildings has become essential. Indoor thermal comfort and energy efficiency are now key criteria in architectural design. In this regard, the World Meteorological Organization (WMO) confirms that 2024 is the warmest year on record, with a global temperature increase of 1.55 °C above pre-industrial levels. Several consecutive months, particularly from January to June, have also exceeded their historical monthly averages. On 22 July 2024, the global daily mean temperature reached approximately 17.15 °C, according to the Copernicus ERA5 dataset, setting a new daily record [1]. Data published by WMO and Copernicus (2024) confirm a worrying trend. Global temperatures now exceed pre-industrial levels by more than 1.50 °C on average. This increase leads to more frequent and intense heatwaves. As a result, the thermal comfort of buildings is directly affected, especially in arid regions such as Algeria. These extreme conditions require a reconsideration of architectural design practices, particularly the configuration of building facades [2].

According to the WMO report (2023), the previous year was the hottest ever recorded globally, with an average temperature about 1.45 °C above pre-industrial levels. In Fig. 1, the large colored numbers indicate the maximum temperatures (°C) officially recorded in each country. The small gray numbers show the year in which these records were set. The color gradient represents heat intensity: dark red corresponds to temperatures above 50 °C, red and orange indicate values between 40 °C and 49 °C, while yellow represents records in polar regions (below 20 °C) [3].

The impact of building envelope parameters varies significantly across climates. In tropical regions, studies show that thermal mass can be disadvantageous because it retains heat during humid nights [4]. In contrast, research in Mediterranean climates highlights the benefits of larger window-to-wall ratios to improve winter solar gains [5]. However, these strategies are not always suitable for the Algerian semi-arid context. In this region, intense solar radiation and large diurnal temperature variations require a different approach. Therefore, optimizing parameters such as orientation, materials, and glazing becomes essential. This study addresses this gap by identifying configurations adapted to hot-dry climates, where conventional Mediterranean or tropical solutions may not be effective.

Despite the importance of building envelope design, many residential buildings in Algeria's semi-arid regions are still constructed without optimizing key parameters such as wall materials, glazing, and orientation. Facades are often treated uniformly without considering solar exposure. This leads to poor thermal performance and increased energy demand. Although thermal comfort has been widely studied, these persistent shortcomings indicate that further research is still needed. This study aims to bridge the gap between theory and practice. It encourages moving beyond standard design approaches and emphasizes energy efficiency as a fundamental requirement in building design.

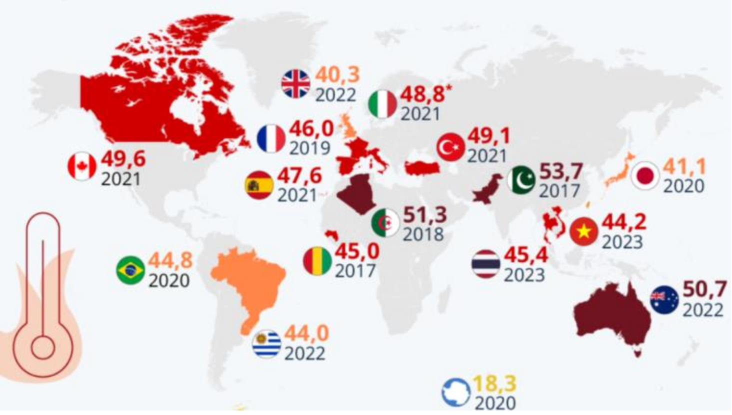


Fig. 1. The heat records recently (10/08/2023) beaten by the World Meteorological Organization 2023. Source: [2]

1.1. Research objective

The goal of this research paper is

1. To identify architectural indicators that provide and promote thermal well-being in residential buildings located in a semi-arid climate based on precisely defined criteria, as well as maximize thermal comfort and minimize thermal Gains/Loads.
2. Evaluate indoor thermal performance dynamically and throughout the year by employing the Hourly Thermal Comfort Index (HTCI) based on ASHRAE 55 standards.
3. To investigate the impact of parametric facade design (windows, shading, materials) on indoor thermal comfort in a semi-arid climate.
4. To assess the transferability of the models to different climatic conditions, providing generalizable design guidance for similar regions

Consequently, this study seeks to answer the following research questions:

1.2. Research questions

1. How can HTCI be used to assess indoor thermal comfort?
2. What contribution does the parametric approach make to exploring new design horizons for building envelopes, and how does this approach enhance the efficiency of technical solutions aimed at achieving thermal comfort in residential buildings?
3. Can the simulation results be generalized to similar climates?

1.3. Literature review

The field of thermal comfort in buildings has received increasing attention in the scientific literature. Many studies have examined the effects of climatic conditions, building materials, and architectural design on achieving indoor comfort. Several works specifically focus on the role of envelope parameters. For example, Hanafy (2025) reports that optimized choices of glazing and facade materials can achieve energy savings of up to 78.4% compared to a reference case [6]. In addition, studies on adaptive facades within new design frameworks show that adjusting envelope properties – such as U-values, SHGC, and orientation – can simultaneously improve thermal comfort, enhance natural lighting, and reduce energy loads [7]. Similarly, Gajjar et al. (2025) demonstrate the effectiveness of shading devices in reducing indoor temperature while improving overall energy performance in buildings located in semi-arid climates [8]. A parametric study conducted in Algeria by Cherier et al. (2024) highlights that glazing type (e.g., Low-E), optimal window-to-wall ratio (approximately 60%), and building orientation vary significantly depending on the climatic zone in order to maximize energy savings [9]. Likewise, Makhloufi and Louafi (2024) focus on envelope optimization in hot and arid regions. Their work emphasizes the importance of architectural design in controlling energy consumption. It also compares locally available glazing types and different WWR configurations, showing that both factors strongly influence energy use and thermal comfort [10].

Moreover, the study by Pérez-Carramiñana et al. (2024) demonstrates that external mobile solar protection systems, such as shutters and blinds, significantly improve thermal comfort and reduce cooling demand. In contrast, internal shading devices provide only limited improvements in dry and semi-arid Mediterranean climates [11]. Overall, these studies confirm that the facade, as the interface between indoor and outdoor environments, plays a critical role in heat transfer through both opaque walls and glazing. It directly affects solar gains, thermal losses, and total energy consumption. In the same context, Lahmar et al. (2022) analyze the combined effect of orientation and WWR using electrochromic glazing in Biskra (Algeria). Their results show energy savings of up to approximately 60%, depending on orientation [12]. Similarly, Uprety et al. (2021) demonstrate that WWR and orientation significantly influence indoor thermal comfort and energy consumption in residential buildings in Nepal [13]. Likewise, Mansouri and Sriti (2019) show that envelope materials, particularly opaque components, have a strong impact on indoor comfort and energy demand in hot and dry climates [14]. Furthermore, Mahar et al. (2019) investigate strategies such as low-U glazing, triple glazing, and increased thermal mass. Their findings indicate that triple glazing improves thermal comfort hours compared to double glazing, although the overall effect remains moderate in dry and semi-arid climates [15]. For instance, a study conducted in Jeddah evaluates different glazing configurations, including selective double glazing, low-U glass, and low SHGC glazing, for residential buildings under extreme climatic conditions. The results show that aerogel glazing (36 mm thickness, U = 0.90 W/m²K, SHGC = 0.30) is particularly effective. It reduces cooling demand by nearly 48.60% compared to single glazing. Indoor temperature decreases to approximately 30.09 °C, compared to 38.43 °C in the reference case, demonstrating a significant thermal improvement [16,17]. Finally, the study entitled Balancing Thermal Comfort and Energy Consumption in Residential Buildings of Desert Areas: Impact of Passive Strategies shows that combining passive strategies – such as enhanced insulation of walls and roofs, along with shading devices – can achieve up to 87% of annual thermal comfort hours (8,760 hours), compared to a much lower percentage in the base case [18].

In light of these findings, most previous studies have focused on evaluating thermal performance using fixed indicators or by analyzing individual facade parameters such as orientation or window area. However, these approaches often rely on general or static assessments. They do not adequately capture the temporal dynamics of thermal comfort, particularly in residential buildings located in semi-arid climates. Moreover, the integration of parametric modeling with real-time thermal comfort indicators remains limited. Therefore, there is a clear need to develop a more precise analytical approach. This approach should rely on a dynamic time-based indicator of thermal comfort to better capture variations over time. In response, this study proposes the use of the Hourly Thermal Comfort Index (HTCI) within a parametric simulation framework. This method aims to provide a deeper understanding of how facade design variables influence thermal comfort in semi-arid environments.

2. Study context

This section aims to define the reference and environmental framework upon which the study is based; accurate simulation is not complete without a deep understanding of external influences and structural characteristics. In this context, we review the climatic determinants of the study area and their direct impacts, followed by a detailed description of the building and its physical components, to ensure that the proposed solutions are consistent with the geographical and architectural reality.

2.1. Climatic context

Batna's semi-arid climate, at an elevation of ~1050 m, is defined by extreme seasonal and diurnal temperature shifts. Summers are characterized by intense heat exceeding 35–40 °C, while winters are cold with nighttime lows reaching –8 °C. These sharp contrasts, featuring significant day-night cooling and dry conditions, present unique thermal challenges [19]. The graphs below, obtained from EPW data [20], provide a detailed overview of the region's climate.

Batna features a semi-arid climate (BSk), characterized by scorching dry summers where temperatures regularly exceed 35°C – peaking above 40°C in July and August (see Fig. 2) – alongside significant diurnal shifts. In contrast, winters are harsh from December to February, with nighttime temperatures frequently dropping below 0 °C. These seasonal extremes, separated by rapid spring and autumn transitions, present major hurdles for achieving consistent thermal comfort through architectural design.

Batna exhibits high solar potential, with peak global horizontal radiation (GHR) regularly exceeding 938 Wh/m² and reaching 1043 Wh/m² around midday between May and July (see Fig. 3). While sustained exposure remains high during summer, values drop significantly to 208–417 Wh/m² from November to February due to the lower solar angle. This intense summer solar energy underscores the critical need for bioclimatic strategies in local sustainable architecture.

2.2. Description of the case study building

The research was conducted in the city of Batna in Algeria, specifically in the 200 Housing Units area of El Nassim (35°31'42"N, 6°10'9"E) (see Fig. 4). This location was chosen for its availability of relevant data and its direct relevance to the study's objectives, making it a particularly suitable setting for carrying out the research.

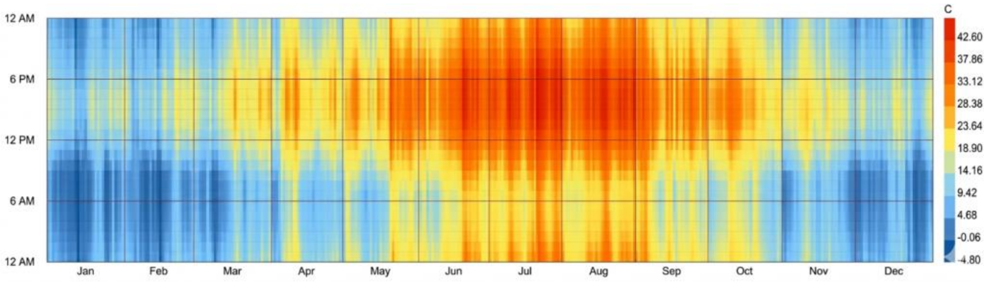


Fig. 2. Dry Bulb Temperature of Batna. Source: [20]

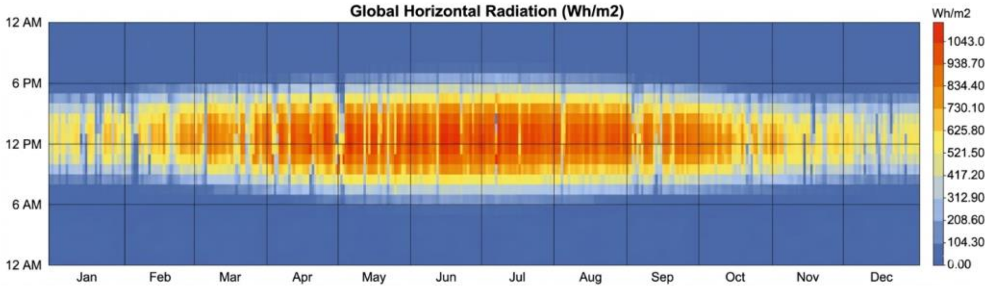


Fig. 3. Global Horizontal Radiation (wh/m2). Source: [20]

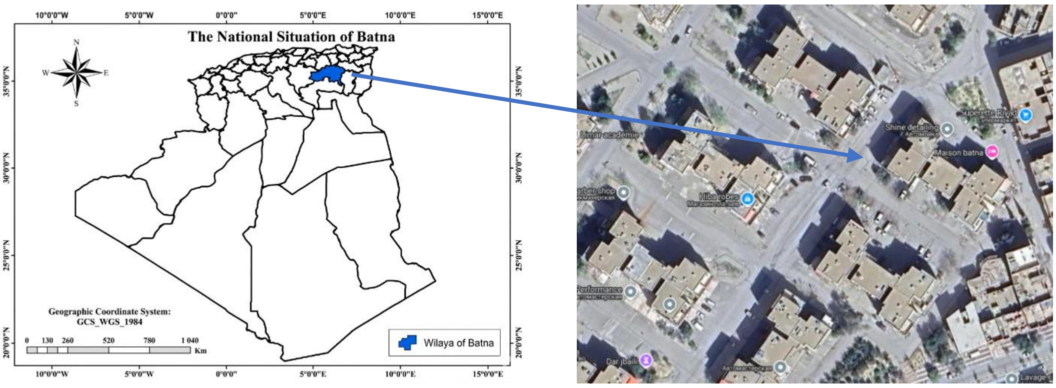


Fig. 4. Geographical location of Batna and EPLF El Nassim within the national context of Algeria. Source: Google Earth

3. Methodology

This study uses simulation-based analysis to evaluate the impact of building envelope parameters – such as wall materials, glazing type, window-to-wall ratio, and façade orientation – on thermal comfort and energy performance in residential buildings under semi-arid conditions in Batna, Algeria. Hourly Thermal Comfort Index (HTCI) is used to assess indoor conditions, with ambient temperatures simulated for realistic climate input [21]. The building envelope considers simple 4 mm glazing and concrete block walls without insulation, highlighting the effects of heat gain and loss. This approach enables a façade-specific evaluation of passive design strategies on indoor thermal comfort and energy demand [22]**.**

3.1. Thermal comfort assessment framework

The thermal performance of the building is quantified using the Hourly Thermal Comfort Index (HTCI), expressed as a percentage (%) of total occupied hours. This index serves as a longitudinal frequency indicator, representing the statistical probability that a space meets the environmental requirements defined by ASHRAE Standard 55 [23]. For each hour of the annual simulation, a binary assessment is performed; these values are then aggregated and normalized against the total duration of occupancy to provide a single representative value of thermal stability. The HTCI is calculated as follows:

$$HTCI\left(\%\right)=\frac{N_{comfort}}{N_{occupied}}\cdot 100 \qquad (1)$$

where: $N_{comfort}$ = number of occupied hours during which indoor thermal conditions fall within the acceptable comfort limits defined by ASHRAE Standard 55, $N_{occupied}$ = total number of occupied hours considered in the analysis [24].

3.2. Simulation environment and tools

In this work, the simulation tools used mainly include Rhino, a 3D modeling software based on NURBS geometry as shown in Fig. 5 and Fig. 6, and its parametric plugin Grasshopper. This platform allows the generation of dynamic and adaptive architectural models through visual programming (see Fig. 7), thus facilitating the rapid creation of design variants. Coupled with extensions such as Ladybug and Honeybee, Rhino/Grasshopper allows the integration of real climate data and detailed thermal simulations on residential building models. These tools are particularly suitable for bioclimatic optimization in the specific context of a semi-arid climate, offering a flexible and intuitive interface to analyze and improve the thermal and energy performance of buildings from the early design phases.

3.3. Parametric modeling strategy

The simulation accuracy is mainly based on the methodology of converting static dimensions into a flexible digital model. Based on the measurements shown in Fig. 5, this section reviews the parametric modeling strategy used, which allows for dynamic coupling between the geometric design and the environmental variables of the room. This section discusses the precise parameters set to ensure realistic simulation, from defining the basic parameters to the final configuration of the model.

3.3.1. Selected parameters for simulation

The simulation framework incorporates a set of discrete and continuous variables, categorized into four primary domains to evaluate their collective impact on the HTCI index:

- Envelope Thermophysical Properties: This includes glazing type (e.g., single, double, or triple), glazing thickness, and material characteristics (specifically the thermal resistance of the uninsulated concrete block baseline).
- Geometric and Aperture Configuration: Focused on the WWR, the dimensions of windows, and the number of windows per facade, which directly influence the building's transparency and thermal exchange.
- Spatial and Contextual Variables: These parameters account for the orientation (cardinal directions), the floor level (to assess vertical thermal stratification), and the implementation of sun protection (shading devices) to mitigate solar gain.
- Internal Load and Operational Factors: To ensure a realistic dynamic simulation, the model incorporates household size (occupancy density) and the number of luminaires (internal heat gains) as operational variables.

3.3.2. Simulation model configuration

In order to simulate indoor thermal conditions, an archetype collective residential building model was defined. The physical and technical parameters of this model are detailed in Table 1, serving as the basis for the thermal performance analysis.

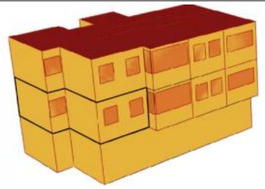
The numerical model was developed focusing on the living and dining room as the key space, with a net floor area of 32.46 m^2 and its dimensions are shown in the architectural plan (see Fig. 5). The building envelope consists of 20 cm thick single-layer hollow concrete block walls (parpaing) with a thermal transmittance (U-value) of 2.20 W/m^2. K. It is important to note that no thermal insulation was incorporated into the walls, and the model accounts for the heat exchange with adjacent walls to reflect realistic indoor conditions. Regarding the fenestration, the simulation integrates the number of windows, their dimensions, glazing type, thickness, and the WWR. However, no sun protection mechanisms were applied to the openings. Furthermore, the model includes the orientation, floor level, and internal gains such as household size and the number of luminaires. The simulation was conducted under natural conditions with windows closed, based on the specific material characteristics defined in the input data.

The attached architectural plan (Fig. 5) shows the exact spatial distribution of the studied area.

In this part, we review the architectural plan (see Fig. 5) that shows the exact measurements of the room that is the subject of the simulation, knowing that all dimensions shown in the plan are measured in centimeters (cm). It aims to provide a clear view of the spatial dimensions, ensuring that the results obtained from the simulation model are accurate and match the assumed realistic parameters.

Figure 6 shows a Grasshopper visual programming script, which is a plugin used primarily within the 3D modelling software Rhinoceros 3D (Rhino). It represents a "parametric" workflow, where instead of drawing objects manually, a user creates a logical sequence of operations to generate geometry.

Table 1. Archetype collective residential building model for indoor thermal condition simulation Source: own study

Component	Materials and properties
Geometry Case study →	
Location	South west
Height Level	1st Floor, 3m
Glass Window	Simple, single, clear, WWR=11%,
U_g-value(glazing)	5.40 W/m^2. K
g-value	0.85 (85%)
Visible Transmittance (VT)	0.80 – 0.90
Number of Windows	Living Room: 3
Wall Type	Single layer concrete block (Parpaing)
Wall Thickness	30 cm
Insulation	None
U-value (Walls)	Concrete block + cement plaster=2.20 W/m^2. K
Living Room Area	32.46 m^2
Ventilation	Natural ventilation / Manual window opening
Roof	hurdles and compression slab
Sun protection	There is no external sun protection
Occupant schedule	Living and dining Room: 8:00 to 23:00 Bedroom: 23:00 to 7:00

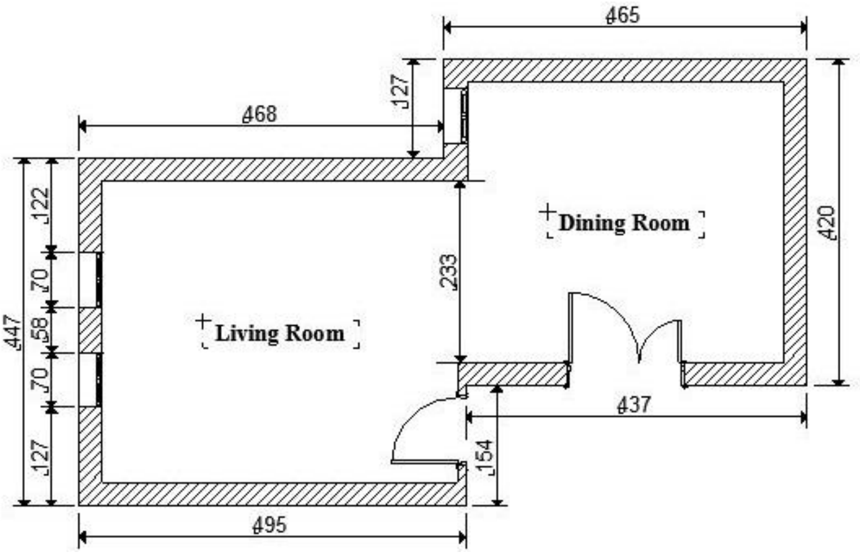


Fig. 5. Detailed plan and dimensions (cm) of the study key space (living and dining room)

This Grasshopper script (See Fig. 7) functions as a manual orientation toggle for a modular building model in Rhino, specifically utilizing Honeybee (HB) components to control spatial data. Rather than an automated solver, the logic uses a Value List and Stream Filter to allow the user to switch the building's rotation between specific cardinal directions, such as North East or South West. As the user selects an orientation, the HB Rotate component updates the 3D geometry in real-time, while the output panel on the right tracks how these changes affect the properties of the Room, facilitating a quick visual and data-driven comparison of different design positions.

Figure 8 shows the practical application of the script you saw previously. It captures the Rhino 3D interface (left) working in tandem with the Grasshopper algorithm (right) to perform an architectural simulation. Specifically, this looks like an environmental analysis or generative design workflow.

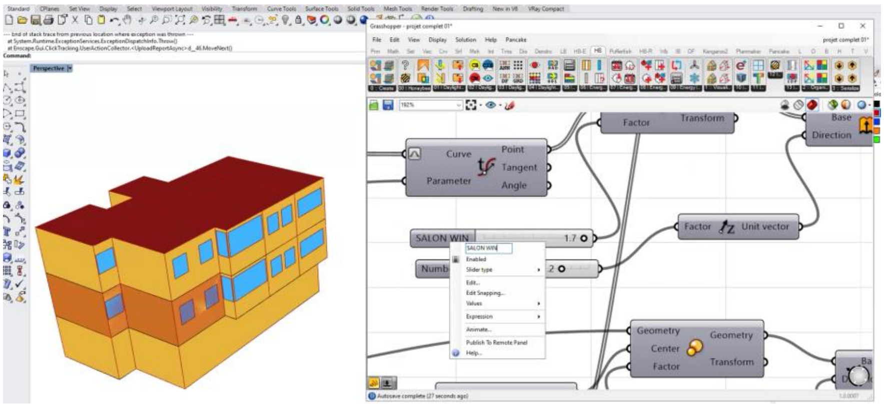


Fig. 6. Parametric modeling script in Rhino-Grasshopper. Source: own study

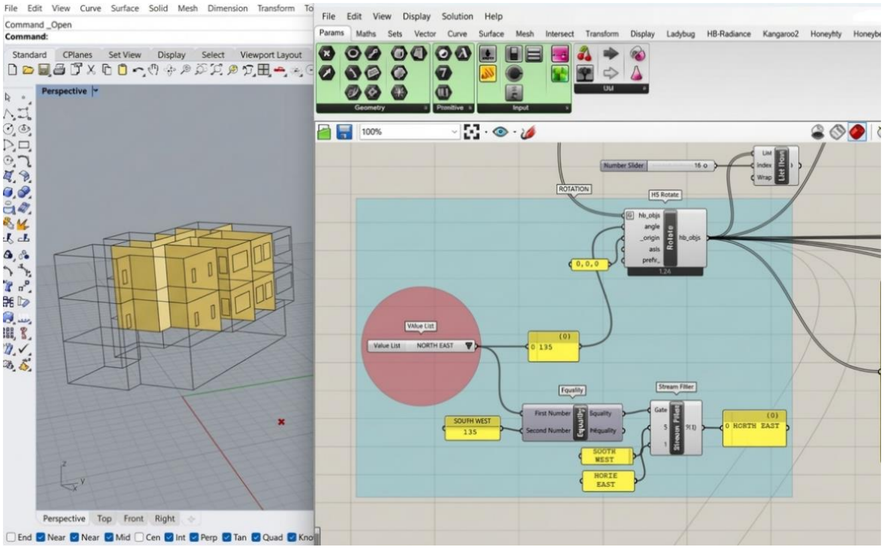


Fig. 7. Parametric modeling script in Rhino-Grasshopper. Source: own study

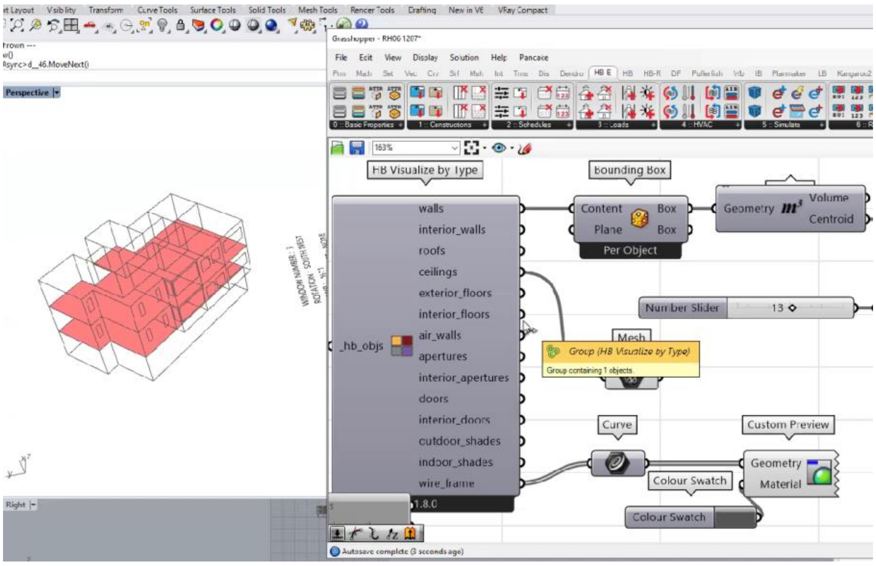


Fig. 8. Representation of numerical model in Rhino-Grasshopper. Source: own study

This script (see Fig. 9) demonstrates a parametric study of user comfort on a clock basis, aiming to evaluate the quality of the indoor environment by analyzing the thermal performance of spaces. The workflow is based on ambient temperature processing derived from room simulation results, considering seasonal changes over specific time periods. This data is processed to produce accurate time results that are displayed as graphical curves, which allow the designer to accurately monitor heat fluctuations and verify how efficiently the design provides a stable thermal environment.

Figure 10 illustrates a professional parametric environmental analysis workflow where an architectural model is linked to a simulation engine via Grasshopper.

The optimization process was conducted using the Galapagos evolutionary solver within the Grasshopper environment. The objective function was configured to maximize the Hourly Thermal Comfort Index (HTCI) by iteratively adjusting three primary design variables: (1) shading device depth, (2) WWR, and (3) glazing thermal properties. The solver employs a genetic algorithm to explore the solution space, identifying the optimal configuration where the highest percentage of annual hours falls within the ASHRAE 55 adaptive comfort boundaries. This ensures that the resulting architectural solutions are not merely aesthetic but are mathematically optimized for thermal performance.

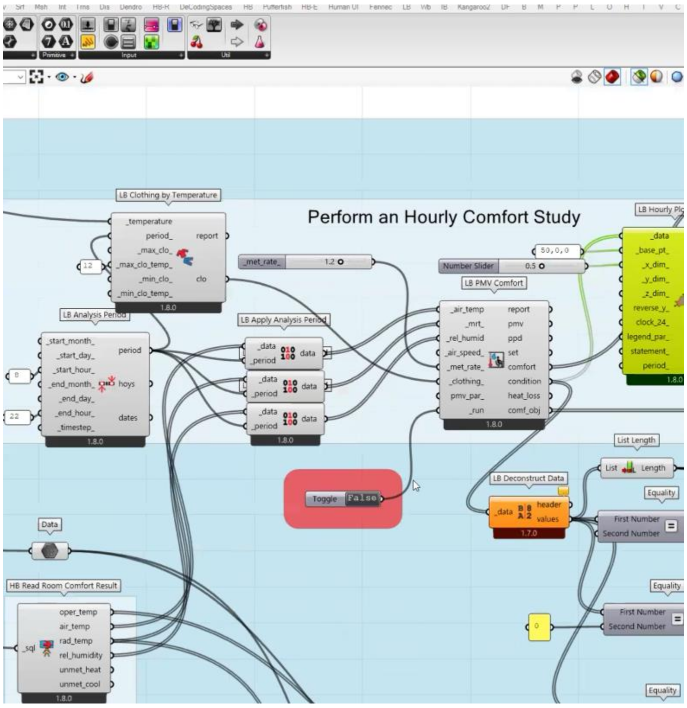


Fig. 9. Parametric modeling script in Rhino-Grasshopper. Source: own study

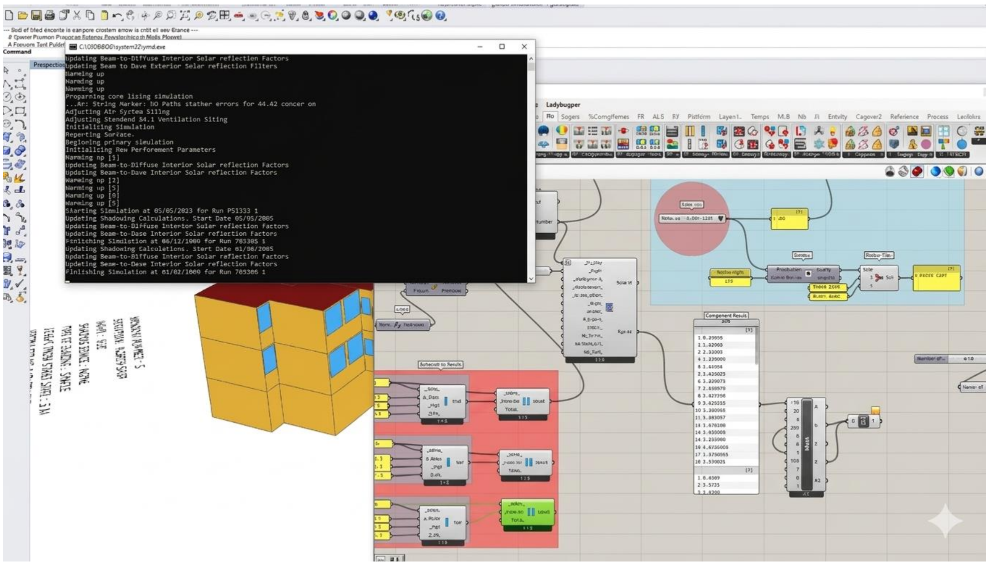


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Fig. 10. Simulation run Processing in Grasshopper. Source: own study

4. Results and discussion

The results below embody the outputs of computer simulations applied to the studied architectural space, relying on the measurements documented in Fig. 5 as a frame of reference. This section aims to link the extracted data to the physical reality of the room to draw final conclusions.

4.1. Parametric analysis results

The results generated by Grasshopper were then imported and visualized in the OriginLab software as the following: (see Fig. 11 and Fig. 12).

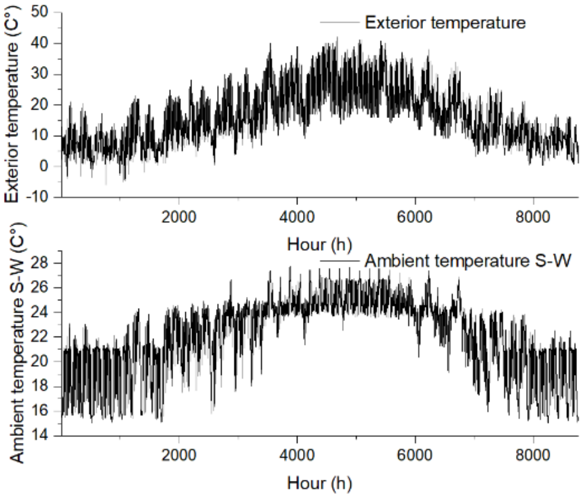

Fig. 11. Comparison of indoor SW and outdoor (EXT) temperatures. Source: own study

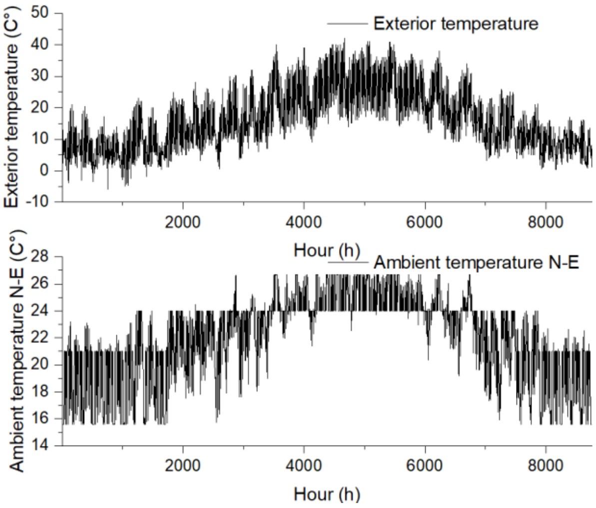

Fig. 12. Comparison of indoor NE and outdoor (EXT) temperatures. Source: own study

The analysis of temperatures recorded over an average period of 19 years highlights a significant thermal discomfort in the stay of the studied residential building, facing Southwest, in a semi-arid climate.

The upper graph shows high variability in outdoor temperature, ranging from about -10 °C in winter to 35 °C in summer, which is characteristic of a semi-arid climate, with high thermal amplitudes and intense sunlight.

The lower graph, representing the ambient temperature in the living room facing south west, reveals an inadequate thermal response of the building:

- In summer, the indoor temperature regularly exceeds 28–29 °C, crossing the recommended upper comfort limit (26 °C). The prolonged exposure to the sun in the afternoon, typical of a Southwest facade in a semi-arid climate, accentuates the risks of overheating.
- In winter, the temperature drops to 14–16 °C, well below the winter thermal comfort threshold (20–22 °C), reflecting a lack of insulation or efficient heating.

This close correlation between the outdoor temperature and the indoor environment reflects low thermal inertia and a lack of suitable bioclimatic strategies (shading, natural ventilation, materials with high thermal capacity, etc.).

In a semi-arid climate, the thermal management of a building is crucial. Observing indoor temperatures ranging from 14 °C in winter to 29 °C in summer demonstrates marked thermal discomfort in the southwest living area of the building. This highlights a poor architectural adaptation to the local climate, justifying the implementation of passive solutions (solar protection, insulation, adapted orientation) or active ones (efficient HVAC systems).

The analysis of the results extracted from simulations over an average of 19 years reveals a situation of significant thermal discomfort in the residence of the residential building modelled, located in a semi-arid climate and oriented Southwest. The temperature curves show that the indoor temperature peaks at 29 °C in summer and drops to around 14 °C in winter, which clearly exceeds the recommended thermal comfort ranges, typically between 20 °C and 26 °C according to international standards [21]. This inability to maintain stable indoor conditions is explained by several architectural and technical factors resulting from the modeling in Grasshopper.

The living-dining room has three windows with a WWR of 11%, oriented southwest, orientation exposed to strong sunlight at the end of the day, especially in summer. However, no sun protection has been integrated (canopy, brise-soleil, etc.), which leads to uncontrolled direct solar gains [25].

The thermal analysis was conducted on a living-dining space with a realistic surface area of 32.46 m² (as detailed in the 2D plans and 3D screenshots). This standardized volume ensures that the internal thermal loads generated by five occupants are distributed across a realistic air volume, providing a more accurate representation of residential heat density. The results indicate that this volume, while standard, still experiences significant temperature variations due to the lack of a thermal buffer from lower levels, as the room is situated on the first floor. These parameters, when simulated under Batna's extreme climatic conditions, confirm that the current design remains poorly adapted to the context, resulting in suboptimal passive thermal comfort performance [26] during both peak summer and winter periods.

The thermal discomfort observed in the studied residential building can be explained by several factors related to glazing characteristics and building orientation. The use of single glazing with a high U-value of 5.40 W/m²·K leads to significant heat transfer. This allows excessive heat gain in summer and heat loss in winter. This value is much higher than the recommended standards for hot or mixed climates (generally < 2.00 W/m²·K) [27]. As a result, indoor temperatures become uncomfortable.In addition, the solar heat gain coefficient (SHGC) of 0.80 indicates a high level of solar energy transmission. This means that about 80% of incident solar radiation enters the building. Consequently, indoor overheating is significantly increased during summer, raising internal thermal loads. Moreover, the visible transmittance (T-Vis) of 0.80 improves natural daylighting. However, if not properly controlled, it can cause glare and additional heat gains. This negatively affects both visual and thermal comfort for occupants [28].

These characteristics are particularly problematic in a semi-arid climate, where high outdoor temperatures exacerbate the effects of these parameters. The southwest orientation of the living room exposes the glazing to prolonged direct sunlight, increasing internal solar gains and ambient temperature. The lack of shading devices and the low window value WWR of 11% limit the possibilities for passive solar control, thus worsening the situation. In addition, the glazing thickness of 4 mm, combined with the lack of thermal insulation in the block walls, contributes to a low overall thermal performance of the building.

The results presented in Fig. 12 clearly show the difference between the outdoor temperature and the ambient temperature of a space oriented North-East over a period of one year (8760 hours). The upper graph shows extreme variations in outdoor temperature, ranging from around −10°C in winter to over 40 °C in summer. In contrast, the lower graph reveals a much more stable ambient temperature, never falling below 16 °C and not exceeding 26 °C. The average ambient temperature is significantly higher than the average outdoor temperature. Compared to the Southwest orientation, the Northeast orientation is distinguished by less significant summer overheating, with a maximum temperature of 26 °C (against 28 °C for the Southwest), as it is in the shade during the hottest hours of the afternoon.

So, the thermal discomfort in the living-dining room results from a combination of factors related to glazing characteristics, building orientation, construction materials, and the lack of passive solar control strategies. An integrated approach, considering these parameters, is essential to improve the thermal comfort and energy efficiency of the building.

4.2. Optimization

To optimize the thermal performance of modeled residential buildings, a parametric approach combined with an optimization algorithm was implemented via Grasshopper’s Galapagos plugin (see Fig. 13). This tool uses an evolutionary algorithm that automatically explores a wide solution space by modifying design parameters in order to identify the configurations offering the best energy and thermal performance.

Thanks to this method, it was possible to test several variables simultaneously, such as the orientation, the size of the openings, or the insulation, and to achieve an optimal compromise between thermal comfort and energy efficiency. The use of Galapagos has thus accelerated the decision-making process and strengthened the robustness of the proposed solutions in the demanding context of the semi-arid climate. From our observations, it is evident that during the summer months, the southwest-facing façade experiences elevated temperatures, which adversely impacts the comfort of its occupants, in contrast to the northeast-facing side. Consequently, we will explore various solutions to alleviate the significant discomfort faced by its residents, particularly in the summer, by opting for 50% glass to achieve clearer results compared to the current situation of 11% and results presented in Table 2 and Table 3 below.

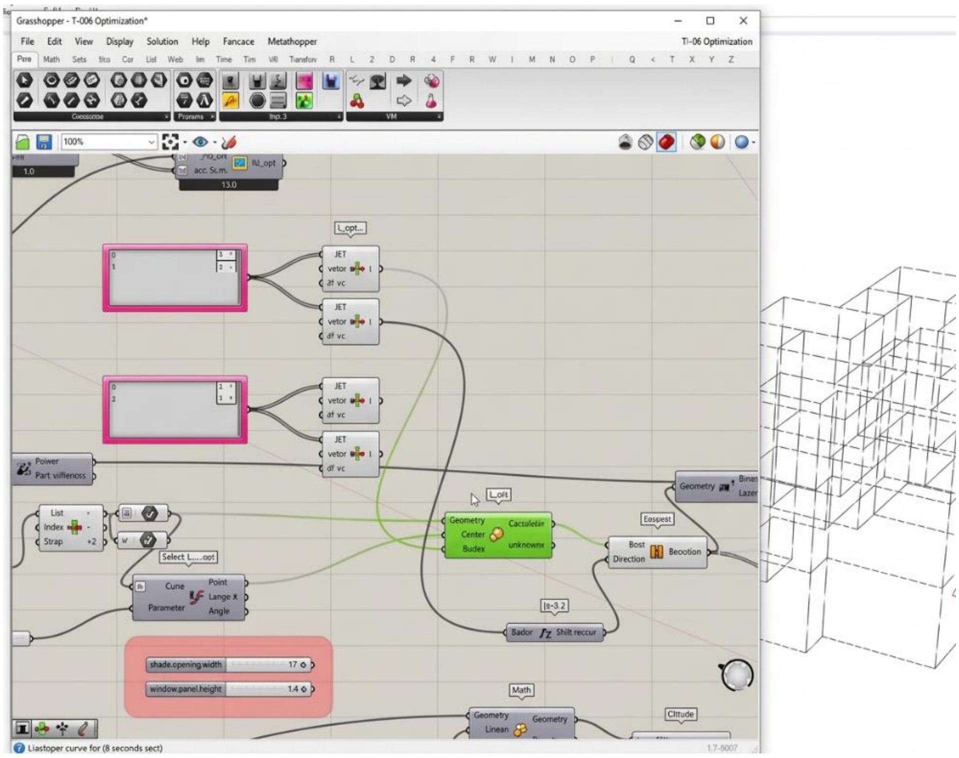

Fig. 13. Optimization process workflow using the Galapagos plugin. Source: own study

Table 2. passive thermal solutions for Southwest facade (WWR 50%). Source: own study

Orientation and ratio	South-west, 50%				
	Thickness	U-Value	SHGC	T-Vis	Hourly thermal comfort study
Choice 1: Simple glazing	4 mm	5.40	0.80	0.80	55.54%
Choice 2: Double glazing + low E + Argon gas	8 mm	1.20	0.50	0.50	61.50%
Choice 3: Double glazing + low E + Argon gas +horizontal shading device 90°	8 mm	1.20	0.50	0.50	75.50%
Choice 4: Triple glazing + low E + Argon gas	12 mm	0.70	0.40	0.40	64.50%
Choice 5: Triple glazing + low E (without gas)	12 mm	0.70	0.40	0.40	62.90%
Choice 6: Triple glazing + low E + Argon gas+ horizontal shading device 90°	12 mm	0.70	0.40	0.40	76.80%

Table 3. Thermal Comfort Variability Across Architectural Alternatives. Source: own study

Choices	Hourly Thermal Comfort	Δ vs Base (%)
Choice 1: Simple glazing	55.54%	–
Choice 2: Double glazing + low E + Argon gas	61.50%	+10.74%
Choice 3: Double glazing + low E + Argon gas + horizontal shading 90°	75.50%	+35.95%
Choice 4: Triple glazing + low E + Argon gas	64.50%	+16.14%
Choice 5: Triple glazing + low E (without gas)	62.90%	+13.23%
Choice 6: Triple glazing + low E + Argon gas + horizontal shading 90°	76.80%	+38.28%

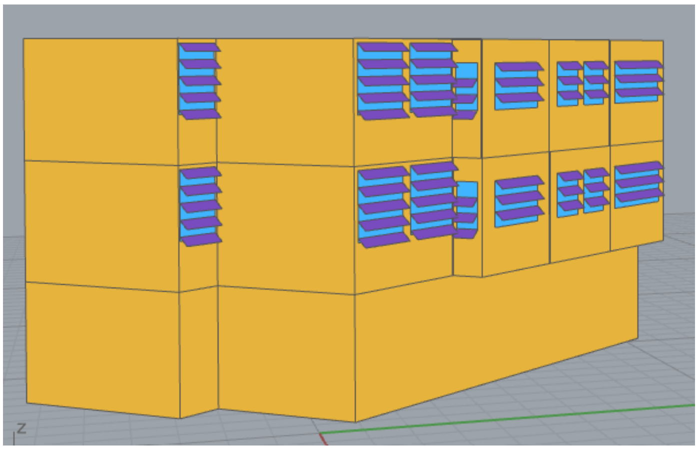

Fig. 14. 3D Visualization of horizontal shading devices applied to the facade. Source: own study

The configuration in Fig. 14 is the optimal thermal choice because it utilizes horizontal projections specifically engineered to intercept high-altitude summer solar radiation, thereby drastically reducing peak cooling loads and preventing interior overheating.

5. Conclusions and implications

5.1 Conclusions

This study underscores the building envelope as a critical thermal barrier where architectural decisions directly dictate energy performance [29-32], moving away from climate-indifferent designs that led to thermal discomfort [33-37]. Simulation results confirm that WWR, shading devices and glazing types are pivotal; specifically, simple glass degrades comfort, whereas Configuration 6 – combining triple glazing (Low-E/Argon) with horizontal shading – significantly increased comfort values from 55.54 to 77.00 (see Table 2 and Table 3). The research demonstrates that true efficiency requires a multi-layered, integrated approach rather than single-parameter optimization. By utilizing a parametric design approach, the study employs algorithm-based optimization to generate multi-objective solutions [38], effectively reducing internal thermal loads and fulfilling the fundamental goal of enhancing inhabitant well-being [39].

The original contribution of this research is to review a set of pivotal results drawn through parametric modeling, which reveal precise optimization solutions for the thermal performance of interfaces, as follows:

1. Combined strategies significantly improve thermal comfort. Scenarios integrating advanced Low-E double or triple glazing with horizontal shading devices demonstrated a marked improvement in comfort indicators. In the case of the southwest-facing façade, the comfort index increased from 55.54 (baseline) to above 77.00, representing a substantial gain. This result highlights the importance of a holistic approach, where shading, insulation, and glazing are considered together rather than individually.
2. The effect of non-glazing parameters is secondary but non-negligible While window-related variables had the most immediate effect, factors such as wall insulation, household size, internal heat gains (from lighting and occupancy), and floor level also contributed to variations in indoor thermal behavior. However, their relative influence was less pronounced compared to glazing and shading parameters.
3. Importance of integrated parametric optimization tools The Galapagos evolutionary solver enabled a multi-objective optimization of WWR, shading, and glazing, automating the identification of Choice 6 as the optimal solution. This computational approach achieved a 77.00% comfort rating, a significant improvement over the 55.54% baseline, providing a high-precision design tool for early-stage architectural decisions.
4. Primacy of external shading over glazing specification. The data demonstrates that in high-altitude semi-arid regions, the implementation of a 90° horizontal shading device is a far more decisive factor for thermal well-being than simply upgrading glazing units. While transitioning from Double Glazing (Choice 2) to Triple Glazing (Choice 4) in an unshaded state yielded only a marginal +3% improvement, the addition of shading to the standard double-glazed unit (Choice 3) resulted in a substantial +25.21% leap in comfort levels (rising from 61.50 % to 75.50%). This suggests that mitigating direct solar gain is thermally superior to relying solely on the conductive resistance of the glass.
5. The "law of diminishing returns" in high-performance glazing. A critical takeaway for cost-effective sustainable design is the negligible performance gap between shaded double glazing (Choice 3) and shaded triple glazing

(Choice 6). With HTCI results of 75.50% and 76.80% respectively, this mere 1.30% difference validates a practical roadmap for prioritizing passive architectural shading as a more economically viable alternative."

6. The Critical Role of Gas-Filled Cavities. The analysis highlights that the thermal integrity of a window system depends heavily on internal specifications, such as Argon gas fills. By comparing Choice 4 (Triple Glazing with Argon) and Choice 5 (Triple Glazing without Argon), a clear drop in the comfort index from 64.50% to 62.90% was observed. This 1.60% decrease underscores the necessity for precise technical specifications in building codes, as even high-tier materials underperform if their internal thermal breaks are compromised.
7. HTCI as a high-resolution decision-support tool. Finally, this study validates the Hourly Thermal Comfort Index (HTCI) as a highly sensitive metric for parametric optimization. Unlike traditional static metrics, HTCI successfully captured the nuanced fluctuations between the scenarios – from the 55.54% baseline in Choice 1 to the optimized 76.80% in Choice 6. This allowed for a clear differentiation between solutions that might appear identical under seasonal averages, establishing the index as a robust tool for evidence-based architectural design in the Algerian semi-arid context.
8. Generality of results for similar climates: Regions with similar climatic profiles can adopt these findings as a ready-to-use benchmark for optimizing thermal performance.

5.2. Recommendations

- We recommend adopting the principles derived from this study as a reliable tool to support decision-making in the initial design stages, to ensure maximum possible efficiency based on the demonstrated results.
- Prioritize shading: integrate 90° horizontal shading as a primary design requirement, as it provides the most significant boost to thermal well-being.
- Optimal configuration: Adopt Choice 3 (Double Glazing + Argon + Shading) as the most cost-effective solution, offering performance nearly identical to triple glazing (75.50% vs 76.80%).
- Technical integrity: ensure the use of Argon gas fills in all multi-pane windows to prevent measurable comfort loss (approx. 1.60%) observed in air-filled units.
- Dynamic Assessment: Shift local building codes from static U-value targets to dynamic indices like HTCI to better address extreme diurnal temperature variations.

5.3. Limitations

- Occupant behavior: The building was modeled based on fixed environmental parameters, excluding unpredictable daily habits like appliance use or door openings.
- Simulation-based constraints: As the results are based purely on numerical simulations, they represent theoretical performance under idealized conditions.
- Need for field validation: There is a critical need for in situ measurements and empirical field validation to confirm these findings against real-world data in the Batna region.
- Need for user feedback: It is essential to conduct occupant satisfaction surveys and usage questionnaires.

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