

Strategies for reducing overheating in residential buildings: a comparison of shading systems in a temperate climate – a case study of Poznań

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Abstract:

The rising demand for building cooling underscores the need to evaluate passive thermal strategies that limit solar heat gain while maintaining acceptable indoor conditions for occupants. This study assesses residential shading systems in a dual-chamber experiment in Poznań, Poland (August 2024), comparing fully and partially deployed external roller blinds, internal roller blinds, and fixed eaves. Fully lowered external blinds stabilised indoor temperatures around 26.5–27.0°C with about ±1.0°C spatial variation and produced the largest reductions, including notable attenuation of near-window temperature peaks. Half-lowered external blinds retained most of the thermal benefit relative to full closure while still admitting daylight, suggesting a practical compromise between cooling performance and perceived space quality. Internal “day/night” blinds provided moderate reductions compared to unshaded conditions but typically maintained indoor air about 1°C warmer than with external blinds, reflecting lower heat-gain mitigation. Fixed eaves sized to half the window height had minimal impact on average indoor temperature and were strongly constrained by solar geometry and orientation. Overall, the results establish comparative performance baselines for indoor air temperature and support layered, context-specific shading strategies deploying external blinds where peak mitigation is critical, partial deployment when some daylight admission is desired, and internal blinds for cost-effective flexibility in controlling solar gains.

Keywords:

sustainable building solutions, shading systems, energy efficiency, indoor air temperature, thermal comfort, operative temperature

1. Introduction

In the era of growing ecological awareness and intensified efforts towards sustainable development, particular attention is being paid to the energy efficiency of buildings [1,2]. One of the key aspects influencing energy consumption in residential and commercial buildings is the management of heat gains within spaces, particularly during the summer months [3]. Excessive sunlight can cause indoor spaces to overheat, increasing demand for air conditioning and other cooling systems and, in turn, higher energy consumption [3,4]. The need to reduce energy consumption and greenhouse gas emissions in buildings, as well as the requirement to counteract climate change, has contributed to the development of technological innovations in the window industry and the creation of more sustainable and energy-efficient products [1,5,6].

In modern residential architecture, windows and glass surfaces play a key role. They are not only aesthetic elements of the structure but also serve a functional purpose, providing access to natural light, which is essential for the health and comfort of the inhabitants. However, these benefits are also associated with certain challenges. One of the most significant issues is excessive heating of indoor spaces during the summer. Large glass surfaces, especially those facing south or west, can lead to substantial heat gain that, on hot days, can cause indoor spaces to overheat. This effect is particularly noticeable in buildings with modern architecture, where large areas of glazing predominate. To address overheating, various technological and architectural solutions are employed. Among these are windows with enhanced thermal insulation, sun protection glazing, and shading

systems such as blinds, shutters, or awnings. Another solution is the use of intelligent energy management systems that automatically regulate indoor temperatures by controlling air conditioning and window shading. Studies, such as those conducted by Lu, Li and Zhao [7,8] and Stegou-Sagia et al. [9], confirm that different types of glass and glazing have a significant impact on energy consumption in buildings. Research by Palmero-Marrero and Oliveira [10] as well as Tzempelikos and Athienitis [11,12] confirms that the design and control of shading effectively reduce the need for cooling and lighting, resulting in energy savings.

Various strategies can be applied to reduce excessive heating in indoor spaces, including architectural, natural, and artificial solutions. The first of these, such as overhangs above windows, play a key role in controlling overheating. Designing overhangs with the appropriate width and angle is crucial for protecting interiors from excessive solar exposure during the summer months. The overhang width should be adjusted to the sun's height at different times of year to effectively block solar radiation during peak sunlight hours while still allowing access to natural light in winter. Optimising these parameters helps reduce heat gains and improve energy efficiency in buildings. Additionally, the appropriate orientation of the building and the placement of windows in relation to the cardinal directions help minimise overheating. Limiting the number of windows on the east and west façades can reduce the impact of intense sunlight during the morning and afternoon hours, particularly in hot climates [13]. Numerous studies have demonstrated that natural vegetation positively impacts temperature reduction within buildings by employing various greening systems across Europe.

Research on vertical green walls has revealed significant thermal benefits: Raji et al. [14] conducted a comprehensive literature review examining how different greening systems-including green façades, living walls, and green roofs-contribute to building energy efficiency by reducing heat transfer through building envelopes and decreasing cooling loads. Perini et al.'s [15] field measurements demonstrated that vertical greening systems create protective air layers within foliage that reduce wind velocity impacts on building surfaces, improving thermal resistance by $0.09 \text{ m}^2\cdot\text{K}\cdot\text{W}^{-1}$ and resulting in measurable temperature reductions of $2\text{--}6^\circ\text{C}$ on vegetated walls compared to bare walls. Studies on green roofs in Mediterranean and Continental European climates have similarly shown substantial energy-saving potential: research of Jawdat Goussous documented [16] total energy savings up to 17% from green roof implementation, while Qadourah's evaluation [17] in Mediterranean climates confirmed that green roofs serve as significant thermal insulation layers that substantially reduce energy consumption through passive cooling mechanisms. In terms of artificial shading, the role of blinds and shutters is crucial in heat management. Studies by Tzempelikos [11] and Al-Tamimi and Fadzil [18] have demonstrated that the use of both internal and external blinds and shutters has a significant impact on controlling overheating in spaces. Research specifically comparing these approaches found that external blinds effectively block solar radiation before it reaches the glass, thereby reducing heat gain and lowering internal temperatures. Athienitis [12] demonstrated that shading design and control directly influence building cooling and lighting demand, establishing the relationship between shading strategies and HVAC system energy consumption.

The impact of shading devices, whether placed externally or internally, is complex and multifaceted. These devices primarily serve functions such as protection against excessive solar heat gain, regulation and modelling of natural light, and minimisation of both direct and reflected glare. These functions significantly influence energy consumption by HVAC systems and electrical lighting, as well as thermal and visual comfort conditions inside the building. However, maximum protection from solar heat gains can lead to a significant reduction in daylight intensity inside, which can negatively affect visual comfort or increase energy consumption for additional electrical lighting.

The effectiveness of blinds depends on many factors, including functional adequacy of the shading device, type of solution used, façade orientation, ease of operation, and control type [1,19-21]. Hu and Olbina [19] developed illuminance-based slat angle selection models for automated control, while Kim et al. [20] conducted experimental studies on the environmental performance of automated blinds in summer conditions. Vine et al. [21] conducted pilot studies examining office workers' responses to automated Venetian blind and electric lighting systems, revealing important insights into user acceptance.

Research by Palmero and Oliveira [10], Athienitis [12], Al-Tamimi and Fadzil [11], and others [18] has shown that the use of window coverings, such as external blinds, can lead to significant energy savings in both cooling and lighting. Alkhatib et al. [22] compared control parameters for roller blinds, while Fitton et al. examined thermal performance of window coverings in whole-house test facilities with single-glazed sash windows. Hu et al. [19] investigated the influence of roller-blind shading strategies on west- and south-facing buildings, and Kim et al. [20] demonstrated the comparative advantage of exterior shading devices for thermal performance in residential buildings. Kim et al. [23] studied the variation in heating and cooling loads with

horizontal shading and venetian blind use in Korean office buildings.

Studies indicate that the main factors influencing users' actions regarding blind operation include incoming solar radiation, light intensity on the working surface, luminance, glare indices, and user behaviour dynamics, including arrival time, length of stay, and departure time from the space. Automated external blinds, particularly in office buildings, have the potential to significantly reduce energy demand related to cooling and lighting, thereby improving energy efficiency. Many previous studies have focused on modern and often costly automation solutions related to external blinds, especially in office spaces and work environments. Kapsis and Athienitis [24] conducted a critical review of manually-operated window shade patterns in office buildings, revealing important behavioral patterns.

In office buildings in cold regions, energy consumption is mainly associated with cooling spaces. Approximately 50% of the cooling system load comes from external building envelopes, with about half of that resulting from solar radiation [25]. Therefore, proper regulation of solar radiation through external shading devices can significantly reduce cooling demand [5]. However, it is equally important to examine these issues in the context of residential environments, where thermal comfort directly impacts the quality of life for inhabitants. Starczyk [26] analysed the parameters affecting cooling demand in collective residential buildings, while Al-Tamimi and Fadzil [18] examined the potential of shading devices for temperature reduction in high-rise residential buildings in tropical climates. Faggal et al. [27] investigated the effects of different window glazing types on energy consumption in hot-arid climates. Automated technologies, although effective, require advanced management systems and significant financial investments, which may limit their widespread use, particularly in residential construction.

Recent studies have highlighted that thermal comfort challenges in residential buildings are not limited to extreme climates. In temperate climates such as Poland, where continental influences combine with maritime weather patterns, seasonal temperature variations create distinct challenges for building envelope performance. Research by Ferdyn-Grygierek et al. [28] on the effects of climate change on thermal comfort in Poland demonstrates that summer overheating has become an increasingly critical issue, even in moderate climates. The study found that while winter heating remains a significant component of Poland's annual energy balance, the summer cooling demand is rising due to climate intensification and the widespread adoption of highly glazed modern architecture.

According to Chwieduk [29], summer direct solar radiation comprises 56% of total irradiance during the peak cooling season (July–August), whereas winter radiation (November–January) is dominated by diffuse components, which account for 65–71% of total irradiance. This seasonal asymmetry has critical implications for glazing design. In a scenario with substantially enlarged south-facing windows (increased from $1\times 1 \text{ m}^2$ to $2\times 2 \text{ m}^2$), the annual cooling demand rises dramatically, accounting for approximately 68% of the climate control energy requirement, compared to 32% for heating. This dramatic shift demonstrates how summer solar gains through enlarged glazing substantially exceed the proportional benefit to winter heating, fundamentally altering the annual energy balance toward summer cooling dominance – a critical consideration for contemporary residential design in Poland.

The aim of this article is to analyse and assess the differences between the use of simple, more cost-effective solutions, such as traditional internal and external blinds, and natural window

shading in a temperate climate, using Poland as a case study. The research focuses on understanding the effectiveness of these simpler methods for heat gain control, which is crucial from both individual users' perspectives and the perspective of sustainable development in residential construction. By comparing the results obtained for different types of shading, the article aims to provide insight into the effectiveness of cheaper and more accessible solutions in minimising overheating of indoor spaces, which can serve as a valuable alternative to more complex and costly automation systems.

2. Materials and methods

The experiment was conducted in Poznań, Poland (52°48'N, 16°47'E), in a temperate climate with strong summer insolation on southeast exposures. Two identical residential rooms (4.10 m × 3.00 m × 2.84 m) were used in a side-by-side configuration (Fig. 1 and Fig. 2). Each room featured a 2.39 m² window (1.64 m × 1.43 m) with a graphite PVC frame and triple, double cavity

glazing with low emissivity coatings ($U = 0.87 \text{ W/m}^2\text{K}$). For this performance class, representative optical properties were adopted: solar heat gain coefficient $g \approx 0.50$ and visible transmittance $T_v \approx 0.70$, ensuring adequate daylighting with moderated solar gains. Each room included three standardised measurement locations: Point 1 (window zone), adjacent to glazing within the direct solar exposure footprint; Point 2 (middle zone), approximately 2 m from the window; and Point 3 (far wall zone), approximately 4 m from the glazing on the interior opposite wall (Fig. 1).

Mechanical ventilation with heat recovery (75% and 0.5 ACH) operated continuously in summer bypass mode during measurements to prevent heat recovery from influencing indoor temperatures. No active cooling was used. This configuration isolates the effect of solar control on operative temperature by minimising HVAC-related confounders and maintaining consistent boundary conditions across variants.

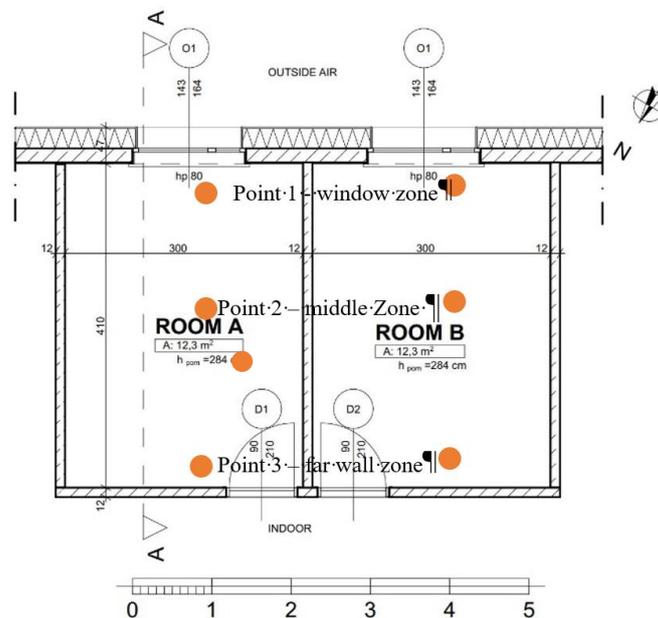


Fig. 1. Test rooms and three standardised measurement locations

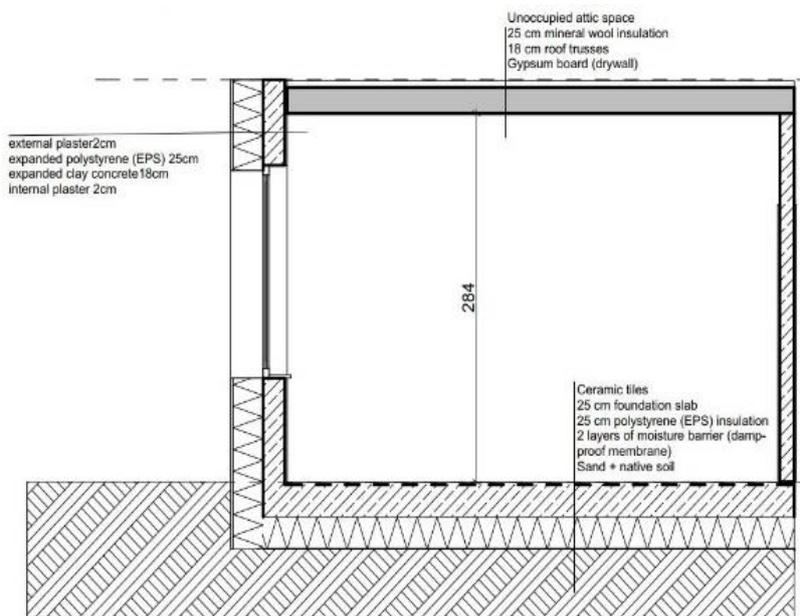
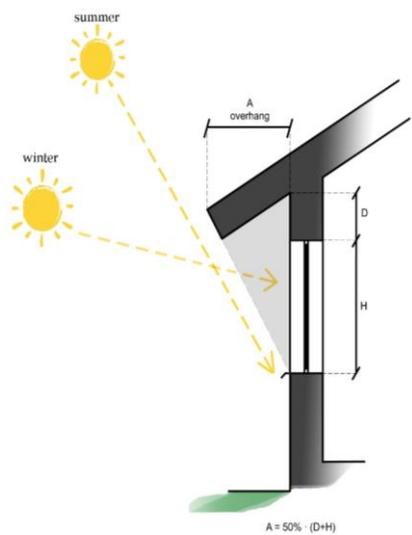


Fig. 2. Cross-section of the test rooms

Three shading modalities were evaluated. External roller blinds (extruded aluminum slats, dark anodized finish) were characterized by typical solar properties: solar transmittance $T_s \approx 0.10$ (allowing only 10% of incident solar radiation to pass through), solar reflectance $R_s \approx 0.30$ (reflecting 30% back toward the exterior), and solar absorptance $A_s \approx 0.80$ (absorbing 80% of incident energy, which is then dissipated to the outdoor environment through convection and radiation). Internal “day/night” roller blinds, representative of residential fabrics, had $T_s \approx 0.45$, $R_s \approx 0.55$, and $A_s \approx 0.25$. A fixed external overhang (canopy) was sized to 50% of window height; its seasonal shielding potential was defined by solar altitude geometry to illustrate time-dependent effectiveness (Fig. 3). Thermal properties for each shading configuration were selected as representative average values available from commercial manufacturers: external blinds represent the high-performance standard from European residential blind producers, internal blinds represent typical semi-transparent fabrics available in the Polish market, and fixed overhangs were sized according to standard passive design methodology for temperate climates.



H	D	A
220	30	125
200	30	115
160	30	95
150	30	90

Fig. 3. Overhang projection scheme depending on the season

Measurements were performed in August 2024 to capture peak summer loads. One room served as a contemporaneous

control without shading (Variant 1). The second room received, in sequence under comparable diurnal conditions (Fig. 4): fully closed external blinds (Variant 2), half-closed external blinds at approximately 50% aperture (Variant 3), internal blinds (two standard fabrics (day/night); Variants 4a and 4b), and a fixed overhang (Variant 5). Sequencing and scheduling were designed to minimise biases from transient weather shifts; each configuration was operated long enough to reach quasi-steady indoor conditions relative to outdoor forcing.

The study measured operative temperature, defined as the weighted average of air temperature and mean radiant temperature, which is the appropriate metric for assessing thermal comfort. This parameter accounts for both convective and radiative heat transfer, affecting occupant comfort, unlike air temperature alone, which would provide an incomplete representation of thermal conditions.

Operative temperature was measured using the Parkside climate data logger without solar radiation shielding, allowing the sensor's plastic enclosure to function as a radiant receptor that captures both air temperature and absorbed solar radiation, thereby providing a realistic measure of the operative temperature experienced by occupants. Although this approach differs from the calibrated black-globe thermometer method specified in ISO 7726, the measurement is valid for comparative thermal performance assessment across the tested shading configurations, with the caveat that the Parkside sensor's consumer-grade construction (Sensirion SHT series chip) provides indicative rather than metrologically-certified operative temperature data.

The temperature in both rooms was monitored in real time, recording data every 60 seconds across various sunlight conditions. The experiment was conducted in August 2024, which enabled precise observation of differences in the heating dynamics of the space depending on the shading system applied. Measurements were taken under varying levels of sunlight and at various times of day, enabling an assessment of the system's efficiency under changing climatic conditions typical of the Poznań region. During the experiment, Outdoor operative temperature was measured using the same unshielded Parkside climate data logger positioned at standard meteorological height (1.5 m above ground). The sensor was deliberately not shielded from solar radiation, ensuring that all temperature values reported in this study – both indoor and outdoor – represent operative temperature and thus maintain methodological consistency and comparability across measurements. This unshielded configuration ensures that the measured outdoor operative temperature reflects the actual thermal environment experienced by building occupants and solar-exposed surfaces, incorporating both the ambient air temperature and the radiative heating effects from direct solar exposure.

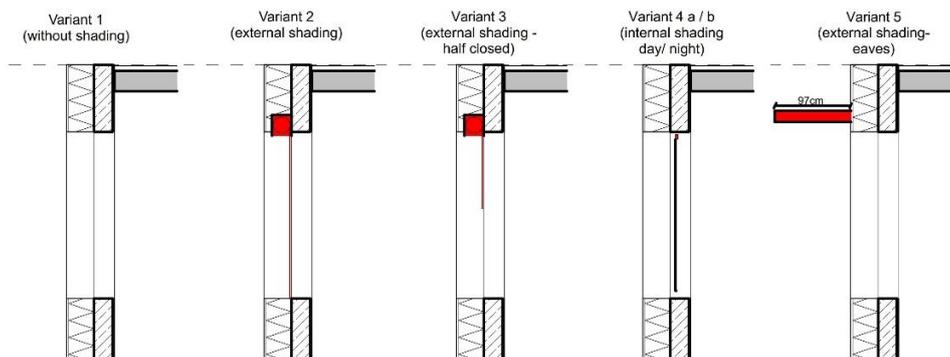


Fig. 4. Analyzed variants

All temperature values reported in the Results section represent operative temperature, incorporating both air temperature and solar radiation effects on the unshielded sensor.

3. Results

This section presents the thermal performance outcomes for each shading configuration tested under controlled environmental conditions. The analyses focus on operative temperature behaviour, spatial temperature differentials, and the extent of solar radiation attenuation achieved by various shading systems. Results are organised by configuration type, with comparative observations summarising performance trends.

Figure 5 presents hourly temperature measurements across four monitoring points in a control room throughout a 24-hour period. Temperature conditions at the three measurement locations are as follows.

The window zone experiences the most dramatic temperature fluctuations, starting at approximately 27°C in the

morning and rising sharply to a peak of about 41.5°C around 11:50 AM due to direct solar exposure. The temperature then gradually decreases throughout the afternoon and evening, dropping to around 27°C by the end of the day. This point shows the most significant temperature variation, reflecting the impact of solar radiation through the window. The room average temperature remains relatively stable throughout the day, with fluctuations only between 27.5°C and 28°C. This point demonstrates consistent temperature performance with minimal variation, suggesting effective temperature stabilisation across the main room space despite the significant temperature changes occurring at the window zone. The far wall zone represents the most stable monitoring location, with temperatures remaining nearly constant around 26.5-27°C throughout the entire 24-hour period. This area, being furthest from solar influence, shows virtually no temperature fluctuation, providing a baseline reference for the room's passive thermal conditions.

Table 1. Basic parameters

Type of assumption	Project assumption
Location	Poznań, Poland, 52°48'N, 16°47'E
Orientation relative to the cardinal directions	Southeast orientation
Ventilation	Mechanical ventilation with heat recovery Efficiency=75%
Function of the room	Residential room
Calculation period	August 2024
Frequency of recording results	Every 60s

Table 2. Sensor' specification (Parkside climate data logger)

Type of sensor	Measurement range	Scale	Accuracy
Operative temperature	-30 °C - 70 °C	0.01 °C	± 0,5°C



Fig. 5. Temperature distribution of the test room – Variant 1

Variant 1 and 2: Fully-Lowered External Blinds

The unshaded control room (Variant 1) exhibited pronounced temperature variations tracking external solar exposure (Fig. 6a, 6b). During the morning hours, as solar radiation intensity increased, indoor operative temperature rose

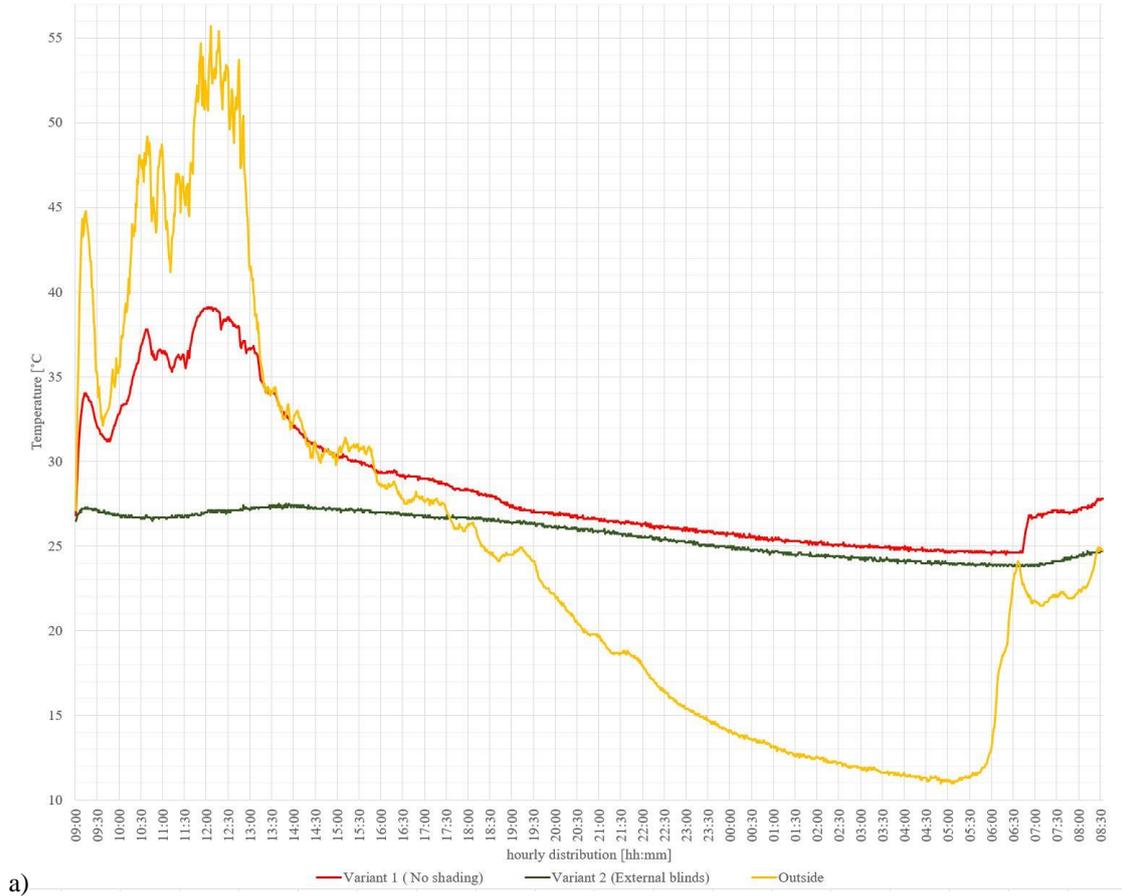
rapidly, closely following the external operative temperature trajectory with a characteristic lag of approximately 10°C. At peak solar exposure, when the outdoor sensor recorded 56°C, the indoor operative temperature at Measurement Point 1 (window zone) reached 39°C. Following the solar noon period and as the

sun's trajectory moved past the southeast-facing window line after 2:30 PM, indoor temperatures began to decline. By evening hours (approximately 7:00 PM), temperatures stabilised, but the unshaded room retained a residual temperature elevation of approximately 1°C above the shaded variants, reflecting the accumulated thermal mass heating during daylight exposure.

The external blind-equipped room (Variant 2) maintained exceptional thermal stability throughout the measurement period.

The operative temperature remained consistently stable at approximately 27°C, with fluctuations limited to ±1°C, even when the outdoor shielded sensor recorded operative temperatures reaching 55-56°C. This 28-29°C temperature difference between the shielded outdoor sensor and the room interior demonstrates the profound thermal insulation effect of the external blind system.

Daily temperature distribution in room A, date 04.08.2024 Poznań, Poland



Daily temperature distribution in room A, date 05.08.2024 Poznań, Poland

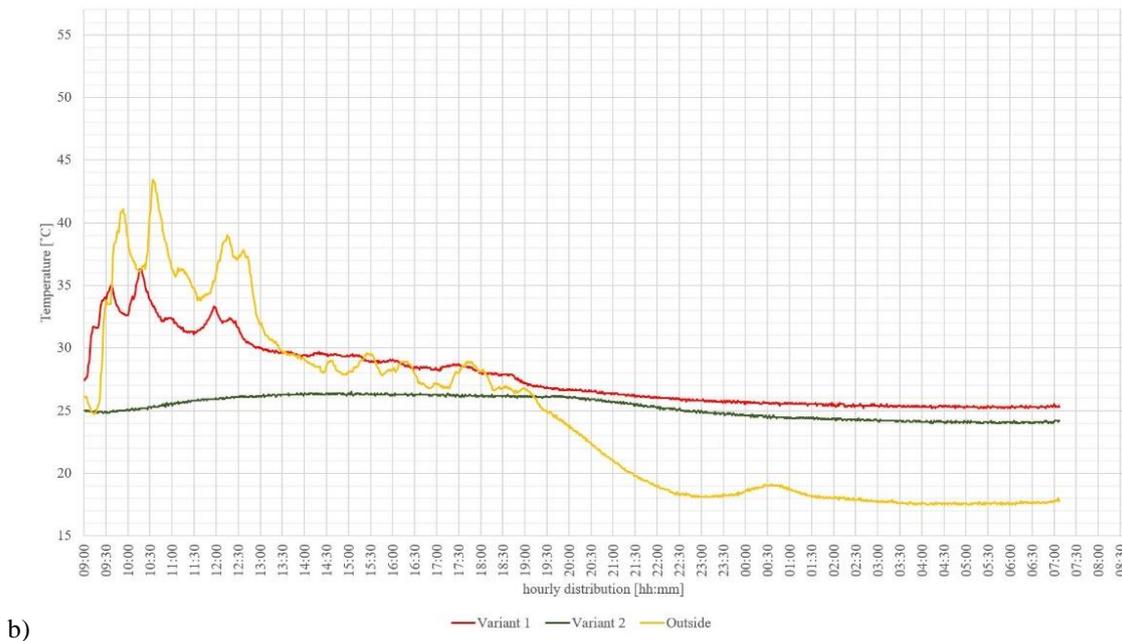


Fig. 6. Daily temperature distribution in test rooms a) test 1 4.08.2024 b) test 2 5.08.2024

The maximum temperature differential between any two measurement locations was 0.4°C, indicating complete elimination of the thermal stratification observed in the unshaded configuration. This near-perfect spatial uniformity indicates that the external blinds successfully suppressed solar radiation penetration to the extent that mean radiant temperature variations became negligible throughout the room, resulting in homogeneous operative temperature conditions. The thermal environment near the window was effectively decoupled from external solar conditions through the external blind barrier.

The comparison between Variants 1 and 2 (Fig. 7) underscores that the external blinds selectively mitigated solar radiation-driven heating. The most significant reduction occurred in the Window zone, confirming that the shading mechanism primarily influences localised solar load rather than producing a generalised cooling effect within the room.

Variant 3: Half-Lowered External Blinds

The half-lowered external blind configuration (blinds deployed to 50% closure, permitting approximately 50% of the

window area to remain exposed to direct sunlight) represented a compromise between solar heat rejection and natural light preservation. Measurement results demonstrated intermediate thermal performance between the fully-lowered and unshaded configurations (Fig. 8).

The maximum temperature differential within the half-lowered blind configuration was 5.7°C (window zone to far wall zone), representing a 61% reduction in spatial temperature variation compared to the fully unshaded configuration (14.5°C differential). Window zone temperature was reduced by 7.5°C compared to the unshaded configuration, while middle zone and far wall zone temperatures remained essentially unchanged from unshaded levels.

These results demonstrate that partial external blind deployment provides substantial localised thermal benefit in solar-exposed zones while maintaining natural light access – a practical compromise for applications where daylighting is a design priority, though with reduced maximum thermal benefit compared to full blind deployment.



Fig. 7. Hourly temperature distribution in Variant 1 and Variant 2

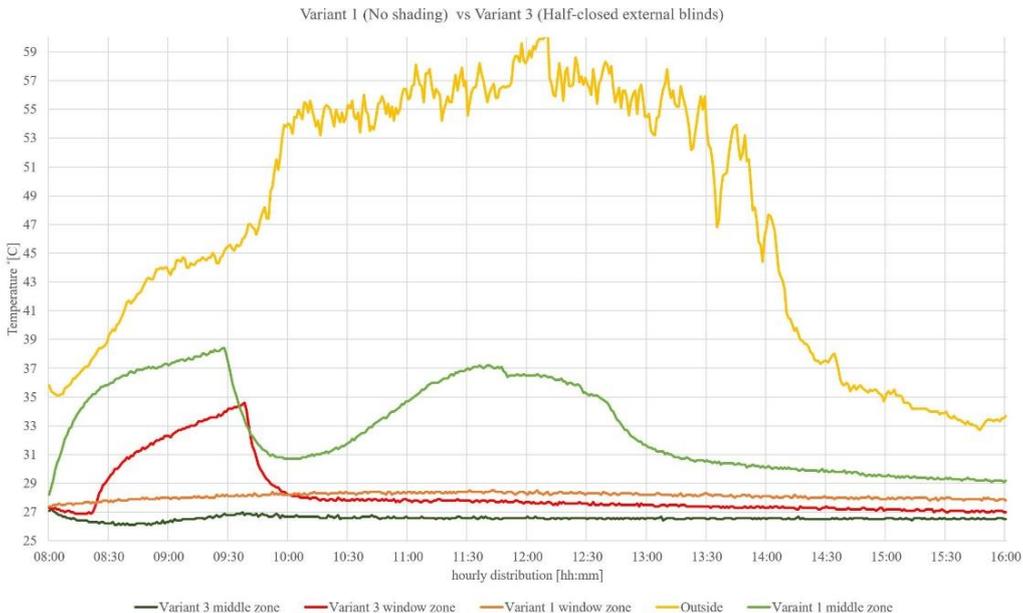


Fig. 8. Hourly temperature distribution in Variant 1 and Variant 3

Variant 4: Internal "Day-Night" Roller Blinds

The unshaded window (Variant 1 – No Shading) configuration serves as the control baseline, with no roller shades deployed. This results in maximum solar exposure at the window zone, reaching approximately 33°C in the morning and peaking at 41.5°C by late morning. The unprotected window demonstrates extreme thermal conditions at the perimeter, while the room average remains relatively stable at approximately 27.5-28°C through natural convection and thermal mass distribution.

During daytime function, internal roller shades with 50% semi-transparent fabric are deployed in Variant 4a, allowing partial solar radiation to pass through while filtering approximately half of the incoming heat and light. This configuration substantially reduces the Window zone temperature compared to the baseline, maintaining approximately 31°C at its peak in contrast to the 41.5°C observed without shades. The semi-transparent shading provides

significant solar gain reduction while preserving daylighting penetration, and the room's middle zone remains stable at approximately 27-27.5°C.

With internal roller shades fully closed with night function in Variant 4b, the Window zone temperature is further reduced to approximately 30.5°C, indicating an additional 1°C improvement over the daytime shaded configuration. The complete opaque closure creates an insulating air gap that eliminates both convective heat transfer and radiative effects more effectively than the semi-transparent daytime fabric. The room temperature in the middle zone remains nearly identical at around 26.5-27°C, while the window zone is protected from thermal extremes throughout the nighttime period.

The day/night roller shade system provides exceptional thermal protection compared to the unshaded baseline: Variant 4a (day mode) reduces peak window temperatures by approximately 10.5°C, while Variant 4b (night mode) achieves an additional 11°C reduction from the baseline.

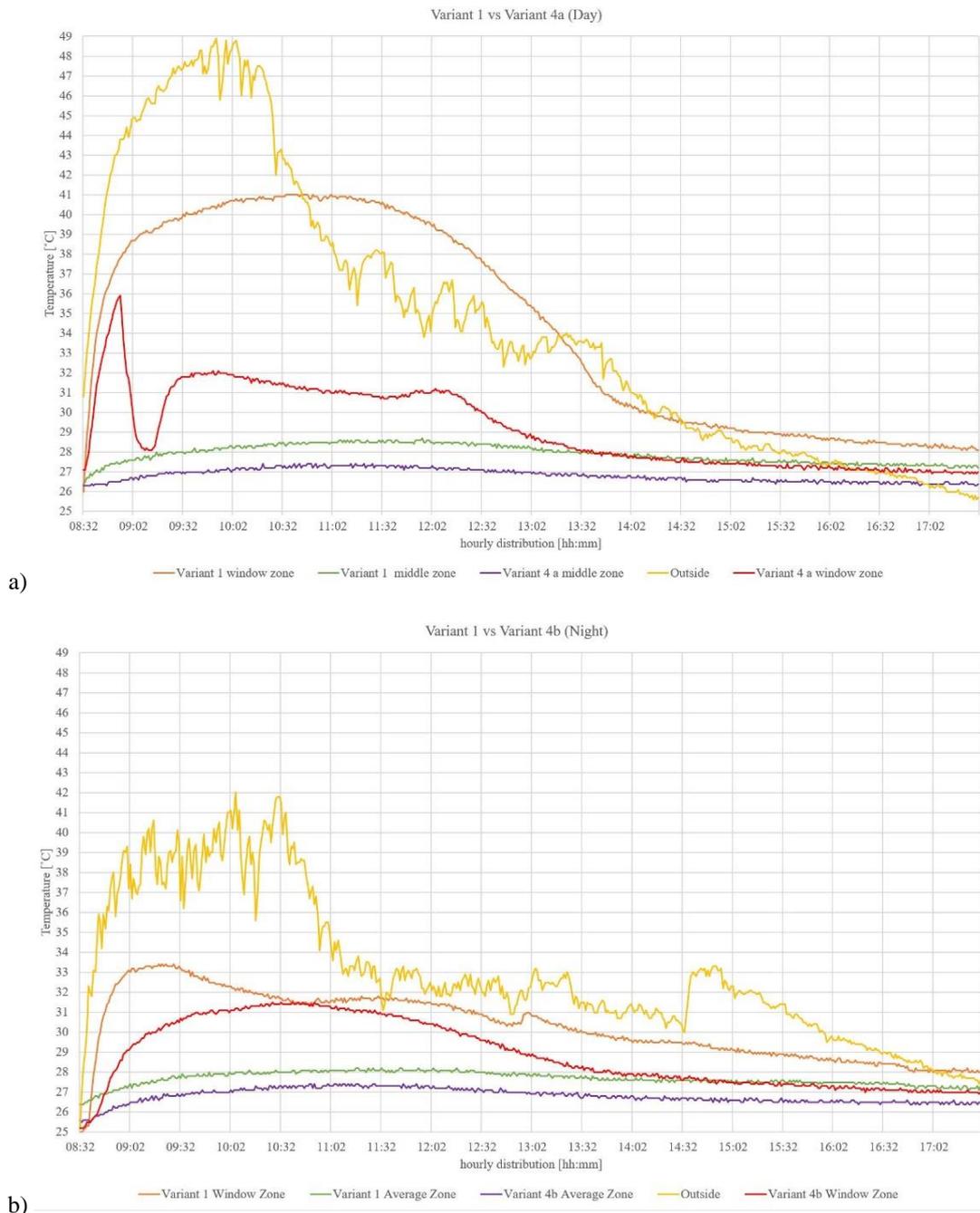


Fig. 9. Temperature distribution of the test rooms with internal blinds a) day mode b) night mode

Variant 5: Fixed External Canopy/Eaves System

The fixed external canopy was designed according to standard eave design methodology, with overhang depth set at 50% of window height. For the test room window (1.64 m height), the calculated overhang was approximately 0.97 m, falling within the typical range of 90-125 cm for residential applications.

The maximum temperature differential was 11.2°C (window zone to far wall zone), representing a 23% reduction in spatial temperature variation compared to the unshaded configuration (Fig. 10). Window zone temperature was reduced by only 2.2°C compared to unshaded conditions, indicating that the fixed canopy provided minimal solar radiation blockage during the August measurement period (mid-summer conditions). The timing of canopy effectiveness is restricted to specific solar angles; during mid-summer, when the sun achieves a high trajectory angle, the southeast-facing canopy provided negligible

protection. This result demonstrates that fixed eaves are most appropriate as supplementary seasonal features in climates with pronounced seasonal sun angle variations, or in combination with operational shading systems for year-round effectiveness.

Complete external blind closure achieved the greatest thermal mitigation, minimizing solar heat gains to near-zero levels (Fig. 11). However, this thermal optimization came at the cost of full daylight obstruction, requiring artificial lighting and potentially diminishing visual comfort and psychological well-being.

Partial external blind closure at 50% aperture represented a more balanced solution. It achieved between 80 and 90 percent of full-shading thermal performance while maintaining substantial daylight penetration. This configuration preserved occupant comfort and lighting autonomy while maintaining stable thermal conditions close to those achieved by full closure.

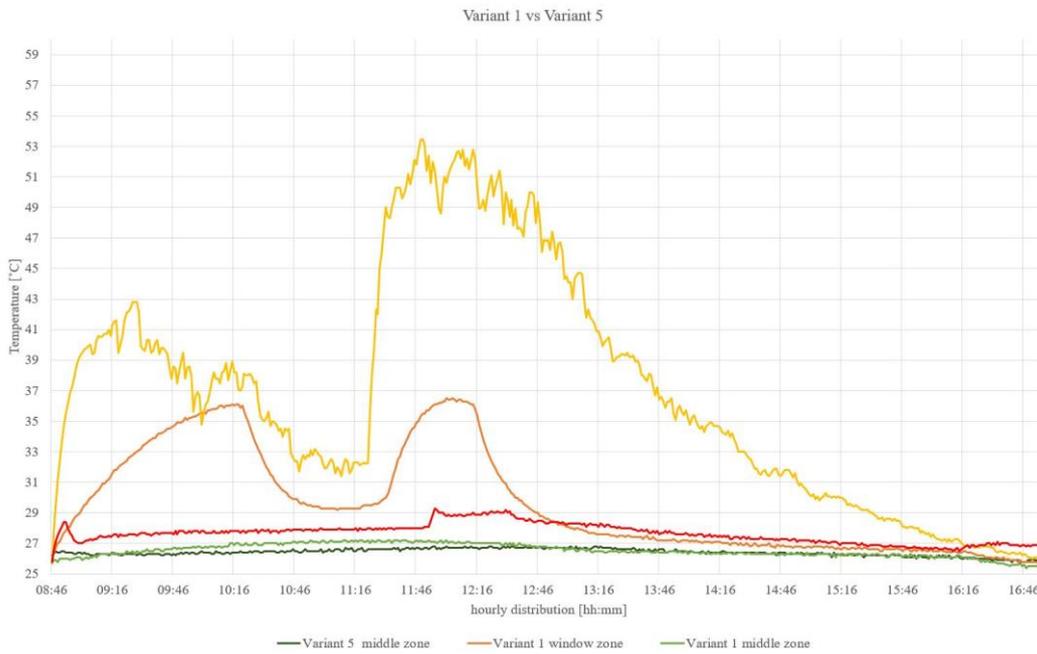


Fig. 10. Temperature distribution of the Variant 1 and Variant 5



Fig. 11. Temperature difference between variants

Internal blind systems exhibited lower but consistent thermal effectiveness, maintaining indoor operative temperatures approximately 1°C higher than corresponding external-blind configurations. Fixed architectural shading elements – such as canopies – proved least effective, reducing temperature by only about 0.5°C relative to unshaded conditions. Their geometric rigidity prevents adaptation to variable solar altitude angles throughout daily and seasonal cycles.

A comparative analysis under extreme ambient conditions (30°C external air temperature, 2:00–3:00 PM) further quantified the relative performance margins (Fig. 12). Fully lowered external blinds produced the lowest indoor temperature (1.4°C reduction versus baseline), followed closely by partial external blinds (1.3°C reduction) and internal blinds (1.2°C reduction). Canopy systems provided negligible benefit, with only a 0.1°C differential. These results indicate that as external thermal load intensifies, shading performance differentials compress, reducing the effective thermal advantage of dynamic systems.

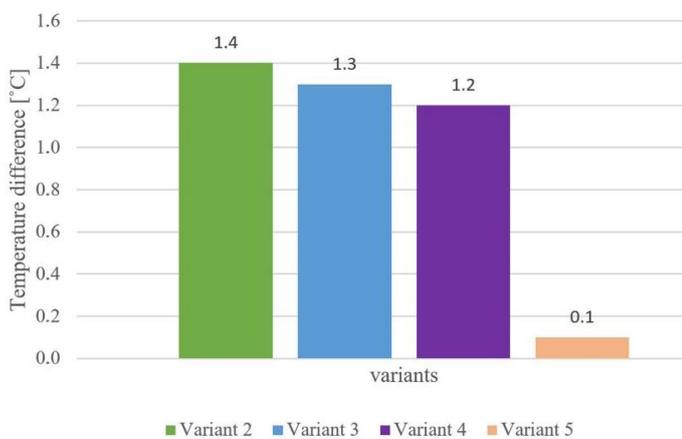


Fig. 12. Difference in temperature between test rooms in external air temperature 30°C

4. Discussion

The experimental findings clearly demonstrate the decisive role of shading configuration in moderating indoor thermal conditions under high-solar-load conditions. The results support the general hypothesis that external, dynamic shading systems are significantly more effective at controlling indoor operative temperature than fixed or internally mounted devices.

The analysis of shading system effectiveness during peak solar radiation hours (10:00 AM – 2:00 PM) reveals critical insights into the transient thermal behaviour of indoor environments. This temporal window represents the maximum heat gain potential and provides the most rigorous assessment of thermal control mechanisms. The differentiated performance of shading typologies during this period underscores the importance of temporal considerations in thermal comfort evaluation.

The findings demonstrate a pronounced trade-off between thermal performance and daylighting quality, with profound implications for holistic building performance. External blinds exhibit superior thermal mitigation capacity, reducing solar heat gain more substantially than their internal counterparts. However, this enhanced thermal control is achieved at a significant cost to natural illumination access and, consequently, occupant visual comfort and circadian rhythm regulation.

Conversely, internal blinds present a more nuanced thermal-visual equilibrium. While demonstrating marginally lower temperature reduction efficacy, internal blind systems maintain superior daylighting availability by permitting controlled solar

transmittance. This configuration enables natural illumination while mitigating overheating risks from direct solar exposure. The capacity to simultaneously moderate thermal loads and preserve daylight access renders internal blinds a pragmatic compromise, particularly in occupational settings where both thermal comfort and visual well-being constitute essential performance criteria.

5. Conclusions

This study confirms that shading system type, placement, and operational mode have a measurable, direct influence on indoor thermal conditions under high-solar-radiation exposure. Half-lowered external blinds (50% closure) retained 80–90% of maximum thermal performance while maintaining substantial daylight access, representing a practical compromise between thermal control and visual comfort. External blinds achieve superior thermal mitigation, reducing indoor operative temperature to approximately 27°C even under peak summer conditions (outdoor ~56°C), while internal blinds maintained temperatures approximately 1°C warmer. The study demonstrates a pronounced trade-off between thermal performance and daylighting quality: external blinds restrict daylight access but achieve superior cooling; internal blinds provide lower thermal effectiveness but maintain superior daylighting availability. Fixed architectural elements (eaves) proved least effective, reducing temperature by only ~0.5°C, and are most appropriate as supplementary elements combined with operational shading systems. Despite superior thermal performance, external blinds entail higher material and operational costs and restrict user daylighting control. Internal blinds, though less efficient, offer greater flexibility while being economically accessible, making them particularly suited for multipurpose spaces with variable occupancy. Optimal thermal and energy performance requires integrated, layered use of complementary shading systems: permanent fixed elements providing baseline solar protection, internal blinds enabling fine-tuned daylighting and thermal regulation at minimal cost, and selective external blinds on critical façades maximising solar heat gain reduction where thermal comfort is prioritised.

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