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SOLAR PROTECTION IN MEDITERRANEAN BUILDINGS, MADRID, SPAIN: DESIGNING WITH ALGORITHMS AND ARTIFICIAL INTELLIGENCE

PROTECCIÓN SOLAR EN EDIFICACIONES MEDITERRÁNEAS, MADRID, ESPAÑA: DISEÑO CON ALGORITMOS E INTELIGENCIA ARTIFICIAL

PROTEÇÃO SOLAR EM EDIFICAÇÕES MEDITERRÂNEAS, MADRI, ESPANHA: PROJETO COM ALGORITMOS E INTELIGÊNCIA ARTIFICIAL

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RESUMEN

Este artículo analiza la integración de tecnologías digitales y algoritmos paramétricos en el diseño de sistemas de protección solar para edificaciones en contextos mediterráneos, como Madrid, España. Se utilizó un modelo base representativo de un edificio de escala media, se evaluaron cuatro configuraciones de protección solar mediante simulaciones avanzadas que incorporaron datos climáticos locales y trayectorias solares anuales. Las estrategias exploradas incluyen parasoles horizontales, inclinados, un diseño biomimético Voronoi y un modelo compuesto que combina estos enfoques. Los hallazgos destacan cómo la inteligencia artificial y los algoritmos computacionales permiten optimizar el rendimiento energético y el confort térmico, al tiempo que redefinen las posibilidades estéticas y sostenibles en la arquitectura contemporánea. Este enfoque propone un marco innovador para enfrentar los desafíos climáticos, que evidencia el potencial de las herramientas digitales en la transformación del diseño arquitectónico hacia un paradigma más resiliente y adaptativo.

Palabras clave
diseño paramétrico, inteligencia artificial, sostenibilidad arquitectónica, protección solar

ABSTRACT

This article examines the integration of digital technologies and parametric algorithms when designing solar protection systems for buildings in Mediterranean contexts, such as Madrid. Four solar protection configurations were evaluated through advanced simulations using a base model representative of a medium-scale building, incorporating local climatic data and annual solar trajectories. The strategies examined include horizontal louvers, inclined shading devices, a biomimetic Voronoi design, and a composite model that combines these approaches. The findings highlight how artificial intelligence and computational algorithms optimize energy performance and thermal comfort while redefining aesthetic and sustainable possibilities in contemporary architecture. This approach proposes an innovative framework to address climate challenges, showcasing the potential of digital tools to transform architectural design into a more resilient and adaptive paradigm.

Keywords
parametric design, artificial intelligence, architectural sustainability, solar protection

RESUMO

Este artigo analisa a integração de tecnologias digitais e algoritmos paramétricos no projeto de sistemas de proteção solar para edificações em contextos mediterrâneos, como o de Madri, na Espanha. Utilizou-se um modelo básico representativo de um edifício de escala média e avaliaram-se quatro configurações de proteção solar por meio de simulações avançadas que incorporaram dados climáticos locais e trajetórias solares anuais. As estratégias exploradas incluem toldos horizontais, inclinados, um design biomimético Voronoi e um modelo composto que combina estas abordagens. As conclusões destacam como a inteligência artificial e os algoritmos computacionais permitem otimizar o desempenho energético e o conforto térmico, ao mesmo tempo que redefinem as possibilidades estéticas e sustentáveis na arquitetura contemporânea. Esta abordagem propõe um quadro inovador para enfrentar os desafios climáticos, evidenciando o potencial das ferramentas digitais na transformação do projeto arquitetônico rumo a um paradigma mais resiliente e adaptativo.

Palavras-chave:
design paramétrico, inteligência artificial, sustentabilidade arquitetônica, proteção solar

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INTRODUCTION

In the current context of accelerated urbanization and environmental challenges, contemporary architecture is emerging as a key discipline to face the effects of climate change. In Mediterranean regions, such as Madrid, solar radiation poses a significant challenge, particularly during the warm months, when the temperature of building interiors substantially increases. This phenomenon intensifies the use of air conditioning systems, which increases energy consumption and carbon emissions. This underlines the need for more sustainable architectural solutions (García Molina et al., 2024).

In these conditions, conventional solar protection strategies, although effective in past contexts, are insufficient in the face of current climate and energy demands. Therefore, it is essential to explore innovative approaches that integrate advanced technologies, such as parametric algorithms, artificial intelligence, and adaptive geometries, to design more precise and effective architectural solutions. These tools allow the development of optimized configurations that respond dynamically to varying weather conditions, thereby reducing thermal gain and improving interior comfort (Sickle-Torres et al., 2024; Kolokotsa et al., 2022; Rodríguez-de-Ita & Sosa-Compeán, 2024).

Advances in digital technologies, computational algorithms, and artificial intelligence have profoundly transformed contemporary architecture, allowing unprecedented energy and aesthetic optimizations. The integration of these tools not only improves energy efficiency but also drives innovative design that pushes the boundaries of traditional approaches. Studies such as Tipán-Renjifo and Tipán-Suárez (2022) highlight how Voronoi patterns, generated using computational algorithms, allow the exploration of complex morphologies that respond directly to climatic and functional conditions. These patterns optimize energy performance and enrich the built environment (Chen, 2021). Additionally, this approach facilitates the prediction and dynamic adjustment of solar incidence, resulting in a significant reduction in total radiation compared to a model without protection (Jalali et al., 2022). Wieser et al. (2024) underline that these technologies enable adaptive customizations that respond to seasonal climatic variations and thermal comfort needs. In particular, this approach optimizes energy efficiency and improves indoor comfort in climates such as Madrid.

Parametric systems not only enable solutions of great formal complexity but also facilitate their production using technologies such as laser cutting or 3D printing. Betman et al. (2023) note that these methods reduce waste, costs, and lead times while increasing the accuracy of designs based on Voronoi patterns. However, these innovations face obstacles, including high initial investment, dependence on specialized software, and the need for advanced technical skills, which may restrict their adoption in resource-constrained environments (Gamal et al., 2024).

From a sustainability perspective, these systems not only significantly reduce the energy consumption associated with air conditioning but also contribute to mitigating buildings' environmental impact, aligning with global carbon emission reduction objectives (Ramos-Sanz, 2019; Aghimien et al., 2022). Aesthetically, the advanced algorithms offer a customization that turns each project into a unique work, while promoting a harmonious integration with the environment. Tipán-Renjifo and Tipán-Suárez (2022) highlight how these solutions reconfigure the dialogue between the building and its context, elevating the architectural experience.

However, Wieser et al. (2024) state that dynamic systems, such as tilted individual sunshades, require maintenance planning to ensure their longevity. This includes redundancies and clear protocols to prevent technical failures. Despite these limitations, the integration of digital technologies, artificial intelligence, and advanced algorithms in architecture redefines contemporary design. Responding to complex challenges, it offers adaptive, sustainable, and creative solutions for the future (Atef et al., 2024). As noted by Betman et al. (2023), these tools not only optimize energy efficiency but also inspire a new generation of innovative architectural proposals.

This article focuses on evaluating advanced solar protection strategies applied to a representative building model in the Mediterranean climate. Four configurations are compared through detailed simulations: a base model without protection, a system with horizontal sunshades, another with angularly adjusted individual sunshades, and a solution based on Voronoi geometric patterns. These configurations are analyzed in terms of their ability to mitigate solar radiation and optimize the buildings' energy performance (Amraoui et al., 2021). The work seeks to demonstrate how digital technologies and approaches inspired by natural systems can overcome the limitations of traditional models by promoting a more sustainable and adaptive architecture (Bertagna et al., 2023). This approach not only addresses the challenges associated with climate change but also establishes a new paradigm in architectural design by integrating functionality, technological innovation, and sustainability in Mediterranean and Ibero-American climates.

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Figure 1. View of the residential building located at Plaza España 6, Getafe (Madrid), along with its location within the urban environment and the volumetric scheme of the site. Source: Google Maps (2025).

METHODOLOGY

This study uses a parametric and computational approach to evaluate solar protection strategies in a Mediterranean climate context, using a real building in Getafe (Madrid, Spain) as a reference case. The methodology is structured in four stages: characterization of the climate and the building, modeling and simulation of solar radiation, design of protection strategies, and a comparative analysis of energy performance.

The first step was to characterize Getafe's Mediterranean climate using global irradiance, temperature, and Köppen climate classification data (Csa: Mediterranean with hot summer). With more than 2,800 hours of sunshine per year and average summer temperatures exceeding 30°C, solar protection is a top priority. The selected building is a medium-scale, multifamily residential building located at Plaza España 6, Getafe (coordinates: 40.309300, -3.724501). It is a rectangular prism measuring 30 m × 50 m × 50 m, with an envelope surface area of 9,500 m² and a total volume of 75,000 m³. Its compact shape allows minimizing the surface exposed to heat exchange, facilitating the analysis (Figure 1).

In a second stage, the base building was digitally modeled without solar protection, establishing a reference scenario. From solar simulations carried out with Ladybug in Grasshopper, the annual radiation distribution was obtained for each of the five exposed faces: north, south, east, west, and roof. The values were calculated precisely according to the specific solar trajectories of Madrid, and the direct radiation was considered as diffuse. This analysis revealed that the southern and upper faces receive more than 60% of the annual radiation, which justifies their prioritization in the design of strategies. The information is summarized in Table 1, which includes the average radiation per surface, and in Figure 2, Figure 3, and Figure 4, which visualize the differences in exposure.

Three solar protection strategies were designed: (1) horizontal sunshades with 1.50 m deep sheets and constant vertical separation; (2) individual tilted sunshades, arranged according to predominant solar angles and adapted by modules; and (3) a biomimetic Voronoi envelope, generated with parametric algorithms that vary the size of the perforations depending on the orientation and solar exposure. Each strategy was applied to the same base model, and three variants were generated, which were then subjected to simulation under identical climatic conditions.

The simulations evaluated the incident radiation per m² on each face of the building. The data was processed with GPT4All, a local AI model with no external connection, to ensure reproducibility and traceability. To optimize the geometric parameters of each strategy, genetic algorithms were used using Galapagos, and custom scripts in GhPython were used to adjust the configurations to the specific conditions of Getafe.

Finally, a fourth variant was designed: a composite model that combines the best solutions detected in each orientation. This includes tilted sunshades on the east, west, and south facades, as well as a Voronoi lattice on the north face and the roof, thereby achieving optimized coverage. The performance of each strategy was compared in terms of total accumulated radiation, percentage reduction compared to the base model, and thermal distribution by orientation. All the information was systematized

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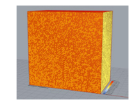
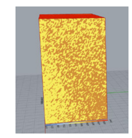
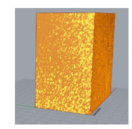
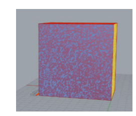
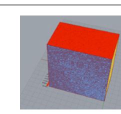
Table 1. Analysis of the base prism by faces. Source: Preparation by the Authors.

Face	Surface area (m²)	Radiation (kWh/m²)	Reduction (%)	Layout
Sur	2500	2.981	00.0	
Este	1500	1.360	00.0	
Oeste	1500	1.398	00.0	
Norte	2500	0.976	00.0	
Superior	1500	2.299	00.0	

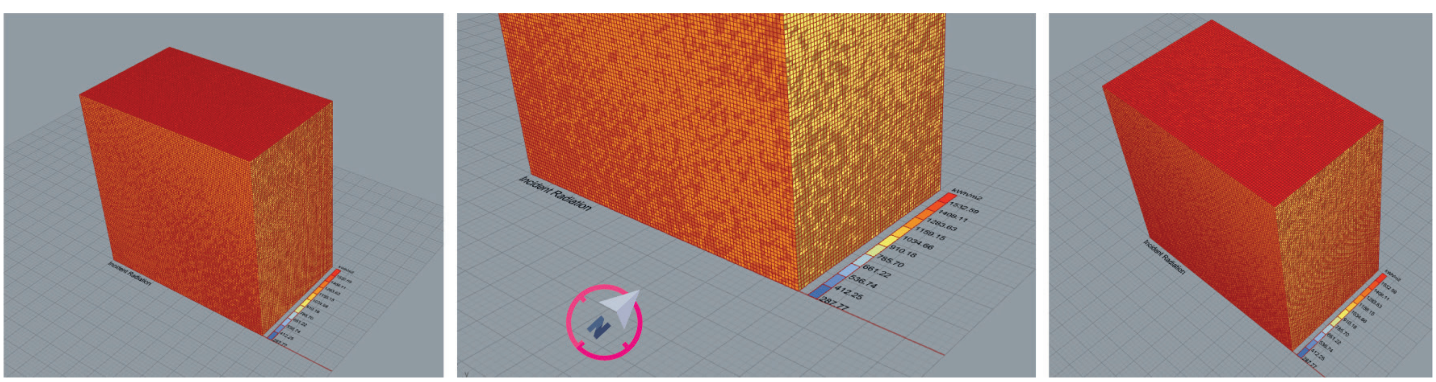


Figure 2. Digital simulation of the base prism with visualization of the solar radiation values on the surfaces. Source: Preparation by the Authors.

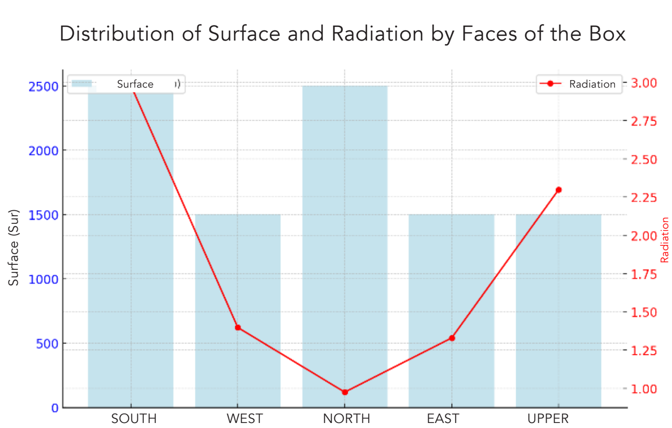


Figure 3. Distribution of surface and radiation on the faces of the base prism, showing the relationship between area and received radiation. Source: Preparation by the Authors.

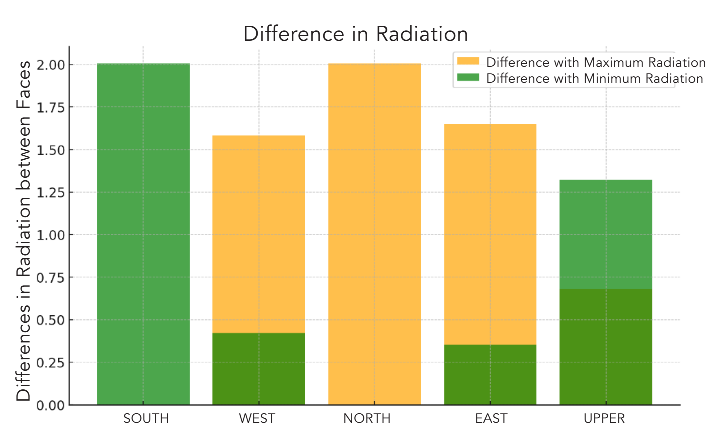


Figure 4. Variations in radiation per face of the base prism, with a comparison of maximum and minimum values observed to highlight the differences in exposure in the analyzed model. Source: Preparation by the Authors.

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in comparative tables and illustrated by graphics and visual simulations, which allowed understanding the performance of each configuration from a technical and project perspective.

DISTRIBUTION OF SOLAR RADIATION BY FACE

Before evaluating the solar protection strategies, the distribution of the incident radiation on each of the base model's surfaces was analyzed without shading elements. This stage allowed identifying which facades concentrated the most exposure, establishing the criteria for geometric intervention. The model accumulates an annual total of 9,415 kWh/m^2, with the southern and upper faces receiving more than 60% of that energy (Figure 2, Figure 3, and Figure 4). Table 1 summarizes the radiation values per face and its surface, which shows the differences according to orientation:

This information served as a comparative basis for evaluating the performance of each strategy in reducing incident solar radiation.

DESIGN OF SOLAR PROTECTION STRATEGIES

According to Urias-Barrera (2024), three solar protection strategies were analyzed and designed to minimize incident solar radiation, optimize energy efficiency, and enhance thermal comfort, compared to the base model. Each strategy was based on principles of geometric optimization and solar behavior and was evaluated using advanced computational tools.

1. Box with horizontal sunshades. Rectangular horizontal sheets, 1.50 meters deep and 0.25 meters thick, were used, evenly distributed on the facades with a constant vertical separation of 0.75 meters. These dimensions were determined to ensure adequate shading at the times of greatest solar incidence, especially in summer. The choice of the horizontal model responds to its proven ability to effectively block direct radiation from high solar angles, typical in Mediterranean latitudes, while preserving an adequate entry of daylight in the less warm months.
2. Box with individual tilted sunshades. This strategy integrates individual elements in the form of square slats inclined at a variable angle between 0° and -90 °, designed according to the prevailing solar angles throughout the year in Madrid. Each sunshade has specific dimensions of 1.50 meters in length, 1.50 meters in horizontal width, and 0.05 meters in thickness. Although, for practical purposes of the initial calculation, a wide modular surface of 5 meters by 5 meters was established, it is important to clarify that, in reality, each visible module internally comprises groups of individual smaller sunshades. This allows efficiently managing the large dimensions seen in the image, making the proposal technically viable, logical, and feasible from a constructive, functional, and architectural perspective. The tilted configuration thus addresses the need for a more dynamic and effective protection against daily and seasonal solar variations, significantly improving the thermal adaptation capacity without negatively affecting the internal daylighting or the building's aesthetic coherence.
3. Box with Voronoi pattern. This model incorporates a biomimetic structure with latticework generated by Voronoi parametric algorithms. The perforations have variable dimensions, ranging from 0.50 to 4.50 meters in diameter, arranged according to a parametric gradient adjusted to maximize protection against both direct and diffuse solar radiation, while maintaining a balance between visual transparency and the shadow generated. The choice of the Voronoi design is justified by its proven ability to effectively disperse incident solar radiation, reduce thermal accumulation, and offer a visually distinctive and functional architectural solution that aligns with sustainable and adaptive principles (Asghar et al., 2020; Trujillo Díaz, 2016).

SIMULATIONS AND COMPUTATIONAL TOOLS

To evaluate each strategy, advanced computational simulation tools were used that combined geometric and climatic models with optimization algorithms and artificial intelligence (Al-Shukri & Al-Majidi, 2020). In this process, Rhinoceros and its native Grasshopper plug-in were used, which integrate different optimization algorithms, such as Ladybug, Galapagos, and algorithms developed in the GhPython Script. The simulations were conducted under the same climatic conditions, using specific data from the Madrid context as a reference.

1. Climate modeling and solar trajectories: Detailed data on global and diffuse solar radiation were included, with annual and seasonal average values. Additionally, daily solar trajectories were modeled throughout the year, taking into account the characteristic inclination of the Mediterranean latitudes. For this, Ladybug, a tool integrated into Grasshopper, was used, which allowed a detailed analysis of the solar parameters and their impact on the building.
2. Energy evaluation: The incident radiation levels per square meter on each surface of the prism were calculated. These calculations were visualized through energy density maps, which allowed a detailed comparison between the strategies. The data were processed using GPT4All, an open-source artificial intelligence model that runs locally on a personal computer, without requiring an internet

Table 2. Analysis of the model with horizontal sunshades by faces. Source: Preparation by the Authors.

Face	Surface area (m²)	Radiation (kWh/m²)	Reduction (%)
South	2500	1.608	46.0
East	1500	0.682	48.7
West	1500	0.717	48.7
North	2500	0.499	48.8
Upper	1500	2.298	0.0

connection or dependence on external services such as ChatGPT or similar commercial platforms, thereby ensuring an autonomous and reproducible analysis.

3. Optimization using advanced algorithms: Genetic algorithms were implemented with Galapagos to optimize the configuration of solar protections, by iteratively selecting the most effective arrangements to reduce solar radiation (Díaz Valdés, 2021). Machine learning methods, supported by GPT4All, complemented the analysis by predicting solar incidence patterns and shadows to more accurately simulate the thermal behavior of facades. Similarly, scripts were developed in GhPython to customize and adjust the optimization parameters based on the specific climatic data of Madrid.

The selection of these three configurations arises from the need to explore different geometric and functional responses to the climatic challenge posed by solar radiation in Mediterranean climates. The horizontal model was chosen for its constructive simplicity and effectiveness against the sun in a high position. The tilted one was chosen for its adaptive flexibility and better performance against variable solar angles. The Voronoi model was chosen for its innovative character and ability to integrate aesthetic and functional criteria through the use of advanced parametric algorithms.

ANALYSIS PARAMETERS

The models were evaluated considering the following aspects:

- Total and diffuse solar radiation: Average annual values were calculated, seasonally segmented.
- Percentage reduction of radiation: Comparison of effectiveness compared to the base model.
- Energy distribution: Identification of critical areas with higher thermal gain.
- Impact on thermal comfort and energy efficiency: Estimation of the reduction in energy consumption associated with air conditioning.

This comprehensive approach made it possible to evaluate the effectiveness of each strategy, considering both its energy performance and architectural implications. In addition, it laid the foundations for developing sustainable and adaptive solutions, aligned with the Mediterranean climatic conditions.

RESULTS OF THE ANALYSIS

SOLAR PROTECTION STRATEGIES

The comparative analysis of solar protection strategies was conducted using a representative base model with an orientation parallel to the cardinal points. The building has a south facade that is completely exposed to direct radiation, while the north facade remains in shadow for most of the year. The east and west facades receive solar incidence mainly during the mornings and afternoons, respectively, and the horizontal roof is exposed throughout the day. This orientation was kept constant in all simulations to ensure the consistency of the results.

Three configurations were evaluated: Horizontal sunshades, individual tilted sunshades, and Voronoi latticework, as well as a hybrid strategy that combined the most efficient solutions of each model. The results obtained for each proposal are described below.

The first strategy, based on horizontal sunshades, achieved a 68% reduction in accumulated radiation compared to the unprotected model, resulting in a total of 3.04 kWh/m². The south face experienced a significant reduction (46%), although the roof remained unprotected, maintaining its exposure levels. The efficiency was moderate on the east and west facades, with values close to 48%, thanks to the constant shading of the slats. However, the lack of upper coverage limited the overall effectiveness of the system, especially in environments such as Madrid, where zenith radiation is high during the summer.

Horizontal sunshades (Figure 5) are effective on vertical faces (south, east, west, and north), as they reduce radiation evenly (Table 2). However, the upper face is still exposed to the maximum radiation, which limits the overall efficiency of the model. The uniformity in the reductions of the east and west faces suggests a design with constant separation, which can be improved

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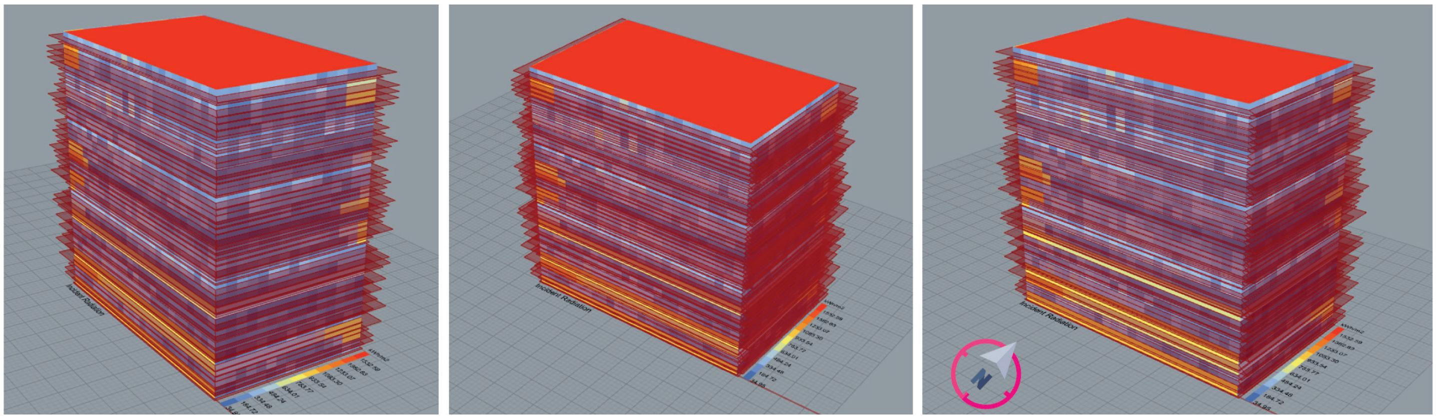

Figure 5. Differences in radiation per face of the base prism with sunshades, highlighting the variations in exposure compared to the extreme values. Source: Preparation by the Authors.

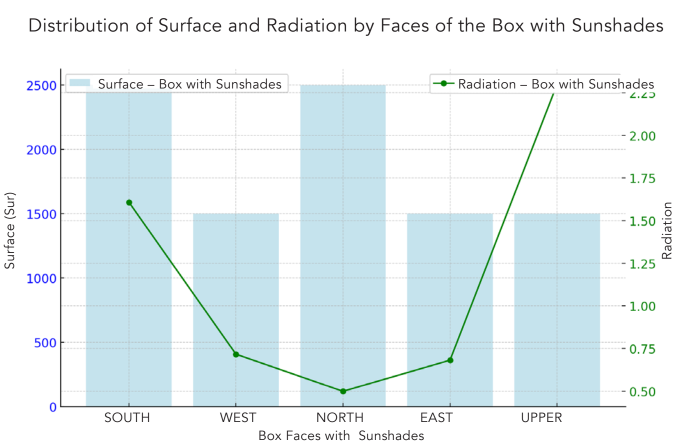

Figure 6. Surface and radiation distribution per face of the box with sunshades, which highlights the relationship between exposed area and received radiation. Source: Preparation by the Authors.

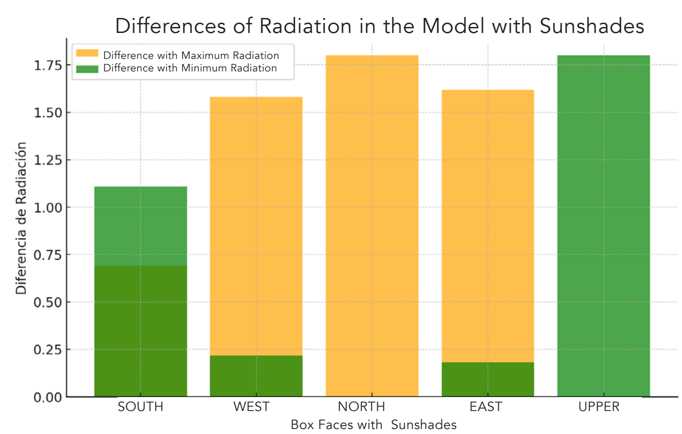

Figure 7. Differences in radiation in the model with sunshades, when comparing each face with the maximum and minimum values of the set. Source: Preparation by the Authors.

Table 3. Analysis of the model individual tilted sunshades by faces. Source: Preparation by the Authors.

Face	Surface area (m²)	Radiation (kWh/m²)	Reduction (%)
South	2500	0.471	84.2
East	1500	0.293	77.9
West	1500	0.301	78.5
North	2500	0.328	66.4
Upper	1500	0.830	63.9

by adjustments in density or length according to solar variations. These results underscore the importance of comprehensive protection that covers all exposed faces to optimize thermal and energy performance in Mediterranean climates (Figure 6 and Figure 7).

In the second strategy, individual tilted sunshades, substantial improvements were observed. The radiation was reduced by 71.8% compared to the base model, accumulating only 2.65 kWh/m^2. This strategy was especially effective on the south facade, where it achieved a reduction of 84.2%, and on the roof, with a decrease of 63.9%. The tilted design allowed a better adaptation to the daily and seasonal solar trajectory by generating dynamic shadow zones without compromising interior daylighting. The reductions were uniform on all sides, confirming the superior performance of this strategy compared to traditional solutions (Table 3).

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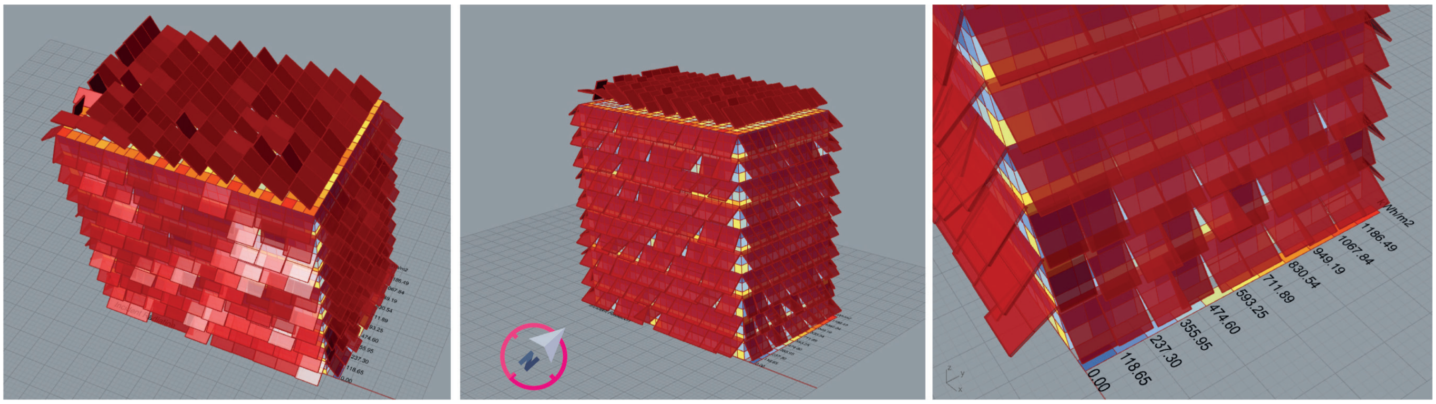

Figure 8. Differences in radiation per face of the base prism with tilted sunshades, each one being compared with the extreme values, highlight the variations in exposure. Source: Preparation by the Authors.

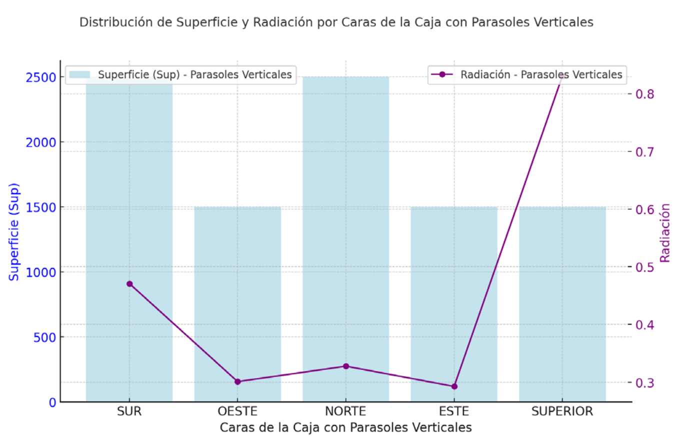

Figure 9. Surface and radiation distribution by prism face with tilted sunshades highlights the interaction between design and solar exposure. Source: Preparation by the Authors.

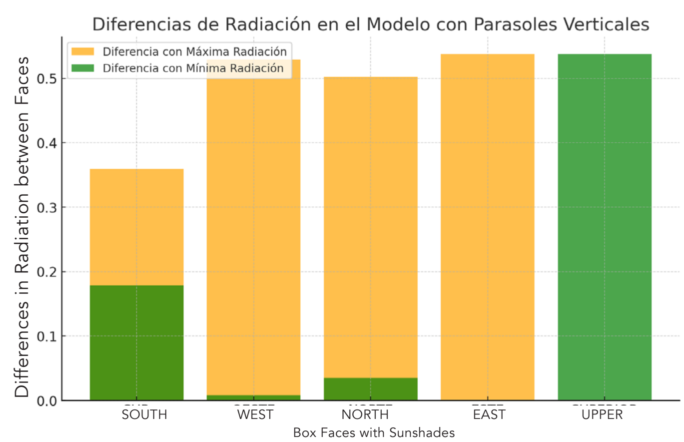

Figure 10. Radiation differences in the model with tilted sunshades, when comparing each face with the maximum and minimum values. Source: Preparation by the Authors.

Table 4. Analysis of the model with Voronoi sunshades by faces. Source: Preparation by the Authors.

Face	Surface area (m²)	Radiation (kWh/m²)	Reduction (%)
South	2500	0.706	76.3
East	1500	0.324	75.6
West	1500	0.329	76.4
North	2500	0.249	74.4
Upper	1500	0.249	89.1

On the south face, the reduction is especially noticeable, which reflects its effectiveness for the predominant orientation in Madrid during the summer (Figure 8). In addition, the decrease in the radiation of the upper face is significant, a result that is not observed with horizontal sunshades. This is due to the shading generated by the vertical elements that cast shadow from the side faces, which demonstrates a more strategic design, adapted to the local climatic context (Figure 9 and Figure 10).

The third configuration evaluated was an envelope based on Voronoi geometric patterns, designed using parametric algorithms with holes of varying sizes. This solution achieved the highest individual efficiency, resulting in a 76.7% reduction in radiation (2.20 kWh/m²). The upper face benefited the most, with a reduction of 89.1%, while the vertical faces reached values between 74% and 76%. The irregular and three-dimensional geometry enabled the effective

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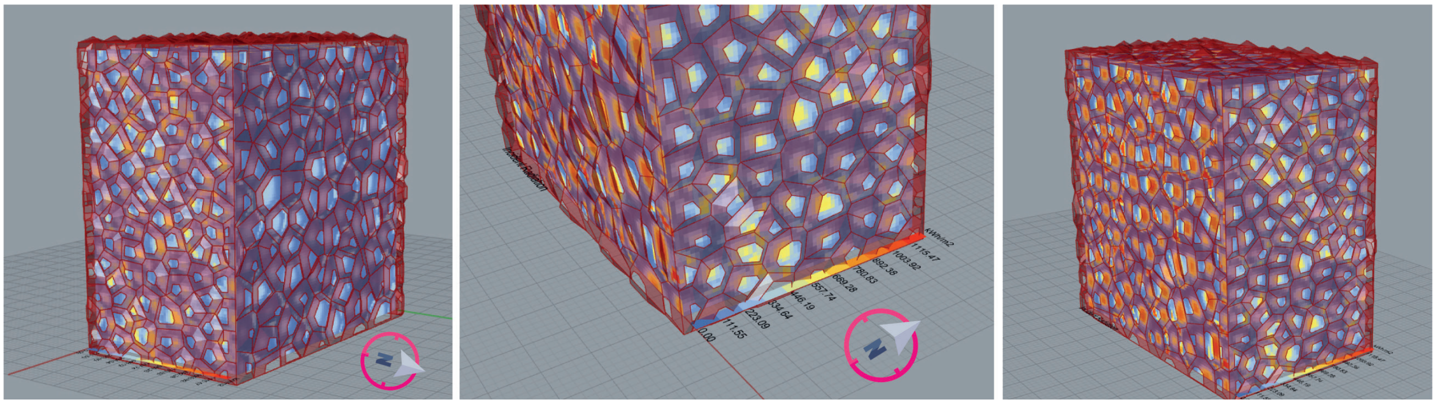

Figure 11. Differences in radiation per face of the base prism with Voronoi sunshades, when comparing each one with the maximum and minimum values observed. Source: Preparation by the Authors.

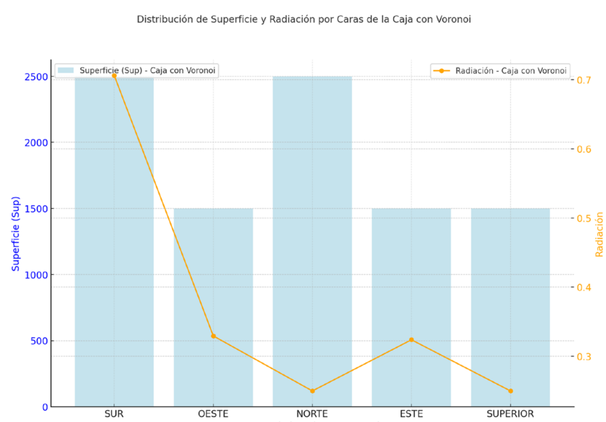

Figure 12. Surface and radiation distribution per face of the prism with Voronoi protection, which highlights the relationship between exposure and geometric design. Source: Preparation by the Authors.

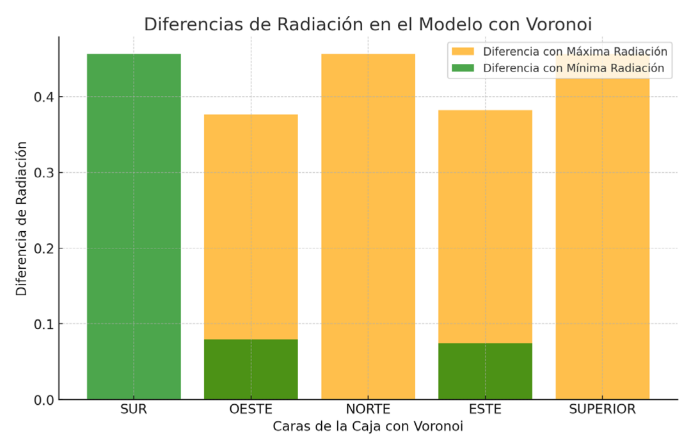

Figure 13. Radiation differences in the Voronoi model, when comparing each face with the maximum and minimum values. Source: Preparation by the Authors.

dispersion of radiation by combining solar control, formal identity, and bioinspired structural criteria (Table 4). However, its constructive complexity could pose a barrier in standard residential contexts, an aspect discussed later (Figure 11).

The Voronoi design not only significantly reduces radiation on all sides but also optimizes the thermal comfort and energy efficiency of the internal volume. Its uniform performance and the outstanding reduction on the upper face make it the most innovative and effective solution, adapted to the climatic conditions of the Mediterranean context (Figure 12 and Figure 13).

Finally, a composite model was developed by integrating the most effective systems by orientation: tilted sunshades on the south, east, and west facades, and a Voronoi system on the north face and the roof (Figure 14). This hybrid model achieved a total reduction of 81.9% (1.62 kWh/m^2), the lowest of all the configurations analyzed. The south face, traditionally the most critical, was reduced to 0.35 kWh/m^2, while the roof decreased to 0.18 kWh/m^2. The east and west faces were maintained at values around 0.23, achieving a balanced distribution and uniform protection in all orientations (Figure 15 and Figure 16). This solution demonstrated a high thermal and formal efficiency, with a level of optimization adaptable to different climatic contexts of the Mediterranean arc. The following table (Table 5) summarizes the annual average radiation values per face and the percentage reduction compared to the unprotected model:

The results confirm that the composite model surpasses the individual solutions by combining the best of each, adapting its response to the building's geometry and solar incidence according to orientation. This flexibility makes it an optimal alternative for buildings with multiple exposed facades in hot climates (Table 6).

Figure 17 and Figure 18 illustrate the radiation patterns by face and the morphology of each strategy, facilitating the visual interpretation of the results and evidencing the formal impact of each proposal. The

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Table 5. Comparison of the results of the different models of sunshades. Source: Preparation by the Authors.

Face	Without Sunshades kWh/m2	Horizontal kWh/m2	Vertical kWh/m2	Voronoi kWh/m2	Composite kWh/m2	Best Solution
South	2.98	1.61	0.47	0.71	0.35	Compositive
East	1.33	0.68	0.29	0.32	0.23	Compositive
West	1.40	0.72	0.30	0.33	0.23	Compositive
North	0.98	0.50	0.33	0.25	0.23	Compositive
Upper	2.30	2.30	0.83	0.25	0.18	Compositive

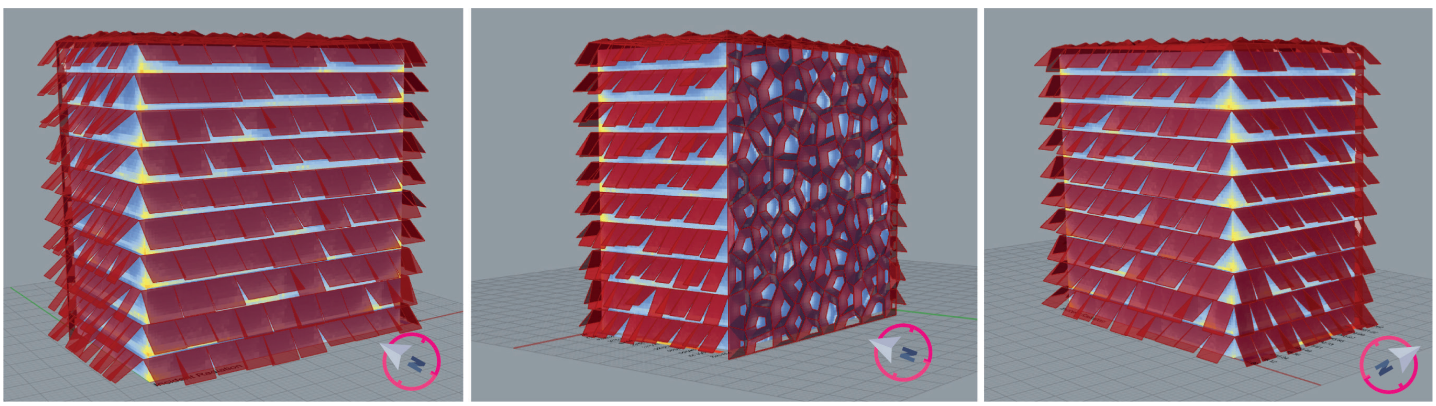

Figure 14. Composite model that integrates tilted sunshades on the south, east, and west facades, due to their high exposure to direct solar radiation, and a geometric system based on Voronoi diagrams on the north and Upper surfaces, optimizing both solar control and the overall energy efficiency of the building. Source: Preparation by the Authors.

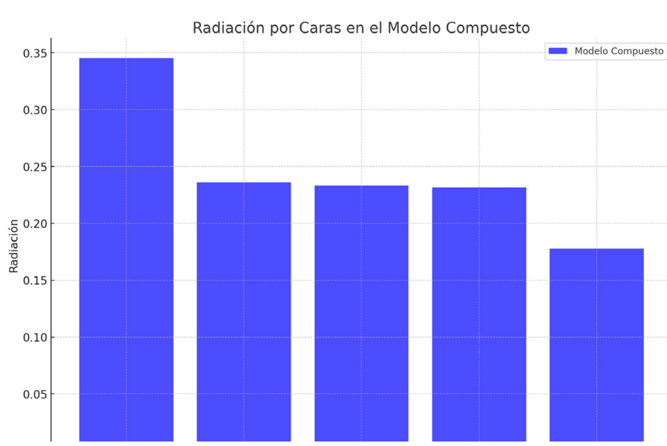

Figure 15. Radiation per face in the Composite Model, which highlights a significant reduction in all orientations. The SOUTH face, although it is the most exposed, reduces its radiation to 0.345 units. The EAST and WEST faces maintain a balanced level around 0.23 units, while the NORTH face shows a low exposure with 0.233 units. The UPPER face registers the least radiation, with only 0.178 units, evidencing the effectiveness of the composite design. Source: Preparation by the Authors.

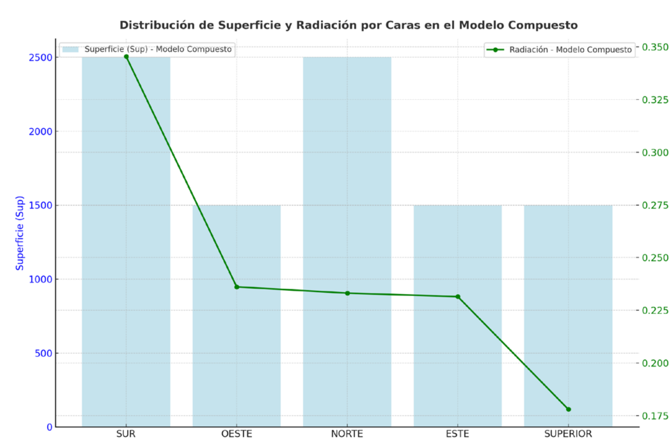

Figure 16. Distribution of the surface by face and the radiation values in the composite model, highlighting the radiation variations according to the orientation and exposure of each face. Source: Preparation by the Authors.

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Table 6. Comparison of the results of the different models of sunshades. Source: Preparation by the Authors.

Model	Total Radiation (kWh/m2)	Reduction (%)
Without Sunshades	8.98	—
With Horizontal Sunshades	5.81	35.4%
With Vertical Sunshades	2.65	70.5%
With Voronoi	2.20	75.5%
Composite Model	1.62	81.9%

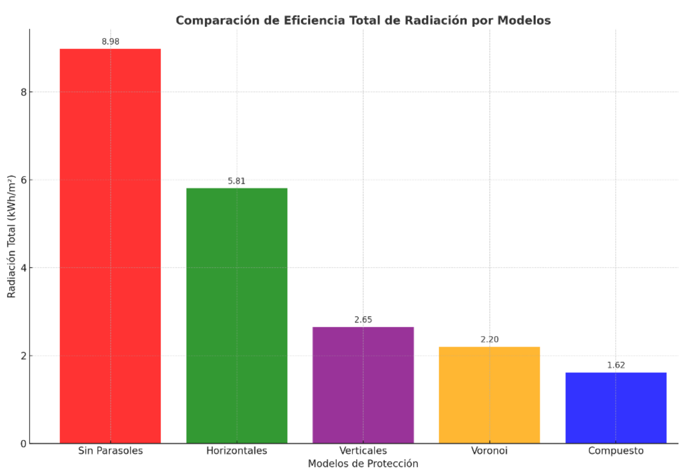

Figure 17. Graphical comparison of the total radiation in the different models evaluated. The graph highlights the model without sunshades as the one with the highest exposure, while the composite model is positioned as the most efficient solution, with the lowest accumulated radiation. Source: Preparation by the Authors.

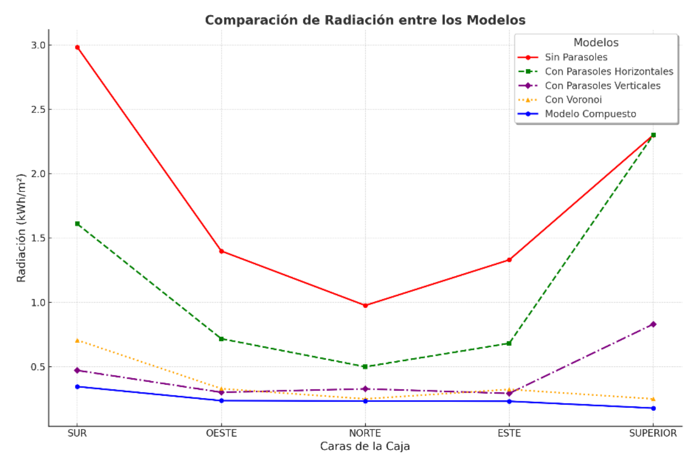

Figure 18. Comparative graph representing the radiation on the different faces of the box for the five models. Source: Preparation by the Authors.

reader is recommended to observe, in particular, the progression between the Voronoi strategy and the composite model, where an effective synthesis is achieved between thermal performance, architectural aesthetics, and technical feasibility.

CONSTRUCTIVE FEASIBILITY AND MATERIALITY OF THE PROPOSED STRATEGIES

Beyond the computer analysis, considering the constructive feasibility of the proposed strategies is essential. In particular, the composite model can be developed using currently available digital manufacturing technologies, without requiring complex or exclusive systems. The tilted sunshades are compatible with modular solutions made of anodized aluminum or low-thickness galvanized steel, with standard anchors for the ventilated facade or auxiliary structure. Thermoformed recyclable plastic panels, suitable for high-solar-exposure environments, could also be used. As for the Voronoi envelope, its materialization is feasible through CNC cutting on sheet metal, 3D printing on technical polymers, or GFRP-type composite panels, depending on the desired degree of rigidity, curvature, and translucency. These techniques allow for the control of the thickness, pattern, and assembly of each module, which facilitates prefabrication and on-site assembly.

In institutional or cultural projects, these strategies can be implemented with total geometric fidelity. In residential programs, it is feasible to adopt simplified versions that maintain the principle of adaptive solar control without incurring cost overruns. The key lies in adjusting the degree of complexity to the program and the budget, maintaining the optimized morphological logic that underlies each solution.

Recent studies have already documented the structural and morphological applications of the Voronoi pattern in architecture, demonstrating its adaptability and efficiency in both mechanical and formal terms. In particular, Agudelo Londoño et al. (2015) highlighted its properties in load distribution and shock absorption, while Sora Yanquén (2007) and Flores Jurado et al. (2020) analyzed its potential in generating optimized three-dimensional surfaces through parametric design. More recently, Habib et al. (2024) and Bormashenko et al. (2021) have explored new classifications and entropy measures in Voronoi systems, applied to the design of adaptive envelopes and the coding of natural patterns. These investigations confirm that Voronoi morphology not only has aesthetic or theoretical value but also offers a viable framework for developing materializable, sustainable, and structurally coherent architectural solutions.

CONCLUSIONS

This study demonstrates that integrating advanced geometric strategies with computer simulation tools enables significant optimization of solar protection in buildings with a Mediterranean climate. Through a rigorous and quantitative analysis, different configurations that responded to real conditions of the urban and climatic environment of Getafe, within the Community of Madrid, were compared.

The results show that the composite model, which combines tilted sunshades on the most exposed facades with a Voronoi latticework on the surfaces that receive diffuse or overhead radiation, achieves the most significant reduction in accumulated radiation, with an improvement of 81.9% compared to the unprotected model. This solution is presented as a balanced and replicable proposal, capable of adapting to various orientations and sunlight conditions without compromising the aesthetic or energy performance of the entire structure.

Unlike horizontal systems, which, although easy to implement, do not effectively protect the roof, and pure Voronoi envelopes, whose complexity can limit their use in conventional residential projects, the hybrid model offers a pragmatic and adaptable alternative. The tilted elements, being arranged according to specific solar angles, maximize the shadow cast on the facades during critical hours without impeding daylighting. On the other hand, the Voronoi pattern, applied exclusively to the roof and north facade, allows for localized geometric optimization with strong expressive and technical potential.

As previously stated, these strategies can be developed using modular construction systems and accessible digital technologies, by adjusting their degree of complexity depending on the architectural program. This technical flexibility opens up new possibilities for its implementation in both institutional contexts and medium-scale residential programs, allowing high-performance solutions with controlled costs and maintenance.

In terms of design, the study confirms the need to abandon generic or standardized approaches in solar protection and move towards solutions that integrate design and simulation from the initial stages. The use of algorithms and climate analysis allows not only improved energy efficiency but also enriched architectural expressiveness without sacrificing functionality. The shape ceases to be an arbitrary aesthetic result and becomes a direct consequence of the interaction between geometry, climate, and program.

Although the post-occupational monitoring phase is not addressed in this article, it is acknowledged that the next step will be to evaluate the actual implementation of these systems in pilot works, which identify thermal behavior under everyday use conditions. Likewise, it is considered pertinent to study its application in non-residential buildings, such as schools, libraries, or cultural centers, where functional flexibility and formal expressiveness allow a freer integration of advanced solar control technologies.

Ultimately, this research not only examines the impact of parametric and bioinspired methods on architecture but also underscores their role in transforming contemporary design culture by fostering a more integrated and systemic approach to design. Far from being limited to a reactive response, architecture must assume a proactive role where the models developed are not definitive solutions, but catalysts for critical speculation that intertwines aesthetics, technique, and ethics, redefining the relationship with space, time, and the environment.

CONTRIBUTION OF AUTHORS CRediT

Conceptualization, M.A.F.N.; Data Curation, M.A.F.N.; Formal analysis, M.A.F.N.; Acquisition of funding, M.A.F.N.; Research, M.A.F.N.; Methodology, M.A.F.N.; Project management, M.A.F.N.; Resources, M.A.F.N.; Software. M.A.F.N.; Supervision, M.A.F.N.; Validation, M.A.F.N.; Visualization, M.A.F.N.; Writing - original draft, M.A.F.N.; Writing - revision and editing, M.A.F.N.

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