Influencia de los Parámetros de Diseño de Protecciones Solares en la eficiencia energética en climas áridos templados fríos, Mendoza, Argentina
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INFLUENCE OF SOLAR SHADING DESIGN PARAMETERS ON ENERGY EFFICIENCY IN COLD ARID TEMPERATE CLIMATES, MENDOZA, ARGENTINA

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INFLUÊNCIA DOS PARÂMETROS DE DESIGN DAS PROTEÇÕES SOLARES NA EFICIÊNCIA ENERGÉTICA EM CLIMAS ÁRIDOS FRIOS E TEMPERADOS, MENDOZA, ARGENTINA

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RESUMEN

El sector de la construcción tiene un impacto significativo en el consumo energético global y en las emisiones de carbono. A pesar de los avances tecnológicos y de materiales, el rendimiento energético de los edificios depende principalmente de las decisiones de diseño arquitectónico. Este estudio evalúa cómo las configuraciones de sistemas de protección solar afectan los consumos energéticos de calefacción, refrigeración e iluminación en un box de estudio ubicado en un clima árido templado frío. Los resultados muestran que la proporción ventana-pared (WWR) y la orientación absoluta son factores determinantes en el consumo energético. Se observó un incremento del 16% en el consumo de refrigeración y del 13% en iluminación con el aumento progresivo del WWR. Además, la demanda de calefacción aumentó en torno al 18% según la orientación. Estos hallazgos destacan la importancia de ajustar las variables de diseño para optimizar la eficiencia energética de los edificios.

Palabras clave
protecciones solares, simulación paramétrica, eficiencia energética, clima árido templado frío

ABSTRACT

The construction sector has a significant impact on global energy consumption and carbon emissions. Despite technological and material advances, the energy performance of buildings primarily depends on architectural design decisions. This study evaluates how solar protection system configurations affect energy consumption for heating, cooling, and lighting in a study box in an arid, temperate, cold climate. The results show that the window-to-wall ratio (WWR) and absolute orientation are key factors in energy consumption. A 16% increase in cooling consumption and a 13% increase in lighting were observed with the progressive increase of the WWR. Additionally, depending on the orientation, heating demand increased by approximately 18%. These findings highlight the importance of adjusting design variables to optimize the energy efficiency of buildings.

Keywords
solar shading, parametric simulation, energy efficiency, cold temperate arid climate

RESUMO

O setor de construção exerce um impacto significativo no consumo global de energia e nas emissões de carbono. Apesar dos avanços em tecnologia e materiais, o desempenho energético dos edifícios depende principalmente das decisões de projeto arquitetônico. Este estudo avalia como as configurações de sistemas de proteção solar afetam os consumos de energia de aquecimento, resfriamento e iluminação em um box de estudo localizado em um clima árido temperado frio. Os resultados mostram que a proporção janela-parede (WWR) e a orientação absoluta são fatores determinantes no consumo energético. Um aumento de 16% no consumo de resfriamento e de 13% em iluminação foi observado com o aumento progressivo da WWR. Além disso, a demanda de aquecimento aumentou em cerca de 18%, dependendo da orientação. Essas descobertas destacam a importância de ajustar as variáveis de projeto para otimizar a eficiência energética dos edifícios.

Palavras-chave:
proteção solar, simulação paramétrica, eficiência energética, clima árido temperado e frio

INTRODUCTION

The building sector is one of the areas most responsible for energy consumption and carbon emissions, aggravating the global environmental crisis. This impact, which will reach 68% by 2050, according to the International Energy Agency [IEA] (2021), is intensified due to the projected population growth. This increase generates a greater demand for energy resources, putting pressure on existing infrastructures (IPCC, 2023). Buildings with thermally inefficient envelopes consume more energy to achieve thermal comfort conditions, contributing to increased global emissions and dependence on non-renewable resources. A critical aspect is the thermal performance of the openings, which influences heat gains and losses. In addition to fulfilling aesthetic roles and allowing ventilation and lighting, windows are key construction systems for controlling solar radiation. The entry of solar radiation can reduce the energy consumption associated with heating in cold climates and improve the thermal and visual comfort of the occupants (Ghosh & Neogi, 2018). However, an inadequate design can lead to glare, increased cooling demand, or increased dependence on artificial lighting. This highlights the importance of designing optimized windows and solar protection systems adapted to each region's climatic conditions (Kaasalainen et al., 2020; Kirimtat et al., 2016). In this context, solar protection and advanced radiation control technologies are fundamental to efficiently managing the flow of solar energy.

Within sustainable architecture, passive strategies for the design of envelopes are key to improving the energy performance of buildings. These strategies, which consider parameters such as windows and solar protections, seek to identify optimal configurations through energy simulations and observational studies (Bustamante & Encinas, 2012). Simulation tools make it possible to systematically evaluate the impact of different parameters on the thermal behavior of buildings, which provides critical information for decisions from the initial stages of architectural design. Correlation analysis, a robust statistical methodology, helps understand how design parameters influence the energy consumption of buildings. Unlike sensitivity analysis, which evaluates the response to changes, correlation allows quantifying the intensity and direction of the relationships between variables without implying causality (Zou et al., 2003). This approach facilitates the identification of patterns between variables, such as the percentage of the glazed area (WWR) and the orientation of the windows, which provide valuable information for bioclimatic design strategies (Alanis-Navarro et al., 2017). These methodologies are fundamental tools when evaluating how factors interact in energy efficiency.

Although several studies have explored the design of windows and solar protections using computer simulations, the use of correlation analysis to identify complex relationships between design parameters and energy consumption remains limited. Research such as that by Koç and Maçka Kalfa (2021), Dabbagh and Krarti. (2022), Khidmat et al. (2021), Mangkuto et al. (2021), and Nazari et al. (2023) have provided valuable perspectives, but do not look closely into the identification of relationships between multiple variables. Betman et al. (2023) analyzed how given geometric parameters affect energy demands and obtained encouraging first approximations. This article will address additional methodologies that explore a specific correlation approach, expanding upon the work in this area, focusing mainly on the city of Mendoza, located in central-western Argentina.

Correlation analysis can significantly contribute to optimizing design parameters such as WWR and solar protection. It provides an in-depth understanding of how these elements impact energy requirements by facilitating the development of strategies adapted to local climatic conditions. In addition, it strengthens buildings' capacity to face environmental challenges, such as climate change and the shortage of renewable resources.

The Metropolitan Area of Mendoza (32° 40' South Latitude, 68° 51' West Longitude), categorized as BWk (cold arid temperate) according to the Köppen classification, has an average annual temperature of 17°C. Its summers are hot and dry, with temperatures up to 39°C, and cold winters, with lows of -6°C. The daily thermal variations, which range between 10°C and 20°C, and a high annual solar radiation highlight the need for a detailed climate analysis to design buildings that respond to the region's climatic and social particularities.

Future climate projections suggest an increase in average temperatures, especially in summer, which highlights the urgency of implementing mitigation and adaptation measures, such as passive shading strategies and cooling technologies to reduce dependence on mechanical systems (National Directorate of Scenarios and Energy Planning, 2019; National Meteorological Service, 2023; IPCC, 2023).

Based on this, this paper explores the relationship between building design parameters and the factors influencing energy behavior in cold temperate arid climates, such as Mendoza. It uses a correlation analysis to identify and quantify how the design parameters of windows and solar protections impact the energy requirements for cooling, heating, and lighting to optimize their performance.

METHODOLOGY

DEFINITION OF THE SIMULATION MODEL AND STUDY PARAMETERS

A project is proposed with an indoor space whose dimensions align with the housing units of the Provincial Housing Institute's development plan for Mendoza, a typology widely reproduced in the last 10 years. It consists of a duplex on two floors. The setting chosen for this study is the bedroom. Thus, the box is formed in an area of 3.00 m by 3.00 m with a height of 2.70 m.

Table 1 outlines the thermo-physical characteristics of typical materials used in construction in the region. During dynamic energy modeling in the EnergyPlus software, the building pattern is associated with these materials and is connected to a single thermal zone. It is marked off by one of the walls in contact with the outside, which includes a window. The rest of the horizontal and vertical thermal envelope is considered adiabatic. This approach allows the analysis of indoor spaces in high-rise buildings. In Table 1, the walls, floor, and ceiling materials are characterized. The window can be opened, has an aluminum frame, and 3mm single glazing. U = 5.8 W/m^2 K.

This study uses solar control devices comprising sunshades formed by vertical and horizontal slats. The parameters evaluated are defined below:

- Window-to-wall ratio (WWR): This represents the percentage of glazed area compared to the total area of the facade. For this analysis, a WWR range between 30% and 90% was considered, with 10% intervals. Values under 30% were not included, as they would limit the evaluation of the impact of variables related to lighting.
- Orientation: Orientations receiving direct solar radiation were analyzed, including three main angles: 0° for the north, 90° for the east, and -90° for the west. Two intermediate positions were also considered: +45° (northeast) and -45° (northwest).
- Arrangement of the slats: The solar protection system includes equidistantly spaced modular slats. Two configurations were proposed: slats arranged horizontally (value of 0 in the software) and vertically (value of 1 in the software).
- Slat tilt angle: Three configurations were evaluated: horizontal position (0°), intermediate tilt (15°), and steep tilt (30°). The value of 0° acts as a basic barrier against solar radiation. The 15° inclination offers a balance between solar efficiency and aesthetics. Finally, the 30° inclination provides greater shading, improving solar protection without affecting functionality or visual design.
- Depth of the slats: The Climate Consultant software shading graph was used for this (Figure 1). The solar angle for 12:00 solar

Table 1. Thermo-physical characteristics of the study model. Source: Preparation by the authors.

MASS MATERIALS							NON-MASS MATERIALS
Construction	Layers	Roughness	Thickness	Conductivity	Density	Specific Heat	Thermal Resistance
			(m)	(W/m°C)	(Kg/m3)	(J/kg °C)	(m2-K/W)
Outside wall	Plaster	Rough	0.025	1.16	1800	1000	
	Brick	Medium-rough	0.2	0.81	1600	835	
	Plaster	Rough	0.025	1.16	1800	1000	
	Gypsum	Soft	0.02	0.4	800	840	
Floor	Subfloor	Rough	0.12	0.78	1600	780	
	Coating	Rough	0.12	0.78	1600	780	
Roof	Membrane						0.55
	Coating	Rough	0.12	0.78	1600	780	
	Mineral wool	Medium-rough	0.05	0.031	50	750	
	Tongue and Groove board	Medium-rough	0.25	0.11	600	1380	

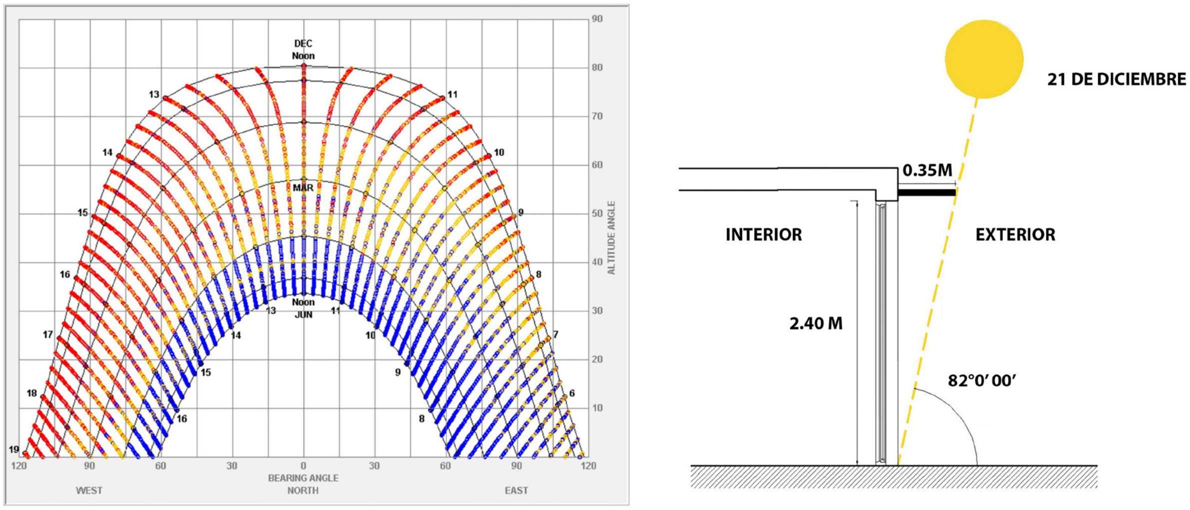

Figure 1. (a) Solar angles for the locality of Mendoza using the Climate Consultant software, (b) Calculation of the solar angle. Source: Preparation by the authors.

Figure 2. Variable conditions of the model. Source: Preparation by the authors.

Table 2. Fixed conditions of the studied model. Source: Preparation by the authors.

Fixed condition	Parameter	Description	Values	Comments
	Winter Thermostat	Temperature established as per ASHRAE 55	21°C	Standard winter clothing (0.9 clo) for sedentary activities
	Summer Thermostat	Temperature established as per ASHRAE 55	26°C	Standard summer clothing (0.5 clo) for sedentary activities
	Lighting Demand	Lighting setpoint at a central point, 0.80 m from the ground	500 lx	Daily use (08:00-23:00) with 4W/m2, without considering internal gains
	Infiltration rate	Air changes per hour	1 change per hour	Constant

time on December 21st was chosen to know the maximum solar height and, therefore, the minimum depth requirement of the protection. For Mendoza, the value of this angle is 82°. Considering the most unfavorable situation, the corresponding calculation was made, represented by an opening with a WWR of 90%. The result yielded an initial depth of 0.35 m, which was increased in ranges of 0.10 m, reaching a maximum of 0.55 m, following aesthetic and functional criteria.

- Spacing between slats: The spacing values were proportional to the depth to maintain aesthetic and functional criteria.
- Distance of solar protection from glazing: Three scenarios were evaluated: (1) the device next to the glass (distance of 0.00 m), (2) an intermediate distance of 0.10 m, and (3) a maximum distance of 0.20 m.

Figure 2 presents a graphical layout of the input variables used in the parametric analysis, allowing the different design configurations to be evaluated.

To create the model, the Grasshopper parametric design software was used with the Rhinoceros 3D visualizer on a three-month educational license. The Ladybug and Honeybee add-ons were integrated for the energy analysis. These allow climate data to be imported from Energy Plus Weather Data (EPW) files and enable running calculations using recognized engines such as EnergyPlus, Daysim, and Radiance. The OpenStudio graphical interface was also used. This connects the three-dimensional model with the simulation tool library, which assigns the properties the 3D model needs to make the simulations. Once the thermostats and setpoints were configured, the goal was to determine the energy demands for cooling, heating, and lighting, expressed in (kWh/m^2/year).

Table 2 presents the fixed conditions used for the model's energy simulation. These conditions include winter and summer thermostats, considerations for lighting demand, and the air infiltration rate.

CORRELATION STUDY

This study seeks to identify and quantify the relationships between different input variables and their impacts on the system outputs. The TTToolbox plugin was used to automate the iteration of the analysis—i.e., the repetition of the process—and record all the values of the possible combinations. The plug-in made it possible to evaluate all possible combinations, a total of 5670, and analyze the incidence of each variable using a correlation analysis. This analysis was performed using the R software and subsequently processed in Microsoft Excel.

The correlation analysis was carried out for the horizontal and vertical sunshade axes. The suitability of the chosen correlation measure was evaluated by checking the distribution of quantitative variables on each axis to verify whether they fit a multivariate normal distribution.

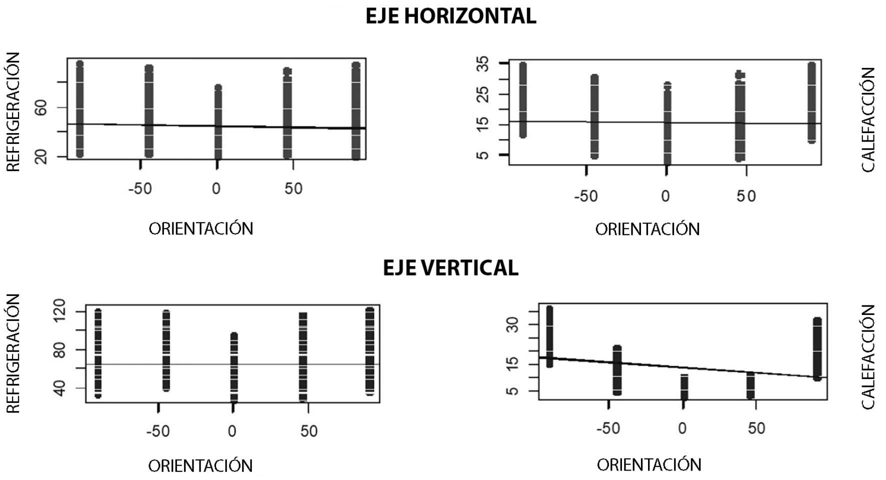

Figure 3. Correlation values of the orientation parameter. Source: Preparation by the authors.

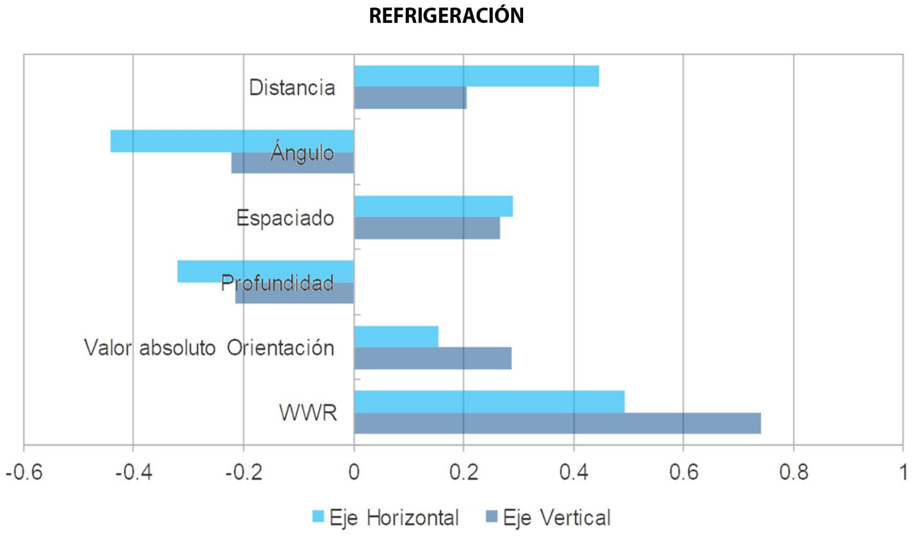

Figure 4. Cooling correlation study. Source: Preparation by the authors.

The Mardia (1970), Henze & Zirkler (1990), and Doornik & Hansen (2008) tests were performed to evaluate compatibility with this distribution. The results of these tests indicate that the variables studied do not follow a joint normal distribution, suggesting that the assumptions necessary to apply parametric tests based on normality are not met. This lack of normality questions the validity of tests such as Student's t or the analysis of variance (ANOVA), which usually require distributed data. Therefore, Spearman's correlation coefficient (1961) was used to evaluate the relationships between the variables of interest (cooling, heating, and lighting) and the parameters defined in the study (WWR, orientation, depth, spacing, angle, and distance). This coefficient does not depend on assumptions about the data distribution and is suitable for non-normally distributed data.

RESULTS AND DISCUSSION

First of all, it is essential to note that, during the process of analyzing the study parameters, a particular situation with the orientation was observed. A significant pattern was evident in the heating and cooling requirements: both extremely high and extremely low values of the orientation (i.e., in the East and West orientations) resulted in an increase in the building's energy requirements. This phenomenon manifests itself through weak correlations that highlight the importance of considering the orientation's absolute value when studying its impact on energy demand. This can be seen in Figure 3.

By focusing on the absolute value of the orientation, a noticeable increase in the magnitude of the estimated

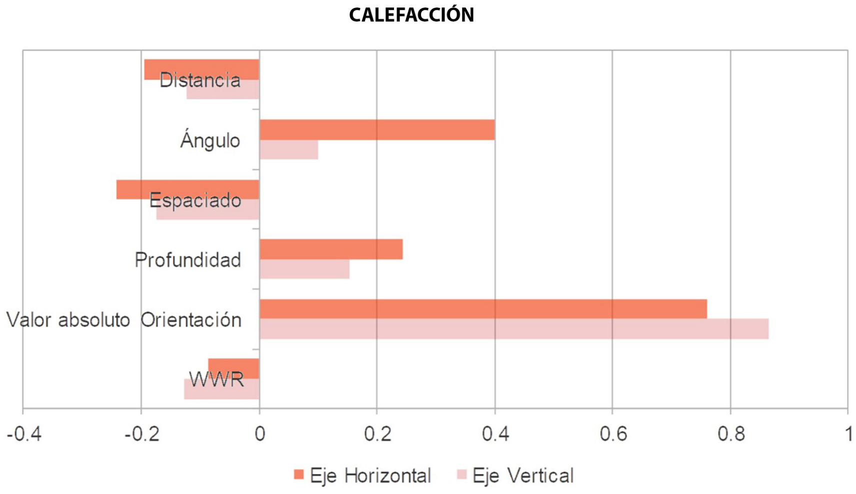

Figure 5. Heating correlation study. Source: Preparation by the authors.

coefficients is observed, accompanied by a sign change. This implies that both cooling and heating, the latter even more markedly, tend to increase as the orientation moves towards the extreme values, i.e., when it moves to the right (approaching 90) in the positive range [0-90] and when it moves to the left (approaching -90) in the negative range. These findings underline the significant influence of orientation on the building's energy requirements. For example, buildings facing east (with orientations in the range of [0-90]) or west (with orientations in the range of [-90-0]) have higher heating and cooling needs compared to those facing north (orientation close to 0).

The results of the correlation study are presented below. Figures 4, 5, and 6 show graphs for the cooling, heating, and lighting variables.

First of all, it is seen that in the iterations carried out, the arrangement of the sunshades, whether horizontal or vertical, does not affect the relationship between the parameters under study and the energy needs. For example, a higher window-to-wall ratio (WWR) increases energy demands in cooling, regardless of whether the sunshades are vertical or horizontal. As the depth of the devices increases, the demands decrease. These relationships are reflected in the correlations observed, whether positive or negative. However, each shading arrangement generates variations in the demands, as shown in the size of the corresponding bar. It is also seen that the heating and lighting variables coincide in the influence of the parameters on energy demands, while, for cooling, the influence is inverse. For example, an increase in the distance of the sunshades translates into higher energy requirements for heating and lighting, while, for cooling, the requirements decrease. This is because a greater distance allows more solar radiation to enter, reducing the need for artificial lighting and heating.

Another relevant aspect of the analysis is that the WWR parameter emerges as the most influential in cooling and lighting demands. An increase in the size of the windows leads to greater cooling requirements due to the greater inflow of solar radiation, while the demand for lighting decreases due to the greater inflow of daylight. This phenomenon suggests that large windows can significantly increase the cooling load during warmer months while reducing the need for artificial lighting during the day.

In addition, it is important to note that the relationship between absolute orientation and heating has a high correlation, which indicates a strong and direct connection between these factors. In contrast, the relationship between absolute orientation and cooling shows a moderate correlation with a downward trend, suggesting a less pronounced connection. Similarly, the relationship between absolute orientation and Illumination has a low correlation, indicating a weaker connection between these factors.

As for the design of the sunshades, several significant correlations compared to the cooling variable are highlighted both in the horizontal and vertical arrangement. In the horizontal arrangement, the cooling shows significant negative correlations with the tilt angle of the sunshades and the depth. These correlations suggest that increases in these design parameters of the sunshades are related to reductions in cooling requirements due to the

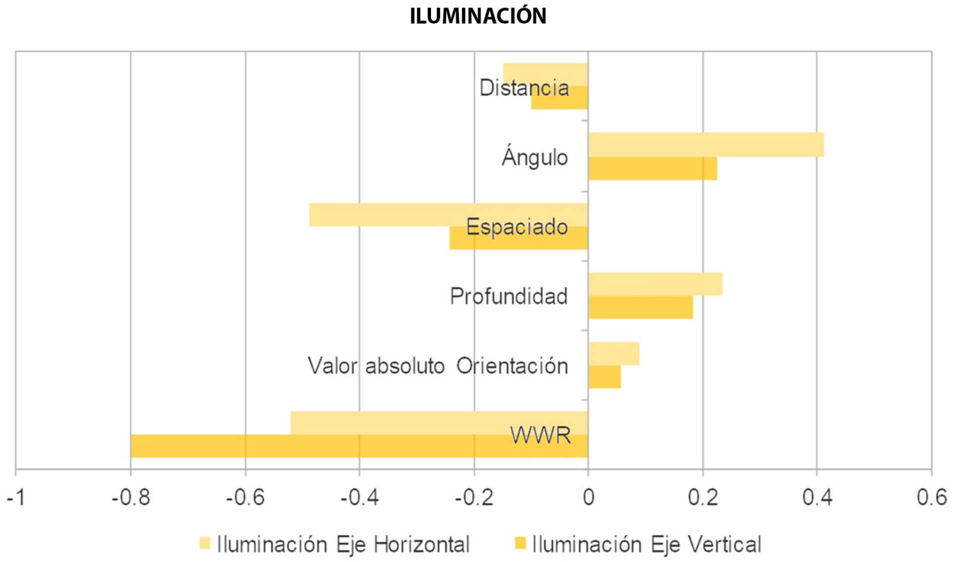

Figure 6. Lighting correlation study. Source: Preparation by the authors.

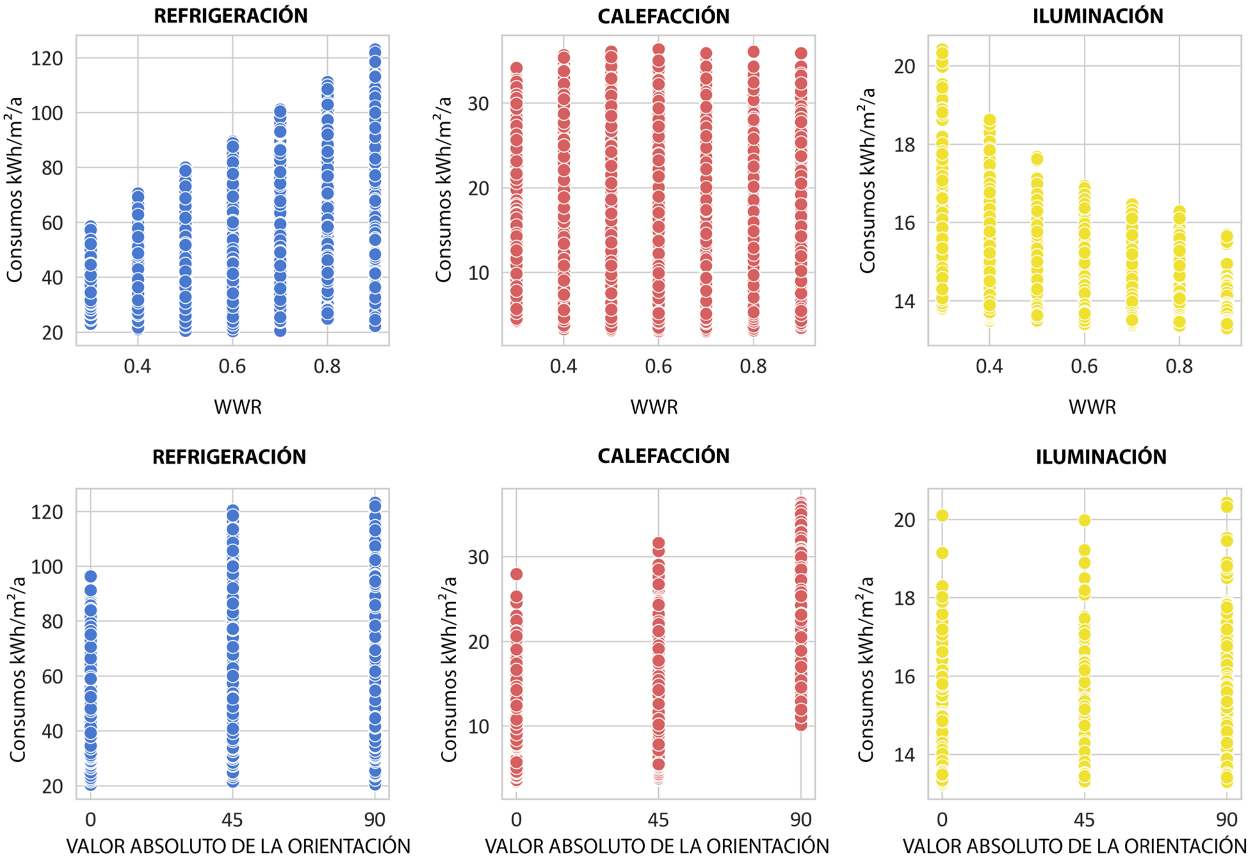

Figure 7. Energy consumption values of the most influential parameters. Source: Preparation by the authors.

greater shading they produce. For example, when the depth and angle of the sunshade slats increase, the shaded area is larger, and consequently, the cooling demand tends to be lower.

On the other hand, significant positive correlations are found between the cooling variable and the WWR, spacing, and distance of the sunshades' parameters, indicating that increases in these parameters are associated with increases in cooling requirements due to the decrease in the solar protection surface. For example, when the window area (WWR), the spacing between the sunshade slats, and the distance between the sunshade and the opening increases, the shading area tends to decrease, which increases the cooling demand because the solar radiation is not being blocked efficiently.

Finally, the heating and lighting variables show different correlations with several factors. Significant negative correlations with the window-wall ratio (WWR), orientation, spacing, and distance are highlighted, indicating that an increase in these variables leads to greater solar radiation input, resulting in a decrease in heating and lighting demands. In contrast, significant positive correlations with depth and angle are observed, indicating that increases in these variables are associated with increases in heating and lighting due to the increased shading area.

The analysis presented highlights the significant influence of the WWR (window-wall ratio) and the absolute orientation as determining variables in the energy requirements of buildings, particularly concerning the cooling, heating, and lighting demands. The graphs of Figure 7 show that an increase in the WWR causes a considerable increase in cooling energy consumption ($kWh/m^2 \cdot y$) due to a rise in solar gains, while simultaneously reducing the demand for artificial lighting due to the greater daylight penetration. This intensity in the WWR is related to a 16% increase in cooling and 13% in lighting. With regard to heating, there is an approximate 18% increase associated with the orientation. The lower graphs of the figure show that extreme orientations (±90°) are related to higher energy demands, while orientations close to 0° (north) have lower energy requirements.

CONCLUSIONS

In the context of the global environmental issue, understanding the correlations between the different energy requirements in the buildings of the city of Mendoza, Argentina is essential. This study reveals that the consumption patterns for heating and lighting are closely related, while cooling shows an inverse relationship. This dynamic suggests that adjustments in one area can significantly impact the others by affecting energy efficiency and total consumption. Although the analysis is based specifically on the climate of Mendoza, the methodology can be replicated in other regions to evaluate factors in different climatic contexts. These findings constitute the first steps towards more optimized designs, allowing progress in strategies that efficiently balance energy demands in buildings.

During the iterations carried out, it was observed that the horizontal or vertical shading arrangement does not alter the relationship between the design parameters and the energy needs. However, the strength of this relationship varies for each axis, as indicated by the coefficient values. As for orientation, energy requirements increase as they deviate from the ideal direction. Specifically, buildings facing east or west require more energy than those facing north. This adjustment directly affects the heating, cooling, and lighting systems, with the case of heating being particularly relevant. An approximate 18% increase in the interval associated with the orientation is observed, which shows that extreme orientations (±90°) are related to higher energy demands. In contrast, orientations close to 0° (north) have lower energy requirements.

The analysis of the design parameters reveals that the window-to-wall ratio (WWR) plays a crucial role in the cooling and lighting demands. A positive correlation is found between the WWR and the cooling demands, indicating that an increase in the window size expands the need for cooling due to a greater solar radiation input. However, this higher radiation reduces the need for artificial lighting, as daylight is better used, which evidences a negative correlation with lighting demands. These findings confirm the increase of 16% in cooling and 13% in lighting in the consumption intervals.

The negative correlations between the cooling demand and parameters such as the angle and depth of solar protections suggest that increasing these factors reduces the need for cooling by providing greater shade. In contrast, the positive correlations found between cooling and factors such as the WWR, the spacing, the distance of the sunshades, and the orientation of the latter indicate that an increase in these parameters is associated with increased cooling needs. This is because less solar protection allows more solar radiation to enter, increasing the cooling demand.

On the other hand, significant negative correlations were found between heating and lighting, the WWR, and the spacing and distance of the sunshades. These results indicate that an increase in these variables favors a greater solar radiation input, reducing the heating and lighting demands. In contrast, the positive correlations with the sunshades' absolute orientation, depth, and angle suggest that an increase in these parameters is associated with higher demands due to the increase in the shading area.

As for the limitations of the work, it is observed that although the study examines several factors of solar protection design, its focus is mainly geometric, which limits the consideration of material characteristics, such as those of glass and the protections themselves. This restriction opens the possibility of future studies that look closer at these material aspects.

In summary, this analysis in temperate climates with high solar exposure offers a solid basis for designing more sustainable buildings, reducing energy consumption and operating costs. It also provides valuable information for decision-making during the initial stages of the design process.

CONTRIBUTION OF AUTHORS CRediT

Conceptualization, B.A. and B.J.; Data Curation, D.S.; Formal analysis, B.A. and B.J.; Research, B.A. and B.J.; Methodology, B.A. and D.S.; Software, B.A. and D.S.; Supervision, B.J. and G.C.; Validation, D.S.; Visualization, B.A.; Writing - original draft, B.A.; Writing - revision and editing, B.A., B.J. and G.C.

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