Optimization of Window Design in Hospital Rooms for Effective Access to Daylight

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Abstract. Proper access to natural light entails a multitude of consequences for human beings, making it a highly significant aspect within the hospital setting. In consequence, it is imperative to undertake an appropriate optimization of windows in architectural design to reduce energy consumption and mitigate environmental impact, while concurrently enhancing the well-being of occupants. The aim of this study is to quantify the relative effectiveness in terms of energy consumption and natural lighting of hospital room windows, analyzing how a set of key design variables –size, proportion, position, and orientation– influence in one of the primary lighting dynamic metrics, Daylight Autonomy (DA). The results indicate that it is recommended to prioritize horizontal window designs over floor-to-ceiling alternatives, allocate a minimum area of 1.20m² to the south (greater on the north side), favor central positioning on the facade, and emphasize a southern orientation for optimal illumination.

1 Introduction

1.1 Background

Lighting design for hospital bedrooms environments must serve two primary objectives: the optimization of conditions for the execution of specific tasks and the creation of an atmosphere conducive to patient comfort [1–3]. Furthermore, it is imperative to achieve these aims while prioritizing the highest attainable level of energy efficiency [4, 5]. The paramount significance of access to natural light warrants accentuation, given its capacity to curtail the requirement for electric lighting [6], concurrently enhancing health [7, 8] and well-being [9–11].

Consequently, the determination of an appropriate parameter value for this indicator within interior spaces should be taken into consideration during the architectural design process [12–14].

In Spain, buildings account for 20% of electricity consumption [15], of which 28% is attributed to electric lighting. Therefore, the utilization of predictive computational models,

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analyzed with dynamic metric for proper window optimization [16–18], holds the potential to significantly reduce electricity consumption [19].

Traditionally, the sizing of windows in architecture was mainly driven for aesthetic considerations, disregarding quantitative criteria for optimization and energy use. However, advancements in calculation methods and the introduction of novel dynamic metrics for natural lighting have paved the way [20, 21], in recent years, a new way for enhancing window design [16], [22, 23] and lighting control strategies [21], [23–29].

Among these dynamic metrics, Daylight Autonomy (DA) stands out, allowing for greater precision in lighting calculations because it incorporates parameters such as orientation, location and sky types throughout the year [30]. Thus, this metric analyses the behavior of a given space through the annual percentage of hours of use when a minimum illuminance threshold is met by daylight alone. Consequently, utilizing DA makes it possible to effectively tailor the placement and size of windows to ensure an adequate influx of natural light, thus minimizing the need for electric lighting during daylight hours. This approach not only contributes significantly to the reduction of energy usage [31], but also enhances the visual comfort and well-being of occupants [2], [13]. It is worth noting that natural light is the most suitable source for promoting a good circadian entrainment for occupants, since the chrono-regulation of the human being has evolved according to the variable spectra of daylight [32]. Finally, dynamic metrics, such as DA, also align with sustainability goals and promoting energy-efficient practices in healthcare facility design.

1.2 Objectives

The main aim of this study is to employ an established methodology [17] that utilizes the calculation of the DA metric for the assessment and enhancement of window design in hospital rooms located in Mediterranean regions. The goal is to improve the working conditions of healthcare personnel and enhance patient comfort, providing a sufficient light to carry out the task, while the circadian stimulus is promoted by a proper use of daylight. In the context of a case study, a hospital room model is situated in Seville and subjected to calculations using the Climate Studio tool. This analysis explores the impact of various variables on window design, encompassing size, proportion, position, and orientation.

2 Methodology

2.1 Calculation Protocol

Fig. 1 represents the flux diagram that leads the presented research. Firstly, 3 different window shapes are selected -square, horizontal and vertical- in accordance with 3 different sizes –12%, 22% and 32%–. The selected openings are facing North or South, depending on the calculation model.

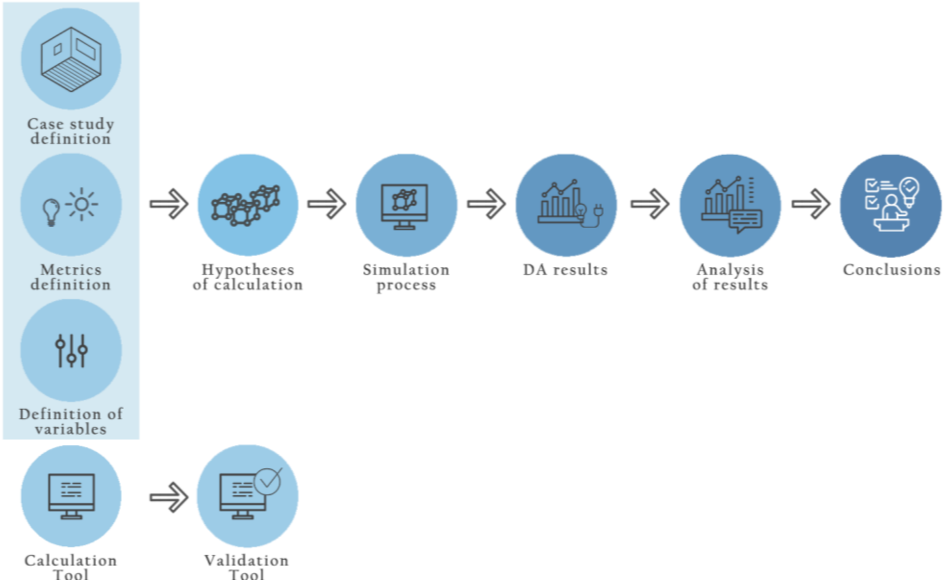

Fig. 1. Flux diagram of the calculation protocol.

2.2 Case study definition

The model under study is an existing hospital room 1.80 m wide by 4.0 m deep by 2.2 m high, with the window located in one of its smaller surface walls. Window size is a variable defined as a ratio of surface in the façade. The inner surfaces have the photometric characteristics described in **Table 1**, considering them as diffuse reflectors:

Table 1. Surface characteristics of materials used.

Materials	Reflectance	Solar Transmittance
Floor	0.60	-
Walls	0.80	-
Ceiling	0.80	-
Window	0.90 (joinery)	0.70 (glass)

The location of the virtual room chosen to perform the analysis is Seville, Spain, with Latitude 37.42°, Longitude 5.40° and mainly clears skies. Its interior is discretised by an overlaid grid of points at 0.5 m x 0.5 m intervals, positioned at a height of 0.76 m above the floor level [33], simulating what would be a plane for patient recognition, as shown in **Fig. 2**. From this grid, the central longitudinal section is taken for analysis.

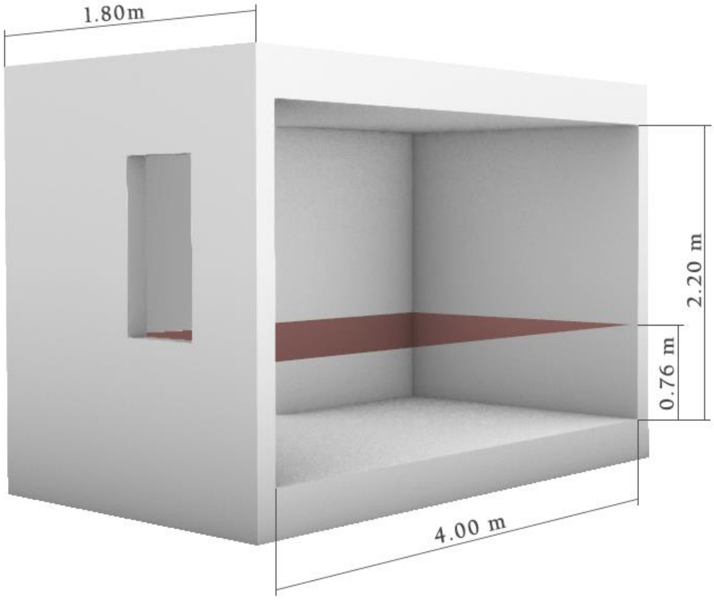

Fig. 2. Hospital room model.

2.3 Selection of variables and calculation models definition

The design of the window located on the exterior facade is modified according to the following variables described in **Table 2**:

Table 2. Selected variables.

Window size	Window proportion	Window position	Window orientation
12%	Horizontal	Centered	North
22%	Vertical	Descentered	South
32%			

Combining these variables generates 16 calculation models, as shown in **Fig. 3** and **Table 3**.

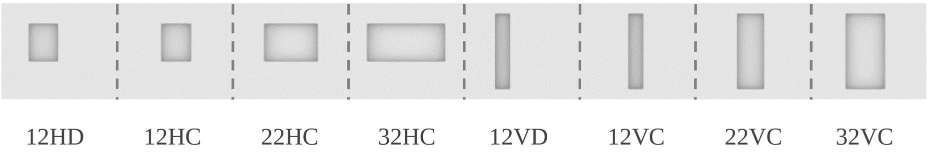

Fig. 3. Calculation models.

Table 3. Hypotheses of calculation.

Model	Window/ facade	Window surface (m²)	Window proportion	Window position	Window orientation
12HDN	12%	0.66	Horizontal	Descentered	North
12HCN	12%	0.66	Horizontal	Centered	North
22HCN	22%	1.21	Horizontal	Centered	North
32HCN	32%	1.76	Horizontal	Centered	North
12VDN	12%	0.66	Vertical	Descentered	North
12VCN	12%	0.66	Vertical	Centered	North
22VCN	22%	1.21	Vertical	Centered	North
32VCN	32%	1.76	Vertical	Centered	North
12HDS	12%	0.66	Horizontal	Descentered	South
12HCS	12%	0.66	Horizontal	Centered	South
22HCS	22%	1.21	Horizontal	Centered	South
32HCS	32%	1.76	Horizontal	Centered	South
12VDS	12%	0.66	Vertical	Descentered	South
12VCS	12%	0.66	Vertical	Centered	South
22VCS	22%	1.21	Vertical	Centered	South
32VCS	32%	1.76	Vertical	Centered	South

2.4 Selecting the calculation metrics

Daylight Autonomy (DA) is one of the most widely used dynamic metric. This concept was proposed in 1989 by the Association Suisse des Electriciens [34] and subsequently redefined by Reinhart [35]. It is defined as "the percentage of occupied time in a space during which the interior natural light reaches the level of illuminance necessary for conducting required tasks" [35].Therefore, the higher the value of DA, the less time spent relying on electric lighting to compensate for lighting deficiencies.

This metric is based on numerous sky models, requiring knowledge of the climatic data of the building's location and performing intricate calculations. This requires the use of lighting simulation programs, which calculate the value for each point. DA is mathematically defined by the following equation:

$$DA = \frac{\Sigma_i (wf_i \cdot t_i)}{\Sigma_i t_i} \in [0,1] wf_i = \begin{cases} 1\ if\ E_D \geq E_R \\ 0\ if\ E_D < E_R \end{cases}$$

Where t_i is the occupied time in the year, w_{fi} is the weighting factor which depends on the illuminance threshold, ED is the daylight illuminance measured at a given point under real sky conditions, and ER is the illuminance threshold.

2.5 User requirements

The illuminance threshold (ER) for the DA calculation of this study is established at 500 lux, a recommended threshold for reading and patient recognition [1]. The occupancy period with daylight hours is defined from 8:00 to 17:00 from Monday to Friday, without breaks, including Daylight Saving Time (DST).

2.6 Selecting the calculation and validation tool

The selected tool for developing the simulations is Climate Studio for Rhino, a dynamic lighting calculating software based on the Radiance calculation engine created by C. Reinhart [35, 36]. Rhinoceros 7.0 has been used to create the 3D model, as it is the interface that supports Climate Studio. **Table 4** shows the calculation parameters used by this programme in this study.

Table 4. Parameters of calculation.

Parameters	Value	Parameters	Value
Ambient Bounces	7	Ambient Divisions	1500
Ambient Super-samples	100	Ambient Resolution	300
Ambient Accuracy	0.05	Limit Reflection	10
Specular Threshold	0.0000	Specular Jitter	1.0000
Limit Weight	0.0040	Direct Jitter	0.0000
Direct Sampling	0.2000		

This tool, along with its calculation engine Radiance [37], has been previously validated in various studies [38, 39], both through the CIE Test Cases [40–45] and by comparing it with annual lighting values obtained from monitoring an existing test cell located in Seville, designed for emulating a bedroom [20], [46, 47].

3 Calculating and analysis of result

The values obtained in each model for Daylight Autonomy (*DA*) are shown in **Table** 5, north-oriented, and **Table** 6, south-oriented. It should be noted that sun shading devices or remote obstructions have not been considered when running the simulations.

Table 5. Values of *DA* for north-oriented models in the central axis.

distance from facade (m)	12HDN	12HCN	22HCN	32HCN	12VDN	12VCN	22VCN	32VCN
0.61	0.66	0.88	0.92	0.93	0.28	0.76	0.89	0.92
1.12	0.51	0.73	0.88	0.91	0.25	0.40	0.83	0.89
1.63	0.30	0.44	0.79	0.88	0.02	0.11	0.73	0.85
2.14	0.05	0.11	0.73	0.83	0.00	0.00	0.61	0.78
2.65	0.00	0.00	0.57	0.80	0.00	0.00	0.50	0.77
3.16	0.00	0.00	0.47	0.75	0.00	0.00	0.45	0.71
3.67	0.00	0.00	0.45	0.73	0.00	0.00	0.34	0.69

Table 6. Values of *DA* for south-oriented models in the central axis.

distance from facade (m)	12HDN	12HCN	22HCN	32HCN	12VDN	12VCN	22VCN	32VCN
0.61	0.86	0.90	0.93	0.93	0.78	0.86	0.90	0.92
1.12	0.82	0.83	0.90	0.92	0.75	0.77	0.86	0.90
1.63	0.77	0.77	0.86	0.89	0.69	0.72	0.83	0.87
2.14	0.69	0.76	0.84	0.87	0.64	0.69	0.79	0.85
2.65	0.67	0.65	0.81	0.85	0.52	0.57	0.77	0.84
3.16	0.65	0.59	0.76	0.84	0.50	0.51	0.75	0.83
3.67	0.53	0.53	0.76	0.82	0.48	0.50	0.71	0.82

Models oriented towards the north yield lower values compared to those oriented towards the south, exhibiting an increase ranging between 1% and 4%. In cases where the window area is enlarged, a corresponding rise in the value of this indicator has been observed. This enhancement is noticeable both at the position nearest to the window and at the rear of the room, showcasing an increase ranging from 12% to 35%. Thus, with window-to-wall ratios of 12% facing south (1.2 m^2) and 22% facing north, it becomes possible to achieve DA values above 50% throughout virtually the entire central axis of the space under study. The proportion of the window also influences the outcomes. In north-

oriented models, a horizontal window configuration results in improved light ingress by 3% to 38%, while in south-oriented models, the enhancement ranges from 2% to 16%.
Fig. 4 and **Fig. 5** show the evolution of each model as the end of the room is reached, enabling a comparison of each calculation model and how the selected variables impact the final value of DA.

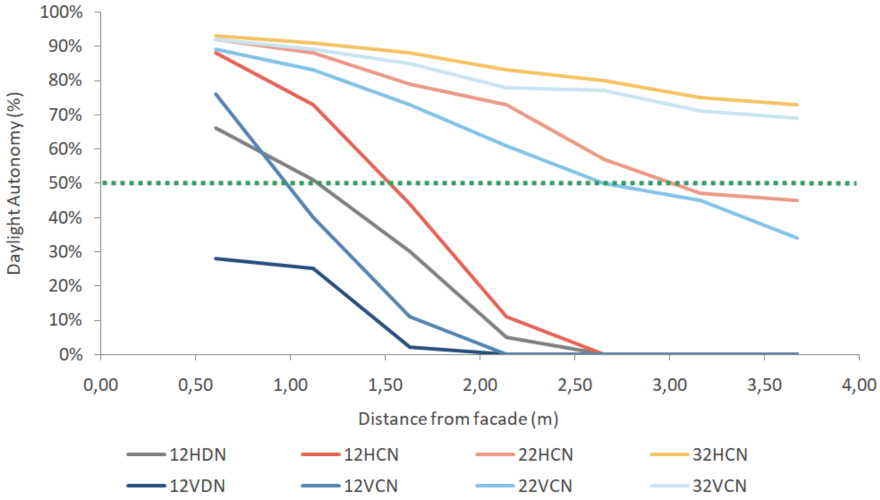

Fig. 4. Evolution of DA by depth. North-oriented models.

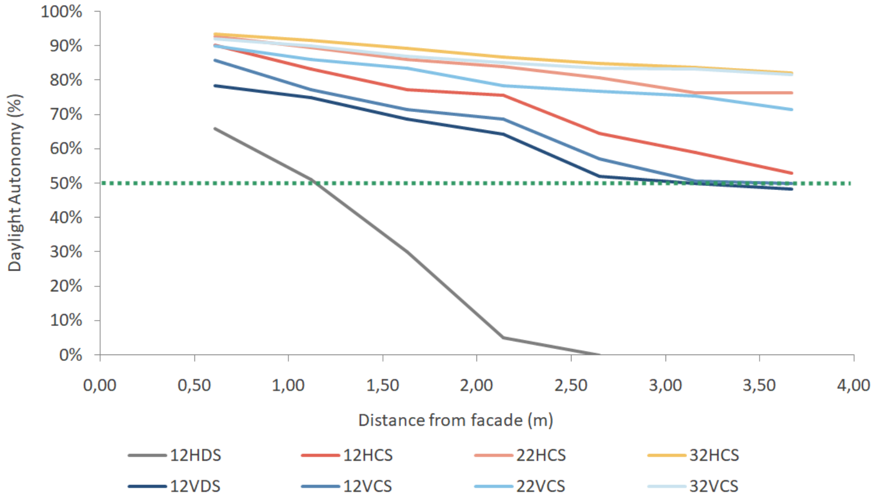

Fig. 5. *Evolution of DA by depth. South-oriented models.*

These graphs reflect the relevance of orientation in daylighting, as well as which variable has a significant impact in each orientation. North-oriented models (**Fig. 4**) generally exhibit lower DA values, both at the point closest to the window and at the back of the room, sometimes even falling below the threshold. Conversely, south-oriented models (**Fig. 5**) yield more consistent values throughout the room.

3.1 Study of limitations

Considering the existing constraints of this study, it is recommended that forthcoming investigations be undertaken. These studies should prioritize the augmentation of the number of globally representative locations to enhance the applicability of the findings. Furthermore, there is a need to broaden the range of room typologies, occupancy schedules, and lighting thresholds. It would also be beneficial to introduce factors such as remote obstructions to assess their impacts on the daylight access.

Moreover, an important aspect not addressed is the evaluation of the maximum window-to-wall ratio. Consequently, it would be of interest to conduct a comprehensive multi-parameter analysis incorporating metrics related to glare and thermal energy consumption. This analysis would provide insights into determining the optimal window-to-wall ratio.

Lastly, the deployment of a lighting monitoring system in existing building scenarios holds the potential to furnish empirical data for the purpose of validating the simulation-derived outcomes.

4 Conclusions

The comparison of the different hypotheses of calculation allows us to understand which variables most influence the obtained results.

South-oriented models yield higher values than north-oriented models, by a range of 1 - 4%. With a larger window area, it has been observed that this indicator's value increases, both at the point closest to the window and at the back of the room, by 12 - 35%.

The proportion of the window also influences the results, with a horizontal window improving light access by 3 - 38% in north-oriented models and by 2 - 16% in south-oriented models.

This study concludes the following recommendations regarding window design:

- Prioritize horizontal designs over floor-to-ceiling alternatives.
- A minimum area of 1.20m² to the south (greater on the north side).
- Favor central positioning on the façade rather than off-centre.
- Emphasize a southern orientation than northern for optimal illumination.

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