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Optimization method for perforated solar screen design to improve daylighting using orthogonal arrays and climate-based daylight modelling

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Abstract

This paper analyses the influence of different perforated solar screens (PSS) in annual daylight conditions expressed using climate-based daylight metrics. The PSS design require parametric studies that are often complex and time consuming due to a large number of simulations. Hence, a new methodology is proposed to optimize PSS design by applying Design of Experiments using Orthogonal Arrays (DOA). A case study from the DOA perspective has been conducted, which involves an office space in Seville, Spain. The goal is to assess the effect of the following PSS design variables in daylighting performance: perforation percentage, matrix, shape and orientation. DOA results reveal that optimized PSS can increase daylit area by 33% and reduce over lit area by 35%, compared with reference models with no PSS. DOA method reduces the number of simulations from the 256 required to 16, so it could save time during the initial stages of building design.

Keywords: perforated solar screens; optimal design; orthogonal arrays; climate-based daylight metrics; daylight availability

1 Introduction

The Energy Performance of Buildings Directive (EPBD) highlights the importance of reducing building energy consumption given that this accounts for over 40% of total energy consumption in the European Union (EC 2010). In Mediterranean climates, characterized by many sunny sky days, much of the available daylight is not used to its full potential (Lim, Ahmad, and Ossena 2013). In fact, artificial lighting consumption accounts for over 30% of the total energy consumption in Spanish office buildings (MITC 2007).

However, daylighting is a way to reduce lighting energy consumption. Suitable architectural design and consideration of local climate variability can ensure a balanced thermal and visual indoor environment, reducing the use of artificial lighting and active thermal conditioning systems (EC 2010;

Bodart and De Herde 2002; Galasiu, Atif, and MacDonald 2004). However, solar radiation is also one of the main reasons for overheating and glare, particularly in summer, so it must also be taken into account (Bodart and De Herde 2002).

Building envelopes are crucial to daylighting as they act as interfaces for building-urban surroundings (Lai and Hokoi 2015). They offer protection from direct solar radiation, provide daylight and allow visual contact (Zawidiski and Kahn 2014). Fully glazed façades in buildings gained popularity in the 1990s. This popularity coincided with the appearance of new solar control systems on façades to provide solar protection and reduce glare and thermal demand generated by emerging modern architectural trends (Blanco et al. 2014).

In this situation, perforated solar screens (PSS) were implemented not only for solar control but also to meet the expectations for the visual image of envelopes (Wang, Rivard, and Zmeureanu 2006; Villalba, Monteoliva, and Pattini 2011). Their design has been governed by aesthetic, morphological and symbolic criteria rather than by parameters relating to their contribution to the improvement of indoor daylighting conditions or the reduction of thermal gains (Villalba, Monteoliva, and Pattini 2011; Goia, Haase, and Perino 2013).

PSS are flat opaque perforated panels, relatively thin in relation to their length and width, which form a double skin for building façades. Placed in front of building fully glazed façades, PSS are not merely decorative. The organization of their perforations filters out incident direct sunlight, which is prevented from directly penetrating into spaces while still allowing users to view outside. The opaque parts of the screen reflect sunlight and act as solar control systems (Aljofi 2005; Pattini et al. 2011).

In recent years, certain design variables for some perforated solar protections and their influence in daylighting and energy consumption have been studied in order to take them into account from the initial building design stages. Sherif, El-Zafarany, and Arafa (2012) find that perforated solar protections on residential building windows reduce air conditioning consumption by 30%, especially with perforation percentages of 80% to the west and north and 90% to the east and south. Sherif, Sabry, and Rakha (2012) recommend using perforation percentages of 40-90% on windows of residential buildings in desert locations, to obtain 200 lux during 50% of annual occupation hours, over at least 30% of space.

Aljofi (2005) determines that the circular shapes openings of solar protection on windows tend to result in lower Daylight Factor (DF) percentages, compared to quadrangular shapes. In addition, the highest daylight contributions are found in the central areas of spaces. Sherif et al. (2011) recommend the use of perforated screens on windows, with a shape ratio (vertical: horizontal) of openings of 18:1 to the north and 1:1 to the south, as they obtain 200 lux on at least 70% of the workplane and reduce energy consumption in desert areas.

Etman, Tolba, and Ezzeldin (2014) conclude that quadrangular openings used in west-facing façades in office buildings in Cairo (Egypt) improve indoor illuminance distribution of 54-78% with illuminance levels of 300-500 lux, for the 6 simulated hours in the 3 days selected. Sabry et al. (2011) conclude that the mean illuminance in the space is directly proportional to the horizontal axial rotation angle of perforated protections used in residential building windows in desert climates.

As seen before, perforated solar screens improve daylighting conditions and reduce energy consumption. Although these studies focus on their application on windows in desert climates, PSS constitute a second façade for buildings and are used in a wide range of climate conditions.

In view of the above, PSS design requires the consideration of a wide variety of variables. A comprehensive study of possible variable combinations requires a large amount of different models, which is difficult to manage. As a result, most research concentrates on a single design variable regardless of its relationship with others.

Nevertheless, statistic Design of Experiments (DOE) tools can simplify the interrelated study of a large number of variables, reducing the number of experiments or simulations and obtaining maximum information which may be of use in the design of PSS (Park 2007). These tools include Design using Orthogonal Arrays (DOA) which selects a representative fraction of all possible combinations of factors so as to distribute the experiments uniformly within the test range, accurately representing the overall situation. This method is highly efficient in reducing the number of experiments required and in achieving optimal combination levels (Taguchi and Yokoyama 1993). The DOA method has been used efficiently in different fields of science, contributing valid conclusions and optimizing processes (Franek and Jiang 2013).

While not specifically applied in the design of PSS, DOA has been applied in the formal design of buildings. Yi, Srinivasan, and Braham (2015) used it to study basic architectural design parameters such as geometry, size and shape of windows, obstructions, orientation, etc. These successfully optimize the design process and reduce construction costs. Chlela et al. (2009) used DOA to study some characteristics of the building envelope: thermal properties of walls, transmissivity and solar absorption of glazing, etc. Simulations were reduced from 1024 to 32, successfully describing the energy consumption model for offices and reducing heating, cooling and lighting demands by 81%, 63% and 45%, respectively.

Gong, Akashi, and Sumiyoshi (2012) use it to optimize 7 passive strategies to reduce annual thermal loads and replace HVAC systems in winter. Wang, Zmeureanu, and Rivard (2005, 2006) implement it to reduce the environmental impact of the building's lifecycle, optimizing orientation, window size, and the insulation materials and properties of green buildings.

Using DOA, Zhu et al. (2013) put the following construction design variables into order of importance: glazing > outer wall > floor > solar protection > ceiling; minimizing carbon emissions, as well as lighting, equipment and climatization consumption. Wei, Zhao, and Chen (2010) implement it to optimize the window design parameters suited to each Chinese location studied, achieving energy savings of 25% for warm climates and 34% for cold climates. Huang and Wu (2014) apply it to establish the order of importance in daylighting and solar control conditions of the parameters of Chinese splayed windows.

As can be observed, DOA presents several advantages in the field of design, especially as regards the effectiveness of results and the reduction of the number of experiments and/or computational simulations arising from the combination of diverse design variables. Therefore, this study develops a new methodology based on DOA to optimize PSS design. It aims to study the interrelation of the impact of different PSS design variables on annual indoor daylighting conditions. A case study has been conducted from the perspective of DOA, which involves a typical office space in the Mediterranean Climate of Seville, Spain. For this, the following design variables have been selected: perforation percentage (PP), matrix (M), shape (S) and orientation (O).

The results obtained in the case study are presented in three phases. The first one analyses the orthogonal array (OA) proposed for each daylighting metric, describing and classifying the importance of the effects of each design variable. In addition, optimal combinations are obtained to ensure useful illuminances on the workplane. OA results are corroborated in the second phase by carrying out daylighting simulations to verify optimal metric results from DOA. In the third phase the optimized series are contrasted with the reference model in order to assess daylighting conditions with and without PSS. Finally, conclusions are stated and future research is suggested.

2 Methodology for applying orthogonal arrays to optimize PSS design

Practical work usually involves three or more variables or factors, which requires multifactor analysis. Multi-factor experiments include full factorial design and fractional factorial design. Full factorial design tests all possible combination of variables. For a full factorial experiment with five factors and four levels, the number of trials is $5^4=625$. The number of full factorial experiment is large and time consuming that it is difficult to be implemented.

As an alternative, the DOA method is used. DOA selects representative points from full factorial experiment in a way that the points are distributed uniformly within the test range and thus can represent the overall situation. The advantages of DOA method are that the number of trials needed to complete the experiment is relatively small and the test results could be analysed through range analysis and variance analysis. This method is highly efficient for the arrangement of multi-factor experiment with optimal combination levels (Zhu et al. 2013).

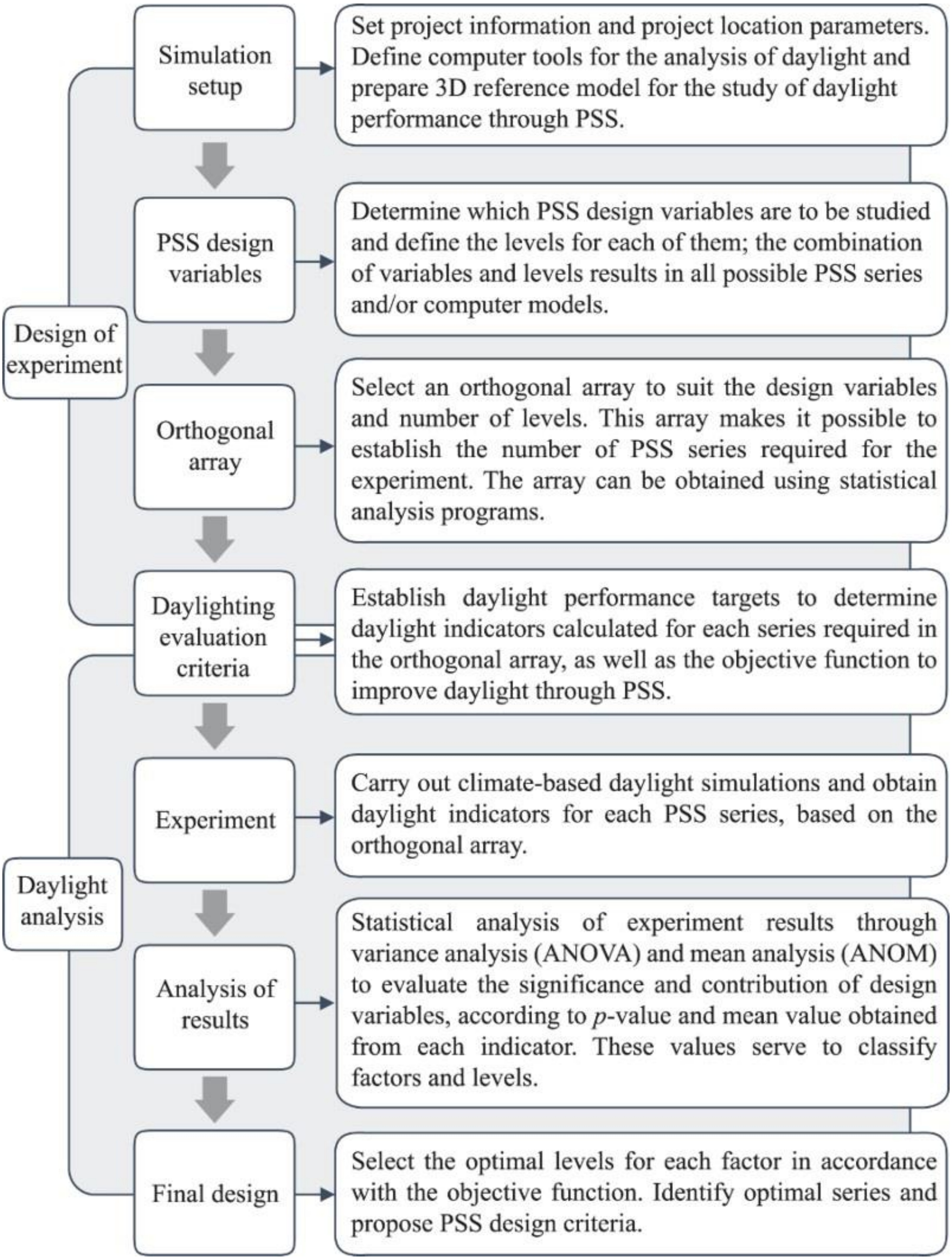
In DOA, the selection of experiments is based on orthogonal array (OA). This is represented by a matrix which is expressed as $L_N (l)^k$, where L is orthogonal array, N the number of experiments, l the level of factors, and k the number of factors or columns (Park 2007). OA follows two properties: on each column the number of occurrences is the same for each factor on different levels; the combination of levels of factors is complete and balanced on every row. These two principles represent the advantages of OA: uniform dispersion and regular comparable. In other words, any factor on any level is compared with all other factors on different levels (Zhu et al. 2013).

This study proposes a new methodology which applies DOA in the optimization of PSS design in order to carry out a cross-section comparison of different PSS design variables, evaluating the effect of each of these and reducing the number of computational simulations required to calculate daylighting conditions. Some of the terminology used in DOA is similar as that used in PSS design (Park 2007). Table 1 presents these equivalences.

DOA	PSS Design	Description of the design
Factor	PSS design variables	Characteristics of the PSS which affect indoor daylighting conditions
Level	Values of design variables	Values which each design factor or variable may have
Characteristic function	Objective function	Daylighting conditions expressed in indicators, which can be maximized or minimized

Table 1. Terminology in DOA and in PSS design.

The methodology proposed consists of seven steps, described in Figure 1. These steps are developed and explained in greater detail in the description of the case study.



Set project information and project location parameters. Define computer tools for the analysis of daylight and prepare 3D reference model for the study of daylight performance through PSS.

Determine which PSS design variables are to be studied and define the levels for each of them; the combination of variables and levels results in all possible PSS series and/or computer models.

Select an orthogonal array to suit the design variables and number of levels. This array makes it possible to establish the number of PSS series required for the experiment. The array can be obtained using statistical analysis programs.

Establish daylight performance targets to determine daylight indicators calculated for each series required in the orthogonal array, as well as the objective function to improve daylight through PSS.

Carry out climate-based daylight simulations and obtain daylight indicators for each PSS series, based on the orthogonal array.

Statistical analysis of experiment results through variance analysis (ANOVA) and mean analysis (ANOM) to evaluate the significance and contribution of design variables, according to *p*-value and mean value obtained from each indicator. These values serve to classify factors and levels.

Select the optimal levels for each factor in accordance with the objective function. Identify optimal series and propose PSS design criteria.

Figure 1. Methodology proposed for the design of PSS applying orthogonal arrays.

3 Case study for DOA methodology

3.1 Simulation setup

Daylight calculations are carried out using Radiance-based software Daysim 3.1e (Ward and Shakespeare 1998; Reinhart 2010). The climate file used is IWEC for the Spanish city of Seville (DOE 2010), at 37°42’N, 5°9’W, with Mediterranean climate. Table 2 shows the set of simulation parameters according to the typical scene 2 used in Radiance (Reinhart 2010).

Ambient bounces	Ambient division	Ambient sampling	Ambient accuracy	Ambient resolution	Direct threshold	Direct sampling
7	1500	100	0.1	300	0	0.2

Table 2. Simulation parameters

The reference model is a 49 m2 surface from a space measuring 7 m x 7 m x 3 m. This is deep and wide enough to be adapted to different variations of the office typology, such as group offices or combined use (IDAE 2011). The space has one fully glazed façade with a double-clear-glazing with a visual transmittance of 78.1%. The height of the workplane is 0.80 m above ground level, with sensors points placed 0.25m apart and 0.50 m from walls. Reflectances of the model surface are found in Table 3. The reference model is represented in Figure 2.

Ceiling	0.80
Floor	0.20
Wall	0.50
PSS (opaque Surface)	0.90

Table 3. Reflectances of model surfaces.

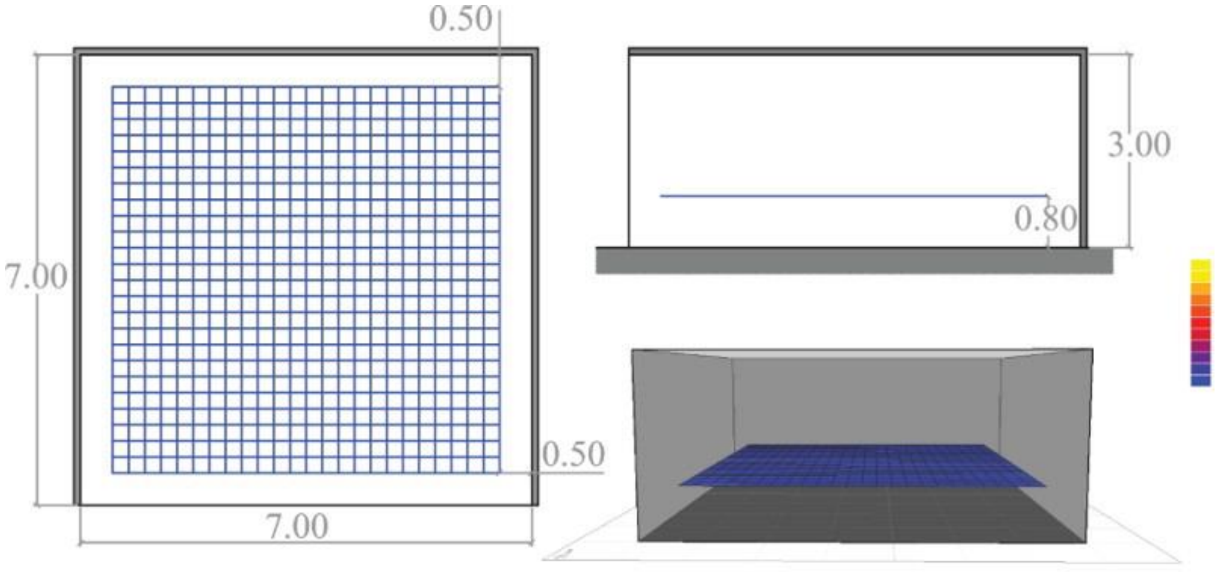


Figure 2. Reference model and calculation grid. Floor, cross-section and perspective.

3.2 PSS design variables

Commonly, PSS are flat opaque perforated panels, without thickness in relation to their length and width, which form an outer skin for building fully glazed façades. The perforations configurations filters out incident sunlight and their design is widely varied. Notwithstanding, different parameters can be assessed in order to study the influence of PSS in daylighting indoors.

In this work, specific PSS input parameters are as follows: The PSS are externally mounted at a distance of 0.05 m from the fully glazed façade. The PSS dimensions are 7 m in width and 3 m in height (the thickness is not considered). Four design variables that are usually determined at the conceptual design stage and that have critical influence on daylighting performance are selected to characterize PSS. Each design variable takes four levels. The four PSS design variables and their four level values are described below and in Figure 3.

(1) Perforation percentage (PP): Ratio of the total surface of the openings to the wall. Four PP are proposed for study: 50%, 37.5%, 25% and 12.5%.

(2) Matrix (M): Distribution of openings on the screen achieving the established perforation percentages. Four regular matrixes are established: 12x28, 9x21, 6x14 and 3x7. The distance between openings for each matrix is of 0.25 m, 0.33 m, 0.50 m and 1.00 m, respectively; it is measured from the centre and is vertically and horizontally equidistant.

(3) Shape (S): Shape of each individual opening. Four regular shapes are proposed: circular, hexagonal, quadrangular and triangular. The different-shaped openings have the same opening area when M and PP are the same.

(4) Orientation (O): The application of the PSS on a façade oriented following the four cardinal points is analysed: North (N), South (S), East (E) and West (W).

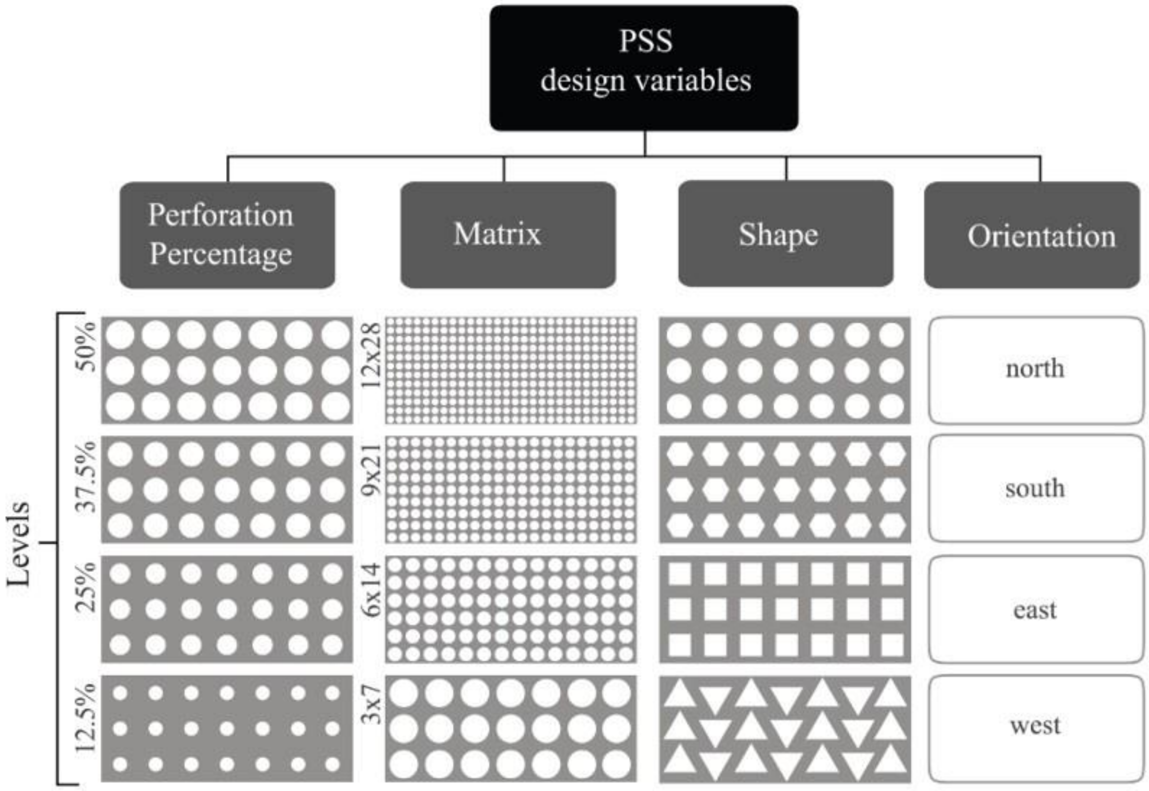


Figure 3. PSS design variables.

The full combination of the four levels of each variable generates 256 PSS configurations. This would lead to 256 computational models and/or simulations, representing a considerable investment in computational time and effort. Thus, implementing OAs is of great useful in the study of the interrelation of the four design variables as it makes possible to reduce the number of study models such as it can be seen in the next step. The nomenclature of the PSS configurations follows the combination of its variables, as laid out in Figure 4. For example, a PSS with a PP of 50%, M of 12x28 and S circular applied on a façade oriented at north is named 501CN.

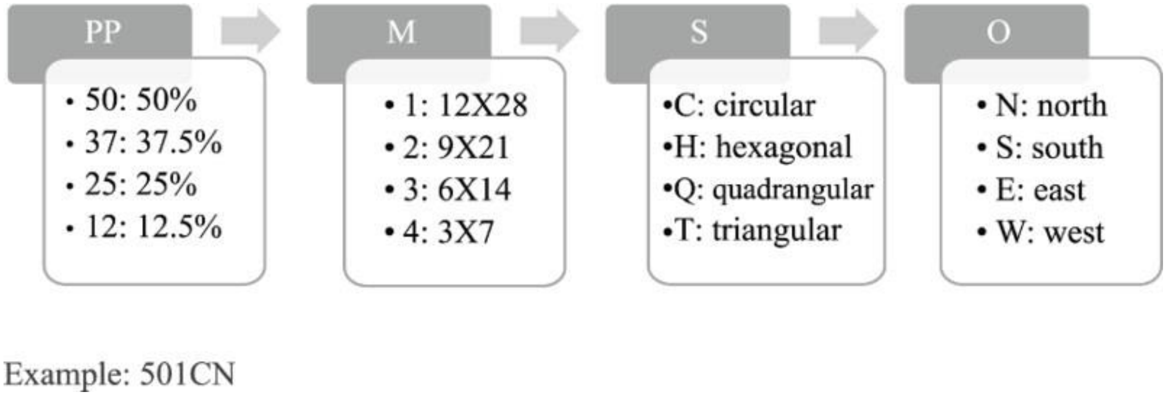


Figure 4. Nomenclature of PSS; the reference model is named REF100 followed by the letter referring to orientation.

3.3 Orthogonal array

For this stage an orthogonal array is selected to compare the cross-section of the design variables in relation to their impact on daylighting conditions. This phase focuses on the order of importance and the significance of the variables.

Choosing orthogonal array is the most important issue in DOA. After the factors and their levels are determined, appropriate orthogonal array can be chosen. The key of using an orthogonal array is to choose the smaller orthogonal as much as possible in order to reduce the number of simulations.

The orthogonal array selected in this work consists of four factors with four levels each, following the criteria of orthogonality and efficiently predesigned arrays by Taguchi: $L_{16}(4^4)$ (Taguchi and Yokoyama 1993). Table 4 summarizes the factors and levels of the orthogonal array.

Levels	Factors			
	Perforation percentage (PP)	Matrix (M)	Shape (S)	Orientation (O)
1	50%	12x28	Circular	North
2	37.5%	9x21	Hexagonal	South
3	25%	6x14	Quadrangular	East
4	12.5%	3x7	Triangular	West

Table 4. Factors and levels of $L_{16}(4^4)$.

The application of orthogonal array $L_{16}(4^4)$ uses only a fraction of the possible 256 combinations of the four factors with four levels each (4^4=256 runs), reducing the number of simulations to 16. Table 5 presents these 16 combinations or PSS, obtained using a statistical analysis program (Minitab 2000). At each factor column, each level appears at the same time. Each row represents a run or simulation; the cell values indicate the factor settings for the simulations of PSS.

Simulation	PSS	Factors			
		PP	M	S	O
1	501CN	1 (50%)	1 (12x28)	1 (Circular)	1 (N)
2	502HS	1 (50%)	2 (9x21)	2 (Hexagonal)	2 (S)
3	503QE	1 (50%)	3 (6x14)	3 (Quadrangular)	3 (E)
4	504TW	1 (50%)	4 (3x7)	4 (Triangular)	4 (W)
5	371HE	2 (37.5%)	1 (12x28)	2 (Hexagonal)	3 (E)
6	372CW	2 (37.5%)	2 (9x21)	1 (Circular)	4 (W)
7	373TN	2 (37.5%)	3 (6x14)	4 (Triangular)	1 (N)
8	374QS	2 (37.5%)	4 (3x7)	3 (Quadrangular)	2 (S)
9	251QW	3 (25%)	1 (12x28)	3 (Quadrangular)	4 (W)
10	252TE	3 (25%)	2 (9x21)	2 (Triangular)	3 (E)
11	253CS	3 (25%)	3 (6x14)	1 (Circular)	2 (S)
12	254HN	3 (25%)	4 (3x7)	2 (Hexagonal)	1 (N)

13	121TS	4 (12.5%)	1 (12x28)	4 (Triangular)	2 (S)
14	122QN	4 (12.5%)	2 (9x21)	3 (Quadrangular)	1 (N)
15	123HW	4 (12.5%)	3 (6x14)	2 (Hexagonal)	4 (W)
16	124CE	4 (12.5%)	4 (3x7)	1 (Circular)	3 (E)

Table 5. Orthogonal Design $L_{16}(4^4)$.

After calculating daylighting indicators for these 16 PSS, the orthogonal array can be used to determine the primary and secondary order of the impact of the four PSS design variables on the annual indoor daylighting conditions. In addition, the optimal combination of PSS design variables and levels can be obtained according to the objective function specified in section 3.4.2.

3.4 Daylighting evaluation criteria

The next step in the methodology is to calculate daylight metrics for the 16 PSS selected in the orthogonal array. In this study, the daylighting criteria used for assessment are based on climate-based daylight metrics results and consist of Daylight Autonomy (DA), Useful Daylight Illuminance (UDI) and Daylight Availability.

3.4.1 Climate-based daylight metrics (CBDM)

As the name suggests, climate-based daylight metrics are derived from anual illuminance profiles, i.e., hourly time series of interior illuminances due to daylight that are generated using a local climate file (Reinhart and Walkenhorst 2001). In order to become usable for design, this massive amount of data has to be converted into an intuitive metric. The first step in this conversion process is to decide on which time of the year the analysis should be based. A common choice is to concentrate of the times when the investigated space will be occupied since daylight 'needs witnesses' to have an effect (Reinhart, Mardaljevic, and Rogers 2006). The next step of the analysis is to decide what daylighting levels to consider 'adequate'. Here the two currently most commonly used approaches are Daylight Autonomy (DA) and Useful Daylight Illuminance (UDI).

DA is defined as the percentage of the occupied hours of the year when a minimum illuminance threshold is met by daylit alone (Reinhart and Walkenhorst 2001). However, the notion of simply achieving a threshold illuminance has restricted value for two reasons (Mardaljevic and Nabil 2005). Firstly, DA does not give significance to those daylight illuminances that fall below the threshold (for example, 300 lux), but which can be valued by occupants and may also reduce the electric lighting loads. Secondly, DA makes no account of the amount by which the threshold illuminance is exceeded at any particular instant. This is significant because high levels of daylight illuminance are known to be strongly associated with occupant discomfort.

Notwithstanding, DA is promoted through the IES LM-83 (IES 2012) as spatial Daylight Autonomy (sDA) that defines a point in a space to be 'daylit' if the daylight autonomy at the point for a target illuminance of 300 lux and for occupancy from 8 to 18 h is at least 50% (in short, DA300,50%). Thus, this daylight metric is expressed as a percentage of area and must meet at least 55 and 75% of analysis area for a 'nominally acceptable' and 'favorably/preferred' space, respectively. Besides, this daylight metric is required in LEED Version 4.0 (USGBC, 2013) to receive the daylight credits. The main advantage over traditional DA is that sDA returns a single value representing the whole analysed area. However, similarly to DA, it makes no account of the amount by which the illuminance threshold is exceeded.

In contrast, the UDI scheme is founded on a measure of how often in the year daylight illuminances within a range are achieved. Thus, UDI is defined as the percentage of occupied hours when daylight levels on the workplane are 'useful' for the occupant, that is, neither too dark nor too bright. Thereby, UDI defines lower and upper illuminance thresholds of 100 lux and 3000 lux for daylight to be 'useful'. Due to the two levels, each point in a space has three UDI values. The upper bin (UDI>3000lux) is meant to represent times when an oversupply of daylight might lead to visual and/or thermal discomfort, the lower bin (UDI<100lux) represents times when there is 'too little' daylight and the intermediate bin (UDI100-3000lux) represents 'useful' daylight. Moreover, the 'useful' UDI bin is subdivided into a 'supplementary' (100-300 lux) and an 'autonomous' (300-3000 lux) range. For UDI-supplementary, additional artificial lighting may be needed to supplement daylight for common tasks such as reading. For UDI-autonomous, additional lighting will most likely not be needed (Nabil and Mardaljevic 2005; Mardaljevic 2015).

Recently, a new metric has been proposed termed 'Daylight Availability' that is meant to amalgamate DA and UDI information into a single one (Reinhart and Wienold 2011). Through this metric, the space area is represented as follows: 'daylit', 'partially daylit', 'over lit' and 'non-daylit' areas. Firstly, the 'daylit area' (also termed 'fully daylit area') percentage is reported according to DA300,50% (Reinhart, Rakha, and Weissman 2014) and must meet at least 55 and 75% of the room area for 'nominally acceptable' and 'favorably/preferred' space, respectively (IES, 2012; USGBC, 2013).

Secondly, the 'partially daylit' area is measured when DA for a target illuminance of 150 lux and for occupancy from 8 to 18 h is at least 50% (in short, DA150,50%). According to the authors, one particular benefit of DA150,50% is that it shows a transition area between 'fully daylit' and 'non-daylit', which starts to account for the subjective nature of light evaluations of spaces (Reinhart, Rakha, and Weissman 2014). Because this 'partially daylit area' necessarily includes the 'fully daylit area', the remaining area is the 'non-daylit'.

Finally, the 'over lit' area is reported when an oversupply of daylight is assumed for at least 5% of the working year. An oversupply is assumed if the illuminance level is above ten times the target illuminance that in this case corresponds to 3000 lux. This also might signify a potential for glare, according to a study (Mardaljevic et al. 2012) in which a potential correlation between the UDI>3000 and Daylight Glare Probability was introduced. The 5% criterion was selected as an analogue method to thermal assessments according to BS EN 15251 (BSI 2007). This threshold of 5% signifies the potential for heat gain (Reinhart and Wienold 2011).

The 'Daylight Availability' concept and its corresponding ranges of daylight illuminances can be summarized in Figure 5. As previously mentioned, it can be inferred that the 'fully daylit area' is part of the 'partially daylit area' since there are no upper limits in DA; besides, the 'over lit area' is included in the 'fully daylit area'; lastly, the remaining area is the 'non-daylit'.

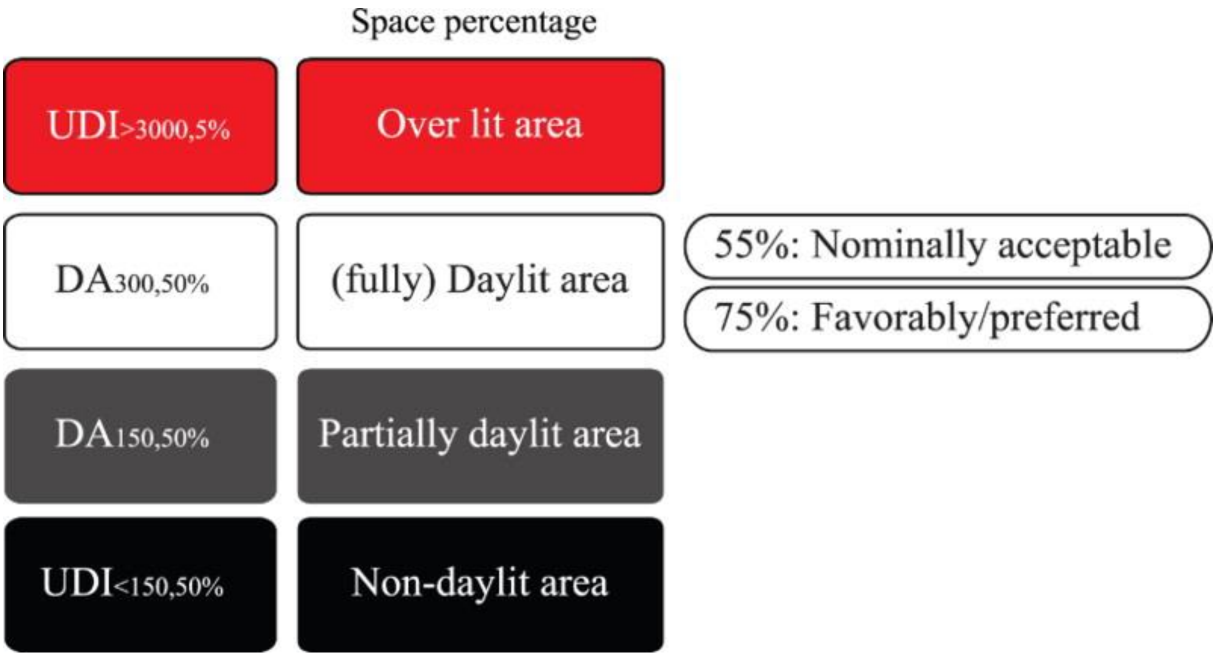


Figure 5. Climate-based daylighting metrics accounted in Daylight Availability.

However, this work aims to account the space area lit exclusively with useful daylight illuminance levels. For this reason, the space percentages of Figure 5 are overlapped on top of each other in order to identify the equivalent area for each one of them.

Consequently, the space percentages considered in this work are termed in the following way:

- The 'actual partially daylit area' is the 'partially daylit area' minus the 'fully daylit area'; so, it can include only those daylight illuminances within the range $UDI_{150\text{-}300,50\%}$. The term 'actual' is used here for a distinction from the area that includes all illuminances of $DA_{150,50\%}$.

- The ‘actual daylit area’ is the ‘fully daylit area’ minus the ‘over lit area’; so, it can include only those useful illuminances within the ranges $UDI_{300\text{-}3000,50\%}$ + $UDI_{>3000,<5\%}$. The term ‘actual’ is used here for a distinction from the area that includes all illuminances of $DA_{300,50\%}$.
- The ‘over lit area’ still accounts illuminances over 3000 lux for at least 5% of the working year ($UDI_{>3000,5\%}$).
- The ‘non-daylit area’ accounts illuminances under 150 lux for at least 50% of working year ($UDI_{<150,50\%}$)

Therefore, non-daylit + actual partially daylit + actual daylit + over lit area = total space area (workplane) as it can be summarized in Figure 6. These areas are calculated as follows. The space percentage value is determined by first predicting the annual timeseries of daylight illuminance values at each sensor point on a grid using software Daysim 3.0. Then, the software Excel for conducting mathematical analyses is used for analysing these results. The occurrence of illuminance values for each grid point within each of the ranges is determined as a percentage of the evaluation period (8 to18 h for every weekday of the year). Lastly, the percentage of sensors exceeding the 50% or 5% of annual time are quantified for obtaining the corresponding areas.

3.4.2 Objective function

The aim of this analysis is to obtain illuminances that are useful to occupants and to minimize excessive illuminance that can be associated with glare and thermal discomfort. Hence, the ‘actual daylit area’ should be maximized because it accounts the space area lit exclusively with useful daylight illuminance levels (primarily within the UDI-autonomous range of 300-3000 lux) at the specified percentages of time. In contrast, the ‘non-daylit’, ‘actual partially daylit’ and ‘over lit’ areas should be minimized because they can be associated with occupant discomfort. Figure 6 shows the objective function according to this last description.

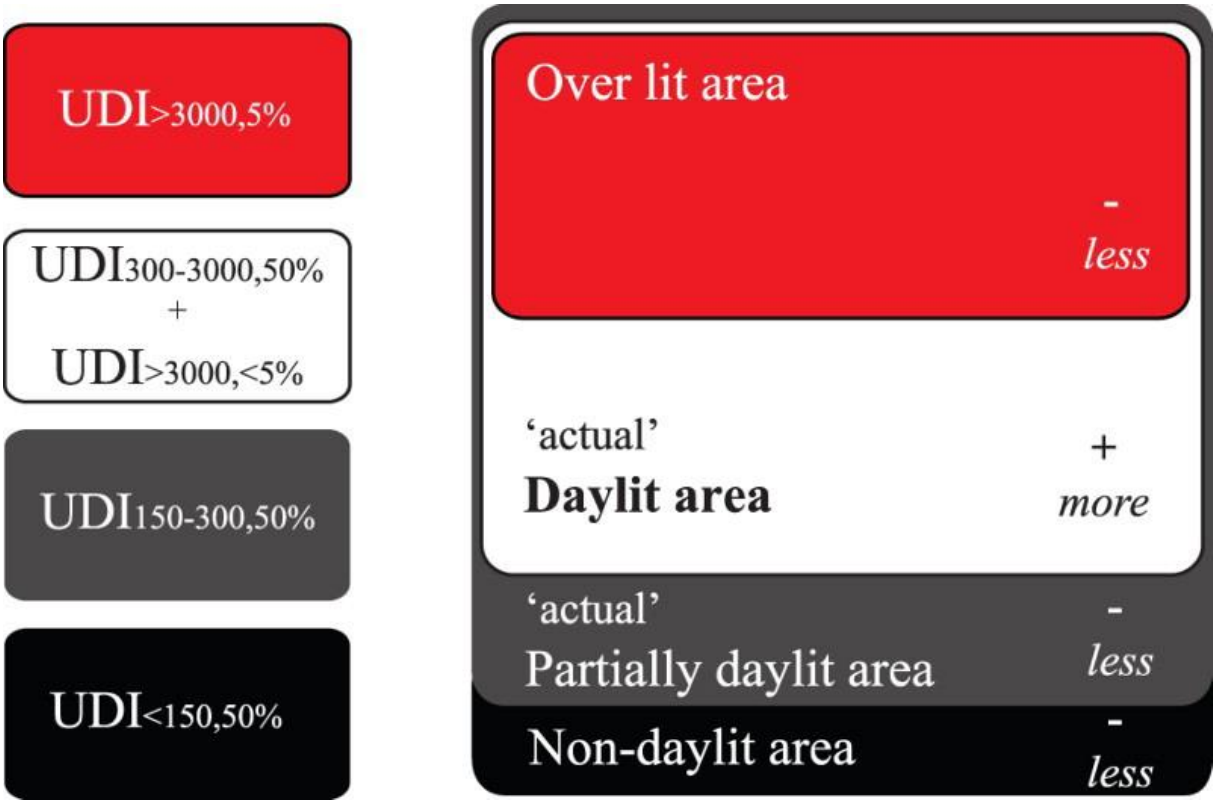


Figure 6. Daylight metrics and objective function.

4 Experiment results

4.1 Analysis of orthogonal array

OA analysis aims to calculate the combination of optimal levels of variables and to propose optimal combinations to maximize useful illuminances for at least 50% of the working year and to minimize illuminances exceeding 3000 lux for at least 5% of the working year (actual daylit area). Table 6 shows the results obtained in the 16 computational simulations of array $L_{16}(4^4)$, for each daylight metric. Additionally, the fully daylit area has been added in order to compare results obtained through the objective function vs those achieved according to code officials.

Simulation	PSS	Space percentage				Fully daylit area (%)
		Non-daylit area (%)	'actual' Partially daylit area (%)	'actual' Daylit area (%)	Over lit area (%)	
1	501CN	0	0	89	11	100
2	502HS	0	0	43	57	100
3	503QE	0	0	42	58	100
4	504TW	0	0	47	53	100
5	371HE	0	0	61	39	100
6	372CW	0	0	57	43	100
7	373TN	0	7	91	2	93

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8	374QS	0	0	47	53	100
9	251QW	0	34	29	37	66
10	252TE	0	34	36	30	66
11	253CS	0	16	41	44	84
12	254HN	0	40	60	0	60
13	121TS	32	31	16	20	37
14	122QN	57	27	16	0	16
15	123HW	47	28	12	13	26
16	124CE	39	25	20	16	36

Table 6. Results of orthogonal array $L_{16}(4^4)$.

Table 7 presents the variance analysis (ANOVA) and statistical significance (p-value) of experimental results when $\alpha=0.05$. The sum of squares (SS) indicates the relative importance of each factor; the factor with the greatest sum of squares has the greatest impact (Minitab 2000). Accordingly, the ANOVA results show significance to 5% of PP for all metrics, S for the actual and fully daylit areas and O for the actual daylit, fully daylit and over lit areas. About SS results, PP is the most important factor for all metrics, except for the over lit area where O is the most important. The second result is S for the actual partially daylit area, O for the actual and fully daylit areas and PP for the over lit area. In case of the non-daylit area, M, S and O show equal relevance.

Metric	Factor	GL	SS	F	*p*	Significance
Non-daylit area	**1 (PP)**	**3**	**5765.84**	**69.22**	**0.00**	*
	2 (M)	3	83.30	1.00	0.50	
	3 (S)	3	83.30	1.00	0.50	
	4 (O)	3	83.30	1.00	0.50	
	Residual error	3	83.30			
	Total	15	6099.05			
'actual' Partially daylit area	**1 (PP)**	**3**	**3257.79**	**26.69**	**0.01**	*
	2 (M)	3	34.98	0.29	0.83	
	3 (S)	*3*	*149.52*	*1.23*	*0.44*	
	4 (O)	3	95.49	0.78	0.58	
	Residual error	3	122.05			
	Total	15	3659.83			
'actual' Daylit area	**1 (PP)**	**3**	**5190.64**	**100.20**	**0.00**	*
	2 (M)	3	256.52	4.95	0.11	
	3 (S)	3	710.30	13.71	0.03	*
	4 (O)	*3*	*2104.64*	*40.63*	*0.01*	*
	Residual error	3	51.80			
	Total	15	8313.91			
Over lit area	*1 (PP)*	*3*	*2212.88*	*19.70*	*0.02*	*
	2 (M)	3	64.67	0.58	0.67	
	3 (S)	3	290.34	2.58	0.23	
	4 (O)	**3**	**3884.58**	**34.58**	**0.01**	*
	Residual error	3	112.35			

	Total	15	6564.81			
Fully daylit area	**1 (PP)**	**3**	**13386.60**	**1130.62**	**0.00**	*
	2 (M)	3	68.90	5.82	0.09	
	3 (F)	3	219.10	18.50	0.02	*
	4 (O)	*3*	*353.00*	*29.82*	*0.01*	*
	Error residual	3	11.80			
	Total	15	14039.40			

Note: The asterisk denotes 5% significance; characters in bold denote first place, and italics second place, in importance.

Table 7. Variance analysis of orthogonal array metrics (α=0.05).

Table 8 presents the results of the mean analysis (ANOM) of array $L_{16}(4^4)$. Delta value is an index used to compare the relative magnitude of effects depending on ortogonal design (Park 2007). Classification or rank is based on Delta values: 1 for the highest Delta value, 2 for the second highest, and so on. Rank indicates the relative importance of each factor to the results of the different metrics (Minitab 2000). Table 8 also shows the optimal combinations which obtain the highest and the lowest percentages of the daylight metrics according to the objective function.

Mean values	Total space area (workplane)				Fully daylit area (%)
	Non-daylit area (%)	'actual'Partially daylit area (%)	'actual' Daylit area (%)	Over lit area (%)	
PP					
T1 (50%)	**0**	**0**	55	45	**100**
T2 (37.5%)	**0**	2	**64**	34	98
T3 (25%)	**0**	31	41	28	69
T4 (12.5%)	44	28	16	**12**	29
Delta	44	31	48	32	71
Rank	1	1	1	2	1
M					
T1 (12x28)	**8**	16	**49**	**27**	76
T2 (9x21)	14	15	38	33	71
T3 (6x14)	12	**13**	47	29	**76**
T4 (3x7)	10	16	43	30	74
Delta	6	4	11	6	5
Rank	3	4	4	4	4
S					
T1 (Circular)	10	**10**	**52**	28	**80**
T2 (Hexag.)	12	17	44	27	71
T3(Quadrang)	14	15	34	37	71
T4 (Triang.)	**8**	18	48	**26**	74
Delta	6	8	18	11	9
Rank	3	2	3	3	3
O					
T1 (N)	14	19	**64**	**3**	67
T2 (S)	**8**	**12**	37	44	**80**
T3 (E)	10	15	40	36	75
T4 (W)	12	15	36	37	73
Delta	6	7	28	40	13

Rank	3	3	2	1	2
Optimal PSS	501TS	503CS	371CN	121TN	503CS

Note: Characters in bold indicate the optimal levels for each factor according to the objective function. Combination of these levels results in the optimal PSS.

Table 8. Results for means of $L_{16}(4^4)$.

For the non-daylit area, the first place in importance is for PP (44) but the other three variables show equal relevance (6). Figure 7 indicates that the non-daylit area increases as PP decreases, however, it still zero for all PP larger than 25%. M and S show fluctuations with results close to each other although optimal values for achieving the lowest values of the non-daylit area are 12x28 and triangular. The most advisable orientation to reduce the non-daylit area is S and the least suitable is N.

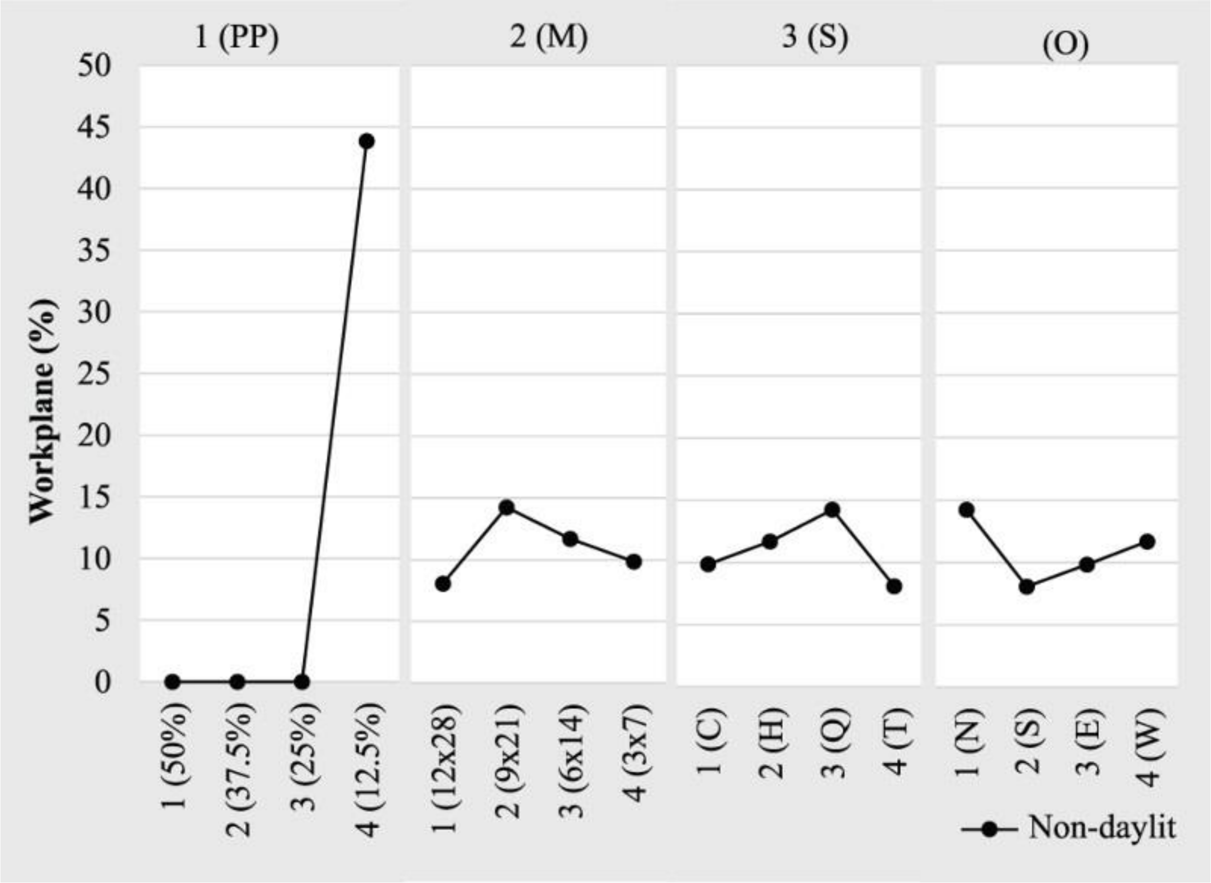


Figure 7. Main effects for the non-daylit area means

For the actual partially daylit area, the order of effects is PP (31) > S (8) > O (7) > M (4). Figure 8 shows that the actual partially daylit area achieves its maximum value at PP 25%, closely followed by PP 12.5%, and its minimum value at PP 50%. Regarding M and S, the lowest actual partially daylit area is for 6x14 and circular, respectively, while the other three levels show fluctuations with results very close to each other. About O, the lowest value is achieved at S and the highest value at N, while similar results are obtained for E and W.

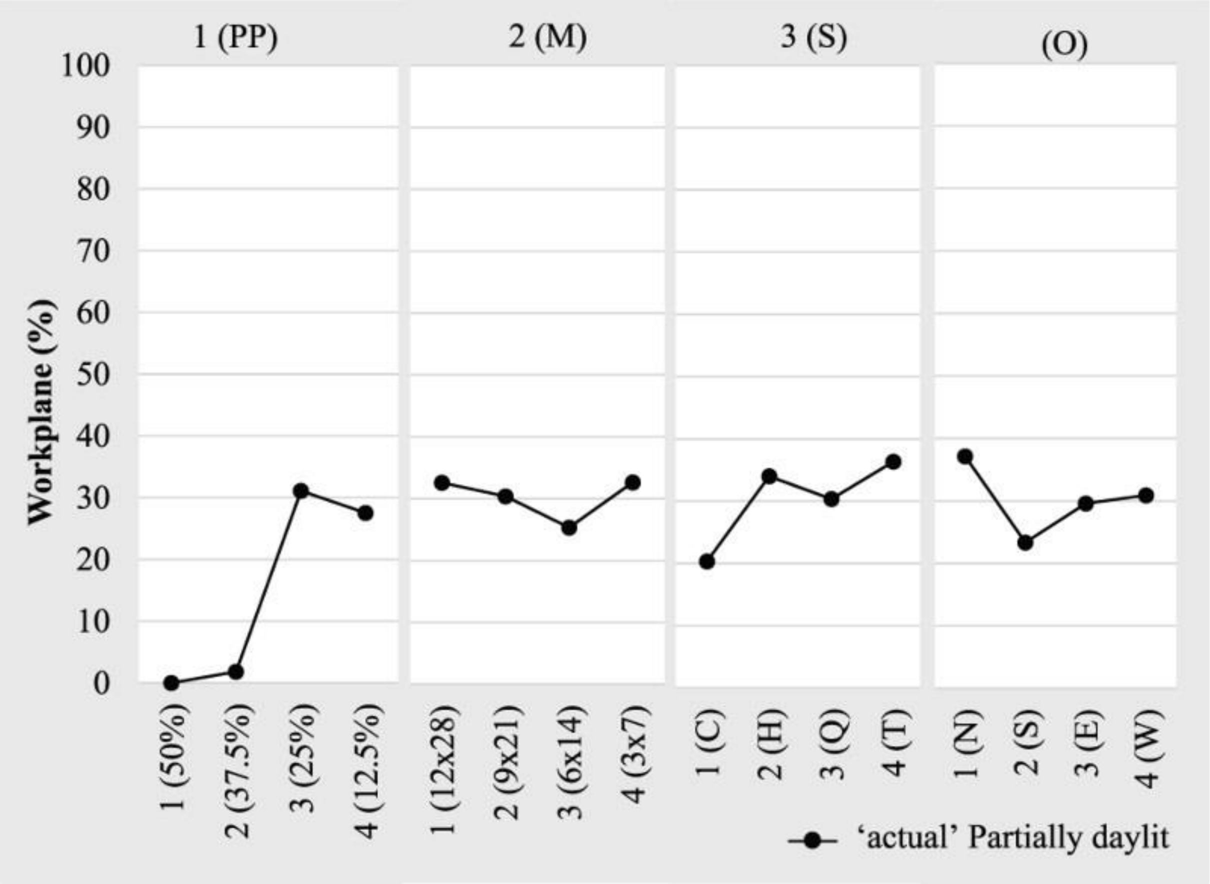


Figure 8. Main effects for the 'actual' partially daylit area means.

For the actual daylit area, the order of effects is PP (48) > O (28) > S (18) > M (11). Figure 9 indicates that the actual daylit area achieves its maximum value at PP 37.5%, followed by PP 50%, and its minimum value at PP 12.5%. M shows fluctuations but it is observed that the highest value is achieved at 12x28, closely followed by 6x14. About S, the highest value is reached in the circular level and the lowest value in the quadrangular one. Regarding O, the highest value is achieved at N and the lowest value is obtained at S.

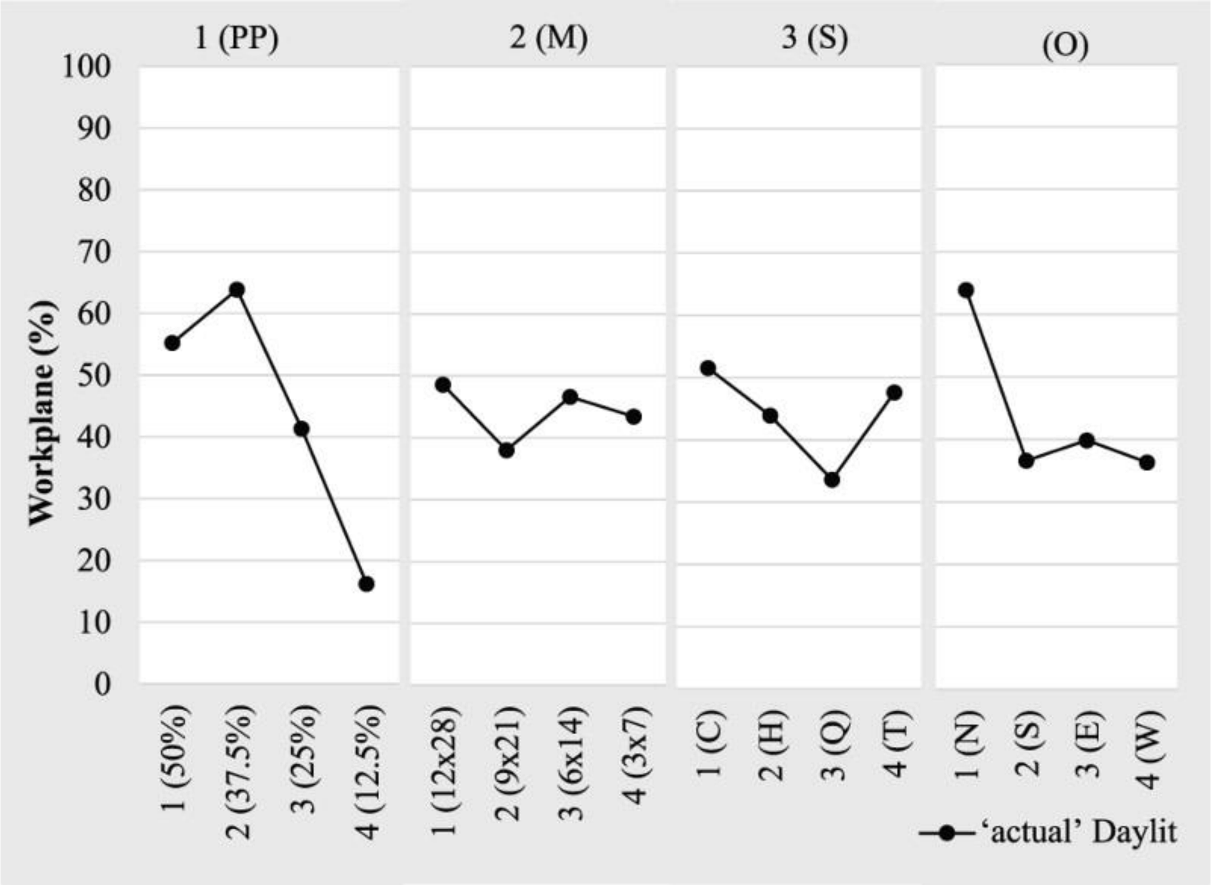


Figure 9. Main effects for the 'actual' daylit area means.

As regards the over lit area, the order of effects is O (40) > PP (32) > S (11) > M (6). Figure 10 shows that the over lit area decreases as PP decreases. M shows fluctuations although it is observed that M 12x28 slightly achieves the lowest values. For S, the quadrangular level gets the highest values while the other three levels achieves lower values and very close to each other. About O, level N is by far the best option because it provides a considerably lower over lit area (3%) in comparison with the other cardinal points that achieves more than 35%. Besides, S is the least favourable orientation because it increases this area, almost over the half of the workplane.

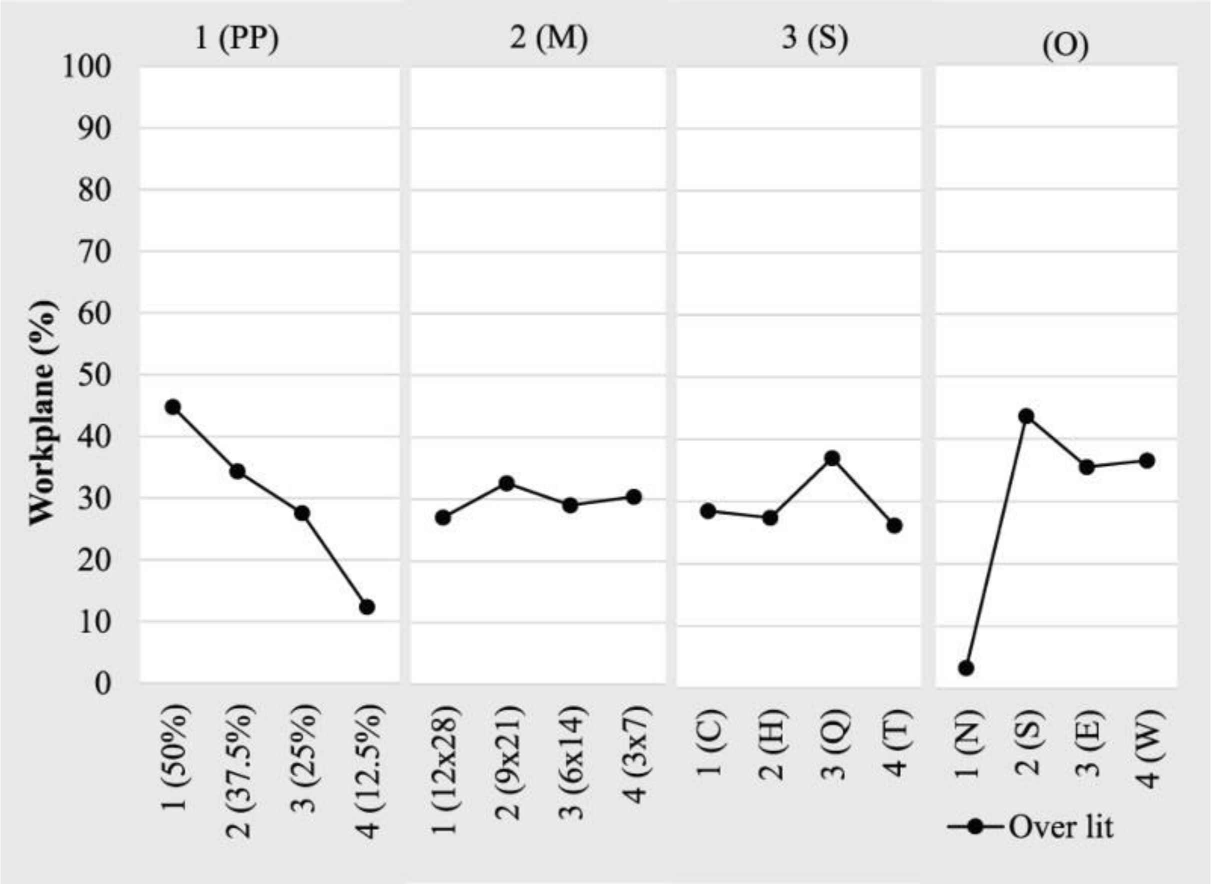


Figure 10. Main effects for the over lit area means.

For the fully daylit area, the order of effects is PP (71) > O (13) > S (9) > M (5). Figure 11 indicates that the fully daylit area decreases as PP decreases. M shows fluctuations with results very close to each other but it can be observed that the highest value is achieved at 6x24, closely followed by 12x28. About S, it also shows fluctuations but the highest value is reached in the circular level while the other three levels show results very close to each other. Regarding O, the highest value is achieved at S and the lowest value is obtained at N.

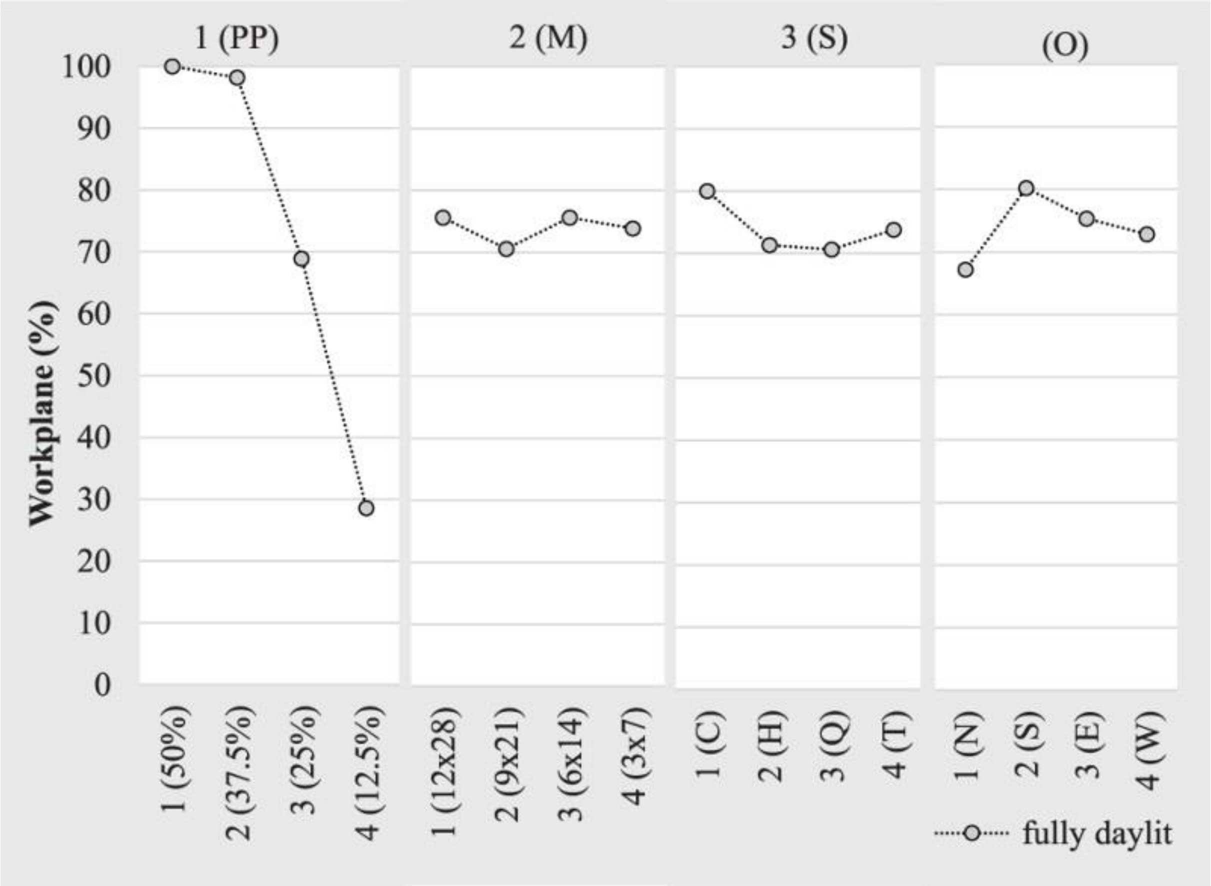


Figure 11. Main effects for the fully daylit area means.

It is important to mention here that the fully daylit area is reported in this paper in order to compare the percentage of workplane that is considered 'fully daylit' according to code officials and green rating systems, against the percentage of workplane that is assessed as 'actual daylit' in this work. About this, Figure 12 shows the comparison between the cited daylit areas and also indicates with the two red dashed lines the nominally acceptable and favorably/preferred percentages of the workplane (55 and 75%, respectively) that are required in LM-83 and LEED V.4.

From this, the results of the fully daylit area indicate that only PP 12.5% do not achieve the nominally area. Moreover PP 50 and 37.5%, M 6x14 and 12x28, S circular and O south and east exceed the favorably area while the rest of levels are within the nominally and favorably areas. With these results, it could be concluded that all levels, except PP 12.5%, are a good alternative for designing PSS according to code officials and green rating systems; however, this assumption is not certainly valid. For example, from Figure 10 it can be observed that PP 50% and south orientation also get the highest levels of the over lit area which result in a contradictory proposal (the best levels of PP and O for maximizing $DA_{300,50\%}$ are 50% and south, but the most recommendable for minimizing $UDI_{>3000,5\%}$ are 37.5% and north). Thereby, the fully daylit area by itself do not allow identifying clearly the optimal levels to design PSS. This is because the fully daylit area also maximize excessive illuminances as there is no upper limit in $DA_{300,50\%}$.

In contrast, from Figure 12 it can be observed that the results of the actual daylit area do not necessarily reach the nominally acceptable or favorably/preferred spaces. About this, only PP 37.5 and 50%, and O north meet at least 55% of the workplane, so just these levels can be considered nominally acceptable according to LM-83 and LEED V.4. Notwithstanding, from Figure 10 it can be observed that PP 37.5% achieves lower values of the over lit area (34%) than PP 50% (45%). Furthermore, N orientation obtains the lowest values of the over lit area (3%) while S achieves the highest percentages (44%). These are two proposals properly showed in Figure 12, since the actual daylit area in PP 37.5% is higher than in PP 50% and since the north is the best orientation for maximizing the actual daylit area and simultaneously minimizing the over lit area. From the combination of these two variables results, it can be concluded that PP 37.5 and 50% at north are the optimal levels. Consequently, these results of PP and O indicate that the best levels predicted by the actual daylit area are the optimal instead of those predicted by the fully daylit area.

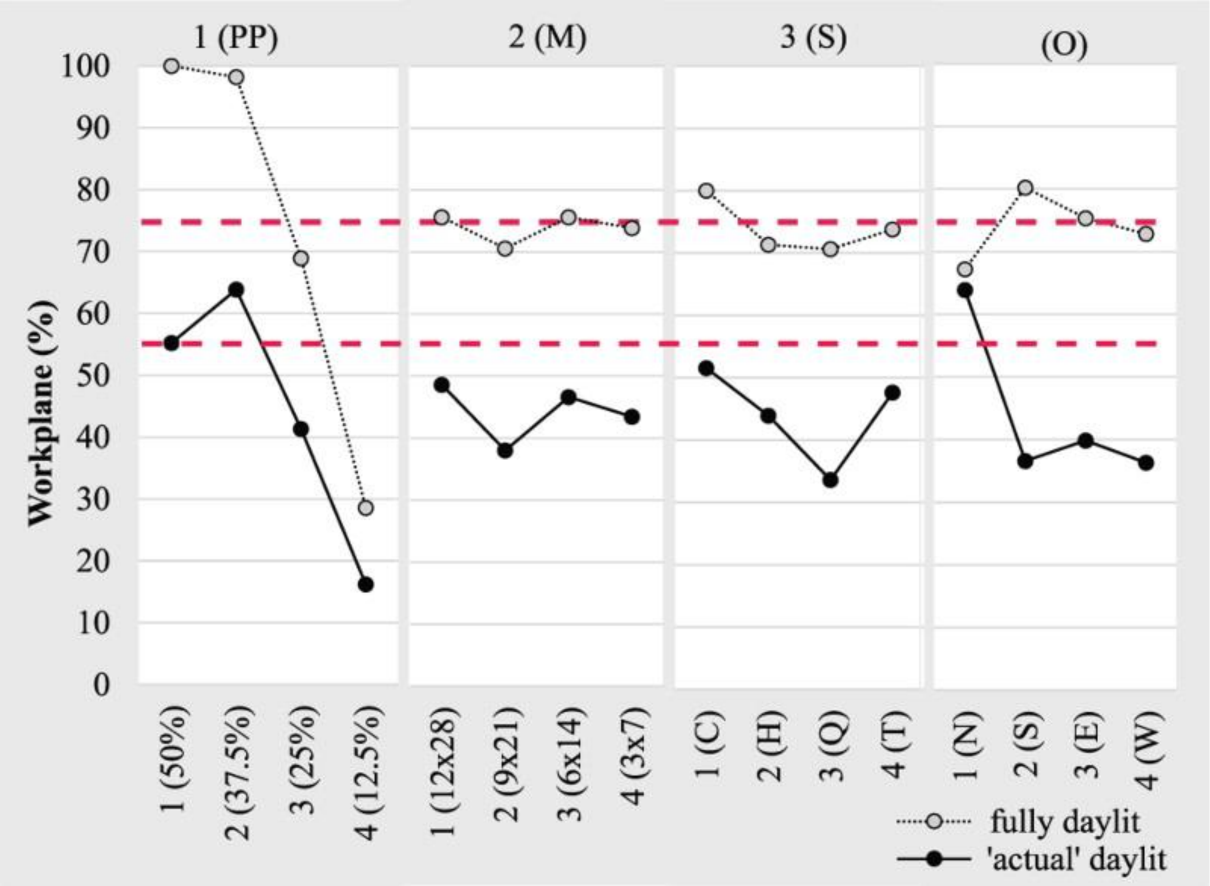


Figure 12. Main effects for the fully and actual daylit areas means.

Regarding M and S, the results of the four levels show larger differences for the actual daylit area than for the fully daylit area. Hence, it can be observed an increase of the actual daylit area in M 12x28 and S circular, and a noticeable decrease in M 9x21 and S quadrangular. Once again, the optimal levels are identified in a clearer way through the actual daylit area instead of the fully daylit area because the first integrates simultaneously the values of the daylit and over lit areas.

Table 9 shows a comparison between optimal PSS derived from code officials and those obtained through the actual daylit area. LM-83 indicates that the fully daylit area must meet at least 55 and 75% of working area for a space nominally acceptable and favorably/preferred, respectively; therefore, LEED V.4 provides two and three credit points, respectively. On the other hand, this paper proposes that the highest values of the actual daylit area indicate the best levels for each variable, so the combination of these best levels can origin the optimal PSS.

	Fully daylit area ranked by LM-83 and LEED V.4	Actual daylit area guidelines
PP		
50 %	Favorably/Preferred (100)	37.5% (64) 50% (55)
37.5%	Favorably/Preferred (98)	
25%	Nominally acceptable (69)	
M		
6x14	Favorably/Preferred (76)	12x28 (49)
12x28	Favorably/Preferred (76)	
3x7	Nominally acceptable (74)	
9x21	Nominally acceptable (71)	
S		
Circular	Favorably/Preferred (80)	C (52)
Triangular	Favorably/Preferred (74)	
Hexagonal	Nominally acceptable (71)	
Quadrangular	Nominally acceptable (71)	
O		
S	Favorably/Preferred (80)	N (64)
E	Favorably/Preferred (75)	
W	Nominally acceptable (73)	
N	Nominally acceptable (67)	

Note: Numbers in parentheses are the results for means of $L_{16}(4^4)$, specifically of the fully and actual daylit areas.

Table 9. Comparison of recommendations for daylit areas.

About this, the fully daylit area results indicate that PP 50%, closely followed by 37.5% is favorably, PP 25% is nominally acceptable and PP 12.5% is negative; but according to the actual daylit area, PP 37.5%, followed by 50%, is nominally acceptable. About M and S, the fully daylit area rank indicates that the 6x14, 12x28, circular and triangular levels are favorably while the others are nominally acceptable, so none is rejected. However, the actual daylit area shows that any level of M and S reaches the nominally space but also that the 12x28 and circular levels can be advisable because they achieve the highest values. Additionally, the fully daylit area rank shows that the S and E orientations are favorably while the others are nominally acceptable, so none level is rejected again; however, the actual daylit area indicates that only N is nominally acceptable.

From this, it can be inferred that guidelines obtained by the actual daylit area are more accurate, so they can be useful to optimize the design process of PSS by the delimitation of all possible variable combinations and the selection of the optimal PSS. Moreover, the actual daylit area has the advantage of considering simultaneously the fully daylit and over lit areas. In this respect, it should be recommended that code and standard officials for green rating systems consider the use of the actual daylit area as an additional compliance path for credits related to daylight availability. This last, taking into account that the percentage obtained through $DA_{300,50\%}$ is always higher than that obtained in the actual daylit area. Furthermore, the actual daylit area, together with the actual partially daylit area, could be used for a two-tier evaluation system to rate the daylight availability in spaces. This last in a similar way than other works suggest: 'A green building rating system or building standard could accordingly provide say one credit point if a desired proportion of a space is partially daylit and a second credit point if that proportion is also fully daylit' (Reinhart, Rakha, and Weissman 2014).

Concluding this section, the following PSS design guidelines from the DOA method:

- Perforation percentage is the variable which should guide PSS design. The higher the perforation percentage, the higher the percentages of the actual daylit and over lit areas on the workplane. In addition, PP 37.5 and 50% are better suited to obtaining useful illuminances and minimizing excessive illuminances (the first PP in a higher percentage).
- Orientation is the second most important variable. The most favourable orientation is N because it results in the highest actual daylit area with the smallest over lit area. In contrast, S orientation results in a larger over lit area.
- Shape is less important as design variable. However, its results show that circular shape increase the actual daylit area; in contrast, the quadrangular shape is the least favourable since it reduces the actual daylit area and increases the over lit area.
- Matrix is the least important variable. However, its results show that it could be better to use more openings (M 12x28) in order to maximize the actual daylit area and minimize the over lit area.

4.2 Confirmation of orthogonal array results

Table 8 highlights the optimal levels of each factor depending on the objective function, so the combination of these levels makes it possible to predict the optimal PSS. For example, in the actual daylit area, the highlighted PP is T2 (37.5%), the highlighted M is T1 (12x28), the highlighted S is T1 (circular) and the highlighted O is T1 (N). The combinations of these levels is 371CN that appears in the last row named 'optimal PSS'. Similar procedure has been conducted for all optimal PSS.

These optimal PSS are summarized in Table 10, specifying their factors and levels and their respective optimized metrics. In this section, the optimal PSS are simulated to confirm the efficiency of the orthogonal array. In addition, two reference models appearing in Table 10 are simulated to contrast daylight conditions generated by using PSS or not, as explained in the next section. Table 11 shows the results of the metrics quantified in these simulations.

Simulation	Optimized PSS	Factors and levels				Optimized metric
		PP	M	S	O	
17	501TS	1 (50%)	1 (12x28)	4 (Triangular)	2 (S)	Non-daylit area
18	503CS	1 (50%)	3 (6x14)	1 (Circular)	2 (S)	Actual partially and fully daylit areas
19	371CN	2 (37.5%)	1 (12x28)	1 (Circular)	1 (N)	Actual daylit area
20	121TN	4 (12.5%)	1 (12x28)	4 (Triangular)	1 (N)	Over lit area
21	REF100N	100%	–	–	1 (N)	–
22	REF100S	100%	–	–	1 (S)	–

Table 10. PSS optimized in $L_{16}(4^4)$ and reference models.

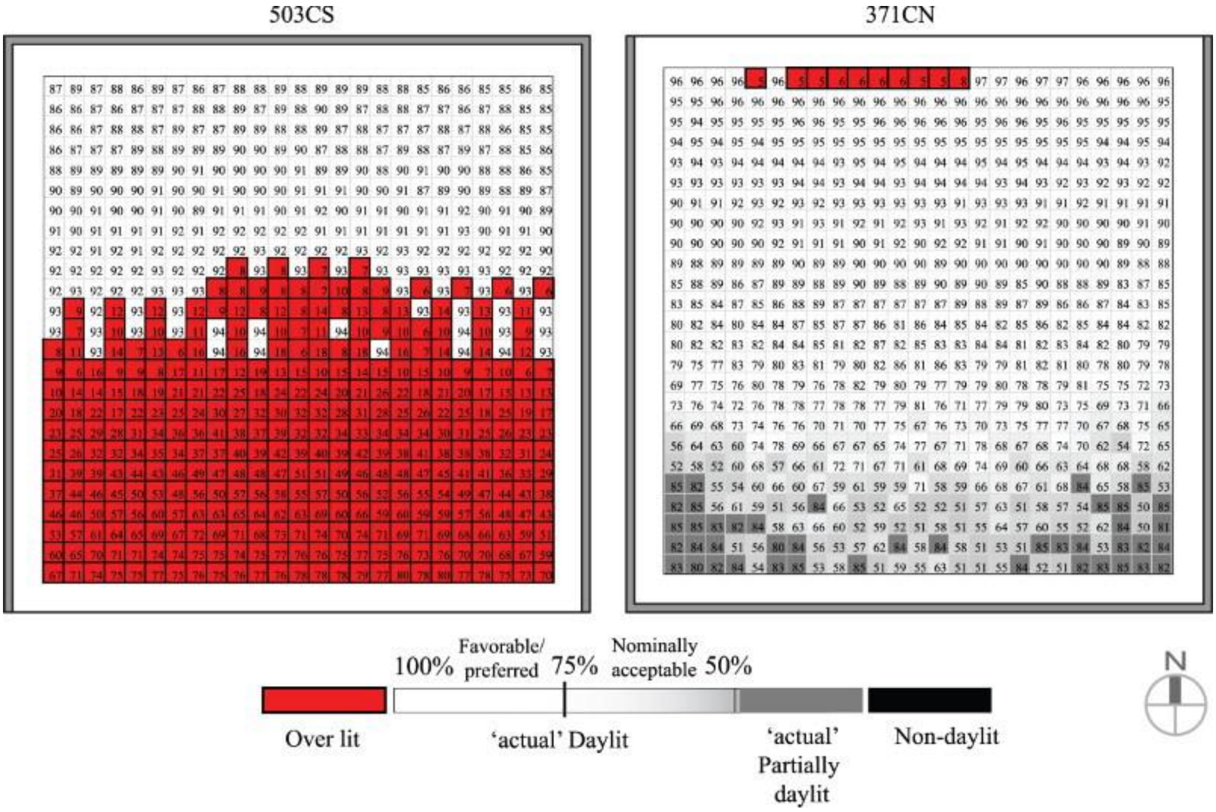
Simulation	PSS	Total space area (workplane				Fully daylit area (%)
		Non-daylit area (%)	'actual' Partially daylit area (%)	'actual' Daylit area (%)	Over lit area (%)	
17	501TS	0	0	43	57	100
18	503CS	0	0	45	55	100
19	371CN	0	7	92	2	93
20	121TN	57	28	15	0	15
21	REF100N	0	0	62	38	100
22	REF100S	0	0	8	92	100

Table 11. Results of the optimized PSS and reference models.

From the 16 simulations selected and the four optimal predicted in the orthogonal array, the following can be observed. 501TS successfully attains the minimum values of the non-daylit area. 503CS achieves the minimum value of the actual partially daylit area and the maximum of the fully daylit area. 371CN achieves the highest percentage of the actual daylit area. 121TN gets the minimum percentage of the over lit area. Thus, the effectiveness of $L_{16}(4^4)$ in predicting the optimal combinations according to the objective function can be confirmed.

Two options of these four combinations are discussed below. Firstly, 503CS model because it is predicted as the optimal PSS according to the fully daylit area. Then, 371CN model because it is predicted as the optimal PSS through the actual daylit area. Table 11 indicates that 503CS obtains 100% of the fully daylit area but also 55% of over lit area. Moreover, 371CN obtains 93% of the fully daylit area with less than 2% of the over lit area.

Figure 13 shows a comparison between the 503CS and 371CN results. It consists on an overlap that shows the non-daylit, actual partially daylit, actual daylit and over lit areas at each sensor point. The white colour represents a sensor with DA_{300} for at least 75% of the working year that do not reach $UDI_{>3000}$ during 5% of the working year (in short, the favorably actual daylit area). The clear gray scale shows sensors with DA_{300} between 50-75% of the working year that do not reach $UDI_{>3000}$ during 5% of the working year (in short, the nominally actual daylit area). The red colour indicates sensors with UDI>3000 for at least 5% of the working year (in short, the over lit area).


503CS

371CN

Figure 13. Daylit diagram showing a comparison between optimal predictions through the fully daylit area rank (503CS) and the actual daylit area guidelines (371CN).

The dark gray colour represents sensors that do not reach $DA_{300,50\%}$ but they achieves DA_{150} for at least 50% of the working year (in short, the actual partially daylit area). In addition, the numerical values at each sensor represent the annual time percentages quantified at each metric.

According to this, 371CN can be considered as the optimal PSS because it maximizes the favourable actual daylit area with a minimum oversupply of daylight. Furthermore, the actual partially daylit area in 371CN is smaller than the over lit area in 503CS. Thus, the effectiveness of using the actual daylit area in predicting the optimal combinations through orthogonal arrays can be confirmed.

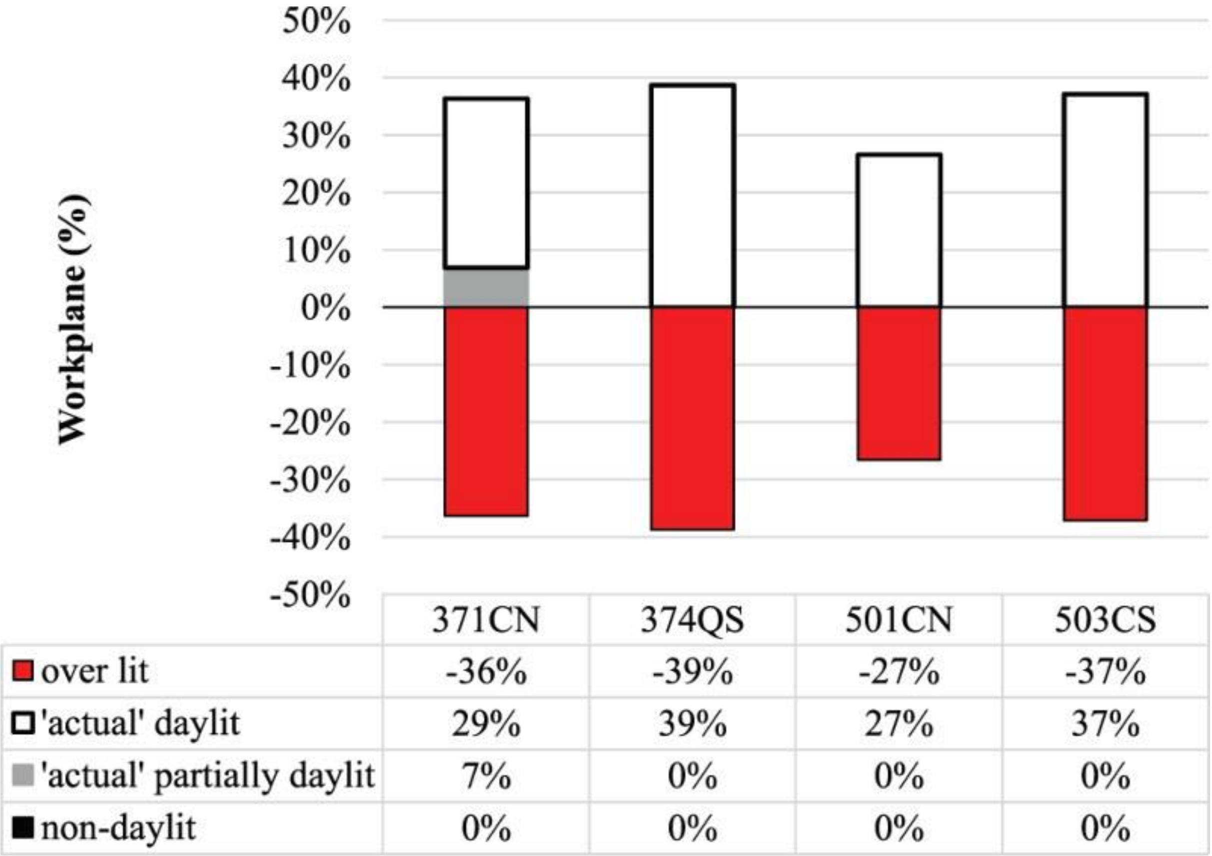
The results of the optimized PSS confirm the usefulness of the DOA method in PSS design to make full use of daylight. This is because DOA makes it possible to effectively identify the optimal levels of the design variables and therefore, the most suitable combination of levels for maximizing useful illuminances and minimizing excessive ones on the workplane.

4.3 Contrasting use or non-use of PSS

In this last phase, the behaviour of daylight in the space with and without PSS is described. The following four PSS are chosen from all simulations because they combine some optimal levels predicted by the actual daylit guidelines and the fully daylit rank: 371CN, 501CN, 374QS and 503CS. Additionally, the reference model is oriented at N or S according to the optimal orientations obtained in $L_{16}(4^4)$.

Thus, the optimized PSS are compared with their respective reference model in the following way: 371CN and 501CN are compared with REF100N while 374QS and 503CS are compared with REF100S. This procedure is because all orientations provides certain levels of daylight. Thereby, the oriented comparison is equitable and it can describe primarily the influence of the optimized PSS and not the influence of orientation. Here, it is important to clarify that the objective of this section is not the comparison between orientations but it is exclusively the contrasting use or non-use of PSS.

Figure 14 shows the differences between metrics quantified in PSS minus those computed in reference models. In general, it is observed that optimized PSS can increase the actual daylit area by 29-39% and reduce the over lit area by 27-39%. Taking the mean of the four PSS into consideration, they can contribute to increasing the actual daylit area by 33% and reducing the over lit area by 35%.



	371CN	374QS	501CN	503CS
🟥 over lit	-36%	-39%	-27%	-37%
☐ 'actual' daylit	29%	39%	27%	37%
▨ 'actual' partially daylit	7%	0%	0%	0%
■ non-daylit	0%	0%	0%	0%

Figure 14. Differences in the space percentages: optimal PSS minus reference models.

5 Conclusions

This study uses DOA to optimize the PSS design in relation to its effect on daylighting conditions. The methodology proposed proves effective and of great use in PSS design, as it allows the optimal levels of design variables to be identified, as well as the optimal combinations to maximize useful illuminances and to minimize excessive illuminances on the workplane. This last using the IES metrics and the actual daylit area that accounts the area of workplane lit exclusively with useful illuminances ($UDI_{300\text{-}3000,50\%}$ + $UDI_{>3000,<5\%}$). It was observed that the optimal levels can be identified in a clearer way through the actual daylit area instead of the fully daylit area ($DA_{300,50\%}$) because the first simultaneously integrates the over lit area. In this respect, it should be recommended that code and standard officials consider the use of the actual daylit area for evaluations of daylit spaces, taking into account that the percentage obtained through $DA_{300,50\%}$ is higher than that obtained in the actual daylit area.

The paper also shows the results in a visual way by using the concept of daylight availability. Thus, the non-daylit, actual partially daylit, actual daylit and over lit areas are overlapped on the total space area (workplane). Furthermore, the DOA method predicts the optimal PSS with the minimum number of computer simulations and models which decrease from 256 to only 16 with orthogonal array. Therefore, the methodology implemented could save time considerably when looking for the optimal solutions and would help architects to make early-design-stage decisions.

In short, the DOA results show that the most important factor for PSS design is PP and that the optimal level for obtaining useful illuminances and minimizing excessive ones over more area of the workplane is 37.5%, followed by 50%. In second place of importance, factor O at level N is the best suited to the latitude studied, while S increases excessive illuminances over a greater workplane and it can cause greater glare and thermal discomfort. The variables M and S are of less importance in design, although it is inferred that the optimal levels for increasing useful illuminances and reducing excessive ones over greater space area are M 12x28 and S circular. In addition, the space percentages of the optimized series compared with the reference models show that PSS use on façades can contribute to increasing the actual daylit area by 33% and reducing the over lit area by 35%.

The study here presented mainly concerns four design variables as an approach to apply the optimization method of PSS design to improve daylighting performance using orthogonal arrays. Other variables such as depth, colors and materials, as well the influence of distance between PSS and façade must be taking into account for the continuation of this investigation. Meanwhile, the seven steps of this new methodology can be applied in order to find optimal solutions for two-dimensional PSS. Thereby, designers could save time during the initial stages of building design supported by statistical results. On the other hand, this study focuses on daylight conditions.

However, other parameters such as infiltration, ventilation and heat loss through PSS also play an important role in energy consumption in indoor spaces. Thus, these conditions should be further explored in future research, identifying how the optimal levels proposed for design variables affect the spaces in terms of energy savings.

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