Statistical methods applied to optimize perforated façade design for daylight availability

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Abstract

Perforated solar screens (PSS) are an important consideration in building façade design due to its contribution to sustainability through daylighting. PSS design requires the consideration of many potential design alternatives that involves a large number of simulations. This paper presents a methodology in which the orthogonal and listing methods are integrated to predict a set of optimum PSS design variables to enhance the Daylight Availability in office buildings located in Seville, Spain. An orthogonal array is selected to perform a transverse comparison of the simulation factors mean effects and to find their statistical significance. Then, a standard level is fixed and used for further detailed analysis of a greater number of factor levels, measuring their daylighting contributions. The main advantage of the integrated method is the reduction of the number of simulations from 720 to 32, so it could save time considerably and would help designers to make early-design-stage decisions. With the optimization, the actual daylit area increased by 29-57% and the over lit area reduced by 36-57%, relative to reference models with no PSS.

Keywords: daylit area; listing method; orthogonal method; perforated façade design

1. Introduction

Many aspects of the overall building performance depend on major decisions at early design stages. These decisions are often not assessed before the detailed building design has been decided. At this stage of the design process, only small changes to the building design are possible and they may not be possible to solve the problems without a major redesign. Often the actions taken to improve the indoor environment after the building is taken in use increase the energy use. To improve the performance of buildings it is important to develop design tools that may be used to assess performance aspects of building designs in the early stages of the design process where the building designer still has the freedom to choose between almost unlimited numbers of different possible design solutions (Nielsen and Svedendsen, 2002).

The energy performance of buildings is often regulated in building codes. There are several standards related to the optimization of new building components. One of the big challenges experienced in the last decades is the relevance of the energy savings factor which is increasing substantially, due mainly to resources constraint, influencing the prescriptions given by the main European regulations consumption (EC, 2010) in terms of emissions and consumptions limitations. Office buildings are of particular interest because of their large amounts of energy consumption and greenhouse gas emissions worldwide (Perez-Lombard, Ortiz and Pout, 2008). In fact, in Spain, artificial lighting consumption accounts for up to 30% of total electric consumption in office buildings (MITC 2007). This despite the fact that, in Mediterranean climates, where there are many hours of solar radiation, there is a great amount of available daylight but it is not used to its entirety (Lim, Ahmad and Ossena, 2013).

Considering the daylight that enters a building is fundamental to design, both as a means of reducing the use of electric lighting and in terms of its influence on visual comfort conditions, user moods, thermal gains and qualitative aspects of the lighted space (Andersen, Mardaljevic and Lockley, 2012). This amount is highly dependent on buildings design and its boundary conditions. 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).

Double-skin façades became popular early in the 1990s, as an effective way of meeting the need to provide curtain-wall-type, stand-out buildings with thermal insulation and improved natural ventilation. Perforated screen façades are an example of new construction solutions for the buildings (Gratia and De Herde, 2004). Works devoted to perforated façades are mostly focused on their thermal behaviour (De Gracia *et al.*, 2013). Most of them examined the influence that wind direction and location have on the velocity of the air inside the ventilated chamber and the temperature distribution along this cavity (Aparicio *et al.*, 2014). Only few works reviewed the design parameters of perforated façades, such as perforation range or orientation, but for reducing the cooling energy and energy consumption (Sherif, Faggal and Arafa, 2010; Sherif, El-Zafarany and Arafa, 2012). These findings concluded that these screens significantly improves the building energy behaviour.

Notwithstanding, there are few detailed studies regarding the daylighting performance of perforated façades. Mahmoud and Elghazi (2016) investigated the impact of kinetic motion of hexagonal pattern on South-facing skin to control the daylight distribution in an office space, finding that all kinetic skins helped improved the visual environment by controlling the excessive sun rays, protecting the workplane from direct sun and eliminating sources of glare. Etman, Tolba, and Ezzeldin (2014) explored the impact of the ratio of rectangular openings in West-facing façades in office buildings, concluding that quadrangular module improved the indoor illuminance distribution by 54-78% with illuminance levels of 300-500 lux.

Other related studies have involved perforated screens that were either located in front of, or integrated with window glazing; besides, they were applied on residential buildings in desert locations. Aljofi (2005) examined the effect of screen shapes on daylighting distribution, showing that illuminance values were lower when rounded shape screen openings were used on windows, as compared with other shapes; also, the contributed reflected light was found to be directly proportional to screen cell diameter. Sherif et al. (2011) suggested that changing the screen opening proportion (horizontal: vertical) from 1:1 at Northern direction to 18:1 at Southern orientation would efficiently enhance daylighting, as they obtain 200 lux on at least 70% of the workplane. Sherif, Sabry, and Rakha (2012) revealed that perforation rates of 40-90% of solar screens provided 200 lux during 50% of annual occupation hours, over at least 30% of space.

The literature review illustrates the fact that very little research work addressed different design aspects of external solar screens on façades and their influence on daylighting conditions although these screens demonstrated their usefulness in enhancing daylighting performance and reducing energy consumption. One of the most complicated issues in the analysis of these types of screens is the geometry design as the plate is composed by a distribution of small holes, opened to the external environment. Hence, the few related studies were limited to addressing the effect of single design variables on screen performance despite the fact that solar screen design requires the consideration of a wide variety of variables. This could be due to a comprehensive study of possible variable combinations requires a large amount of different models, which is time-consuming and difficult to manage. As a result, most research concentrated on a single design variable regardless of its relationship with others.

Nonetheless, statistic Design of Experiments (DOE) tools can simplify the interrelated study of a large number of variables, reducing the number of required experiments and achieving significant results (Park, 2007). This paper uses the orthogonal method validated in a previous study (Chi *et al.*, 2016) in which some design variables of perforated solar screens (PSS) were analysed in terms of their statistical significance on daylight conditions. In the orthogonal method, the prediction of the preferable level of each of the design variables is performed through analysis of means, meaning that the achieved results (space areas) are merely the average values of the common levels. Thus, the orthogonal method can only detect statistically significant differences between design variables, but it cannot quantify the real lighted percentages of space areas through PSS. Therefore, it is necessary to complement the orthogonal method with another statistical tool that can describe in detail the results of the design variables and compare quantitatively the daylighting performance of the PSS.

This work proposes an approach in which the orthogonal method (Park, 2007) and the listing method (Wei, Zhao and Chen, 2010) are integrated to simplify the interrelated study of more than one single variable, reducing the number of simulations and obtaining maximum information which may be of use at early design stages of PSS. The orthogonal method 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. Furthermore, it is highly efficient in reducing the number of experiments required and in achieving optimal combination levels (Taguchi and Yokoyama, 1993; Franek and Jiang, 2013). Listing method studies one design variable at a time while keeps other design variables fixed as the standard level. It is used to further analyse the optimal level for each design variable, and then, determine the optimal combination (Wei, Zhao and Chen, 2010). Thus, it also requires only an adequately chosen fraction of all combinations in order to describe and analyse the results in a comparative way.

While not specifically applied in the design of PSS, both methods have been applied in building shape design. Wei, Zhao, and Chen (2010) implemented the orthogonal and listing methods 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. Gong, Akashi and Sumiyoshi (2012) integrated these methods to explore how energy consumption is minimized in residential buildings by optimizing seven passive design measures for each of the 25 Chinese cities studied. Huang and Wu (2014) applied both methods to establish the order of importance in daylighting and solar control conditions of the parameters of Chinese splayed windows. Furthermore, Yi, Srinivasan, and Braham (2015) used the orthogonal method to optimize architectural design parameters, reducing construction costs. Chlela, Husaunndee, Inard, and Riederer (2009) used this method to study some characteristics of the building envelope. Study 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.

As can be observed, the orthogonal and listing methods present several advantages in the field of design, especially as regards the effectiveness of results and the reduction of the number of simulations arising from the combination of diverse design variables. Therefore, this study aims to develop a methodology that integrates both methods to optimize PSS design for daylighting performance. The purpose is to examine and quantitatively describe the effects of different PSS design variables on annual indoor daylighting conditions and determine the optimal value for each design variable that increases the area lit with useful illuminances and reduces the area lit with excessive ones. A case study has been conducted from the perspective of this methodology, which involves an office space in Seville, Spain.

2. Methodology

The methodology proposed consists of three stages, as shown in Fig. 1. The first stage involves the experimentation approach in where project information, project location parameters and other information, such as space type and design units, are suited. Also, the PSS design variables with their respective levels and the daylighting criteria with dynamic metrics are established.

The second and third stages involve the experimental design. The second stage consists on a transverse comparison of the design variables with respect to daylighting performance through the orthogonal method, which was fully validated and reported in a previous study (Chi *et al.*, 2016). Four design variables (considered to be 'factors'), with four values (considered to be 'levels) each one, were selected on this method. The order of importance, the significance and the identification of the preferable level of each factor, through the average results, were the focus on this stage. The outputs of the preferable levels (considered to be the 'standard levels') are used for developing the next stage.

For the third stage, the listing method, which is a statistical tool that studies one design variable at a time while keeps other design variables fixed as the standard level, is used to further analyse the optimal level for each design variable with a total of four to six levels, and then, determine the optimal combination. The listing method allows to investigate the detailed effects of the design variables and to characterize quantitatively the daylighting performance of PSS.

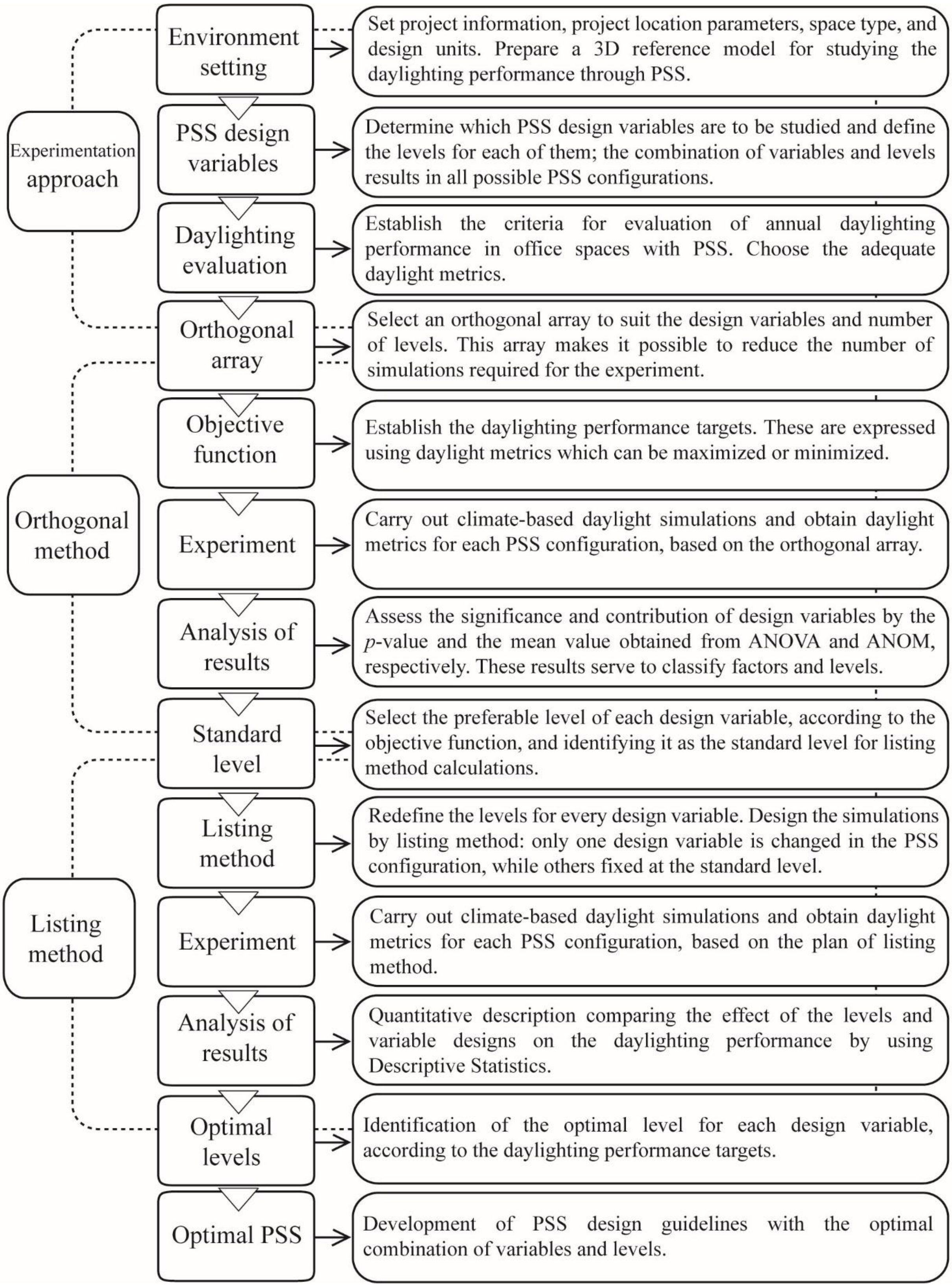


Fig. 1 Integrated method

2.1 Stage one: Experimentation approach

2.1.1 Environment setting

The case study of a typical office space in the Mediterranean Climate of Seville, Spain (37°42'N, 5°9'W) is studied. The reference model consists on an office space daylight-illuminated from one side, located on the first floor with spatial dimensions of 7 m x 7 m, with a height of 3 m, as shown in Fig. 2. The space has one fully glazed façade with a double-clear-glazing with 78.1% of visual transmittance. The workplane on which daylighting performance is simulated contained 576 measuring sensors in a grid of 0.25 m x 0.25 m, with a height of 0.80 m. The workplane runs at a 0.50 m from the room perimeter and it is deemed representative of most tasks involved in office activities (SLL, 2012). Reflectances of the ceiling, floor and walls are 80, 20 and 50%, respectively. No external obstruction is assumed. An external ground reflectivity of 20% is used. All these aforementioned model characteristics remain fixed in all tests in order to focus the study on the examination of the design variables tested and their combinations.

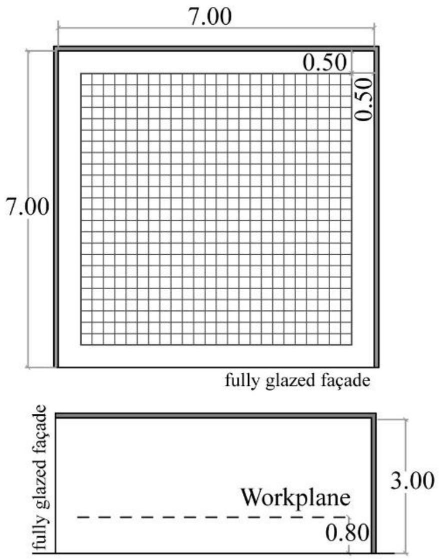


Fig. 2 Reference model and calculation grid

2.1.2 PSS design variables

PSS have recently been applied as second skins on transparent building façades and they have been mainly used as permanent sun shading systems. PSS consist on opaque perforated panels, usually made by metal sheets that are only few millimetres thick (which is typically in the order of 2 to 7 mm depending on the material) (Mainini *et al.*, 2015). Accordingly, it was decided that the PSS material would be considered as two-dimensional thin in this work. To diminish the interference of this PSS simplification in the daylight transmittance, a minimum dimension of the holes has also been considered which is 10 cm in diameter for the regular shapes and 8 cm in length for the irregular ones.

PSS are externally mounted at a distance of 0.05 m from the fully glazed façade of the reference model. Their dimensions are 7 m in width and 3 m in height. Reflectance of its opaque surface is 90%. Four design variables that are usually determined at the conceptual design stage and that have a critical influence on daylighting performance are selected to characterize PSS. These are the following:

1) Perforation percentage (PP) is the ratio of the total surface of the openings to the wall.
2) Matrix (M) represents the distribution of openings on the screen achieving the established perforation percentages.
3) Shape (S) of each individual opening.
4) Orientation (O)

Four to six levels are assigned to each one of the PSS design variables as follows:

a) PP: 75%, 62.5%, 50%, 37.5%, 25% and 12.5%.
b) M: 12×28, 9×21, 6×14, 3×7, random and irregular. The first four are regular distributions and the distance between their openings 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. The random and irregular distributions are studied because of its current marketing in Seville.
c) S: circular, hexagonal, quadrangular, triangular and irregular. The regular shapes have an equal opening area when M and PP are the same.
d) O: The four cardinal directions are considered.

Fig. 3 shows the design variables with their corresponding levels. Full combination of all levels of the four variables generates 720 PSS configurations or simulations, representing a considerable investment in computational time and effort. The nomenclature of every PSS configuration follows the combination of its levels, as laid out in Fig. 3. For example, a PSS with a PP 75%, M 12×28 and S circular applied on a façade oriented at North is named 751CN. Reference models are termed REF followed by 100 referring to their fully glazed façade and then by the letter referring to orientation (e.g. REF100N).

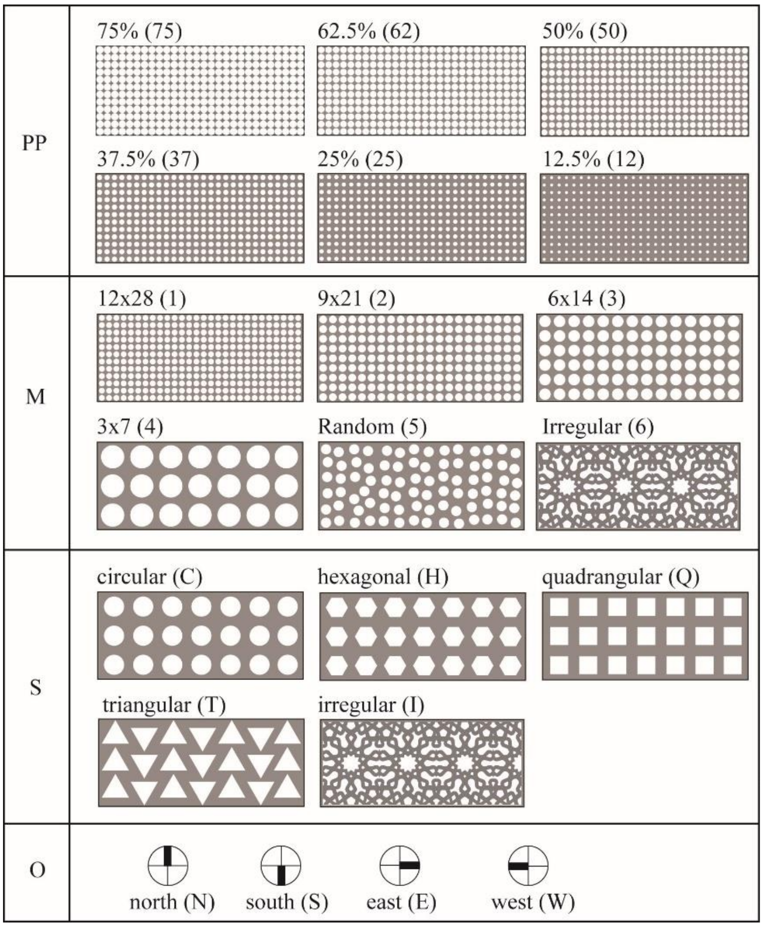


Fig. 3 PSS design variables with values. Nomenclature is showed between parentheses

2.1.3 Daylighting evaluation criteria

In recent years, Dynamic Daylight Metrics (DDM) have found their way into North American standards and green building rating systems. Therefore, the daylighting criteria used in this work for PSS evaluation are based on DDM and consist of Daylight Availability. Simulations are performed using the Radiance-based software Daysim 3.1e (Ward and Shakespeare, 1998; Reinhart, 2010). Testing is carried out using the International Weather for Energy Calculations (IWEC) data file of Seville and the following radiance parameters: –ambient bounces 7 –ambient division 1500 –ambient sampling 10 –ambient accuracy 0.01 –ambient resolution 300 (Reinhart, 2010).

The Daylight Availability defines the daylit area as where 'indoor illuminance levels due to natural light should be adequate, useful and balanced for most of the year'(Reinhart, Rakha and Weissman, 2014). 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 when the daylight autonomy at the point for a target illuminance of 300 lux and for occupancy from 8 to 18 h is over 50% (in short, $DA_{300,50\%}$) (Reinhart, Rakha and Weissman, 2014). Daylight Autonomy (DA) is defined as the percentage of the occupied hours in a year when the illuminance is above a given target level (Reinhart and Walkenhorst, 2001). Thereby, DA has the inconvenience that makes no account of the amount by which the illuminance threshold is exceeded; this is significant because high levels of daylight illuminance are known to be strongly associated with occupant discomfort (Nabil and Mardaljevic, 2005). Despite that, the 'daylit' area has been approved by IES LM-83-12 (IES 2012) and is required in LEED Version 4.0 (USGBC, 2013) to receive two or three daylight credits. It must meet at least 55 and 75% of workplane for a 'nominally acceptable' and 'favourably/preferred' space, respectively.

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, $DA_{150,50\%}$). According to the authors, one particular benefit of $DA_{150,50\%}$ 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 daylight illuminance exceeds the maximum threshold of 3000 lux for more than 5% of the occupied hours. The' over lit' area might signify a potential for glare and heat gain (Reinhart and Wienold, 2011; Mardaljevic *et al.*, 2012).

Since there are no upper limits in DA, it can be determined that the 'fully daylit area' is part of the 'partially daylit area' and that the 'over lit area' is contained within the 'fully daylit area'. Thereby, these metrics account coincident percentages of the workplane. Notwithstanding, this work aims to account the space area lit exclusively with useful daylight illuminance (UDI) levels by means of assessing the annual occurrence of illuminances across the workplane that are within a range considered 'useful' by occupants (Nabil and Mardaljevic, 2005). Accordingly, all of the space areas must be overlapped on top of each other in order to identify the equivalent area for each one of them. Thus, the space areas considered in this work are quantified as follows:

- The 'non-daylit' area accounts illuminances under 150 lux for at least 50% of the working year (UDI<150,50%)
- The 'actual partially daylit' area includes only those daylight illuminances within the range 150-300 lux when they do not reach the time percentages for either the 'non-daylit' or the 'actual daylit' areas.
- The 'actual daylit' area includes only those useful illuminances within the ranges UDI300-3000,50% + UDI>3000,<5%.
- The 'over lit' area accounts illuminances over 3000 lux for at least 5% of the working year (UDI>3000,5%).

Therefore, non-daylit + actual partially daylit + actual daylit + over lit areas = total space area (workplane) as it can be summarized in Fig. 4.

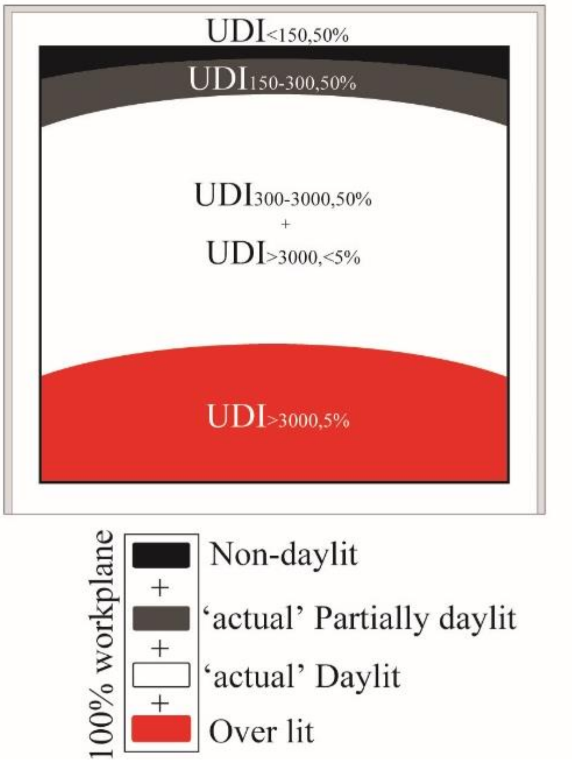


Fig. 4 Space areas accounted in this work for Daylight Availability metric

2.2 Stage two: Orthogonal method

In the orthogonal method, the selection of experiments is based on an orthogonal array (OA). This is represented by a matrix which is expressed as LN(l k), where L is OA, 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. The advantages of the orthogonal 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 (Park, 2007).

2.2.1 Orthogonal array L16(44

The first step in the orthogonal method is to select an OA according to the number of design variables and the number of levels. Taguchi and Yokohama (1993) tabulated many standard OAs for using the orthogonal method. One of these arrays can be applied directly as planning the simulation cases. As this work established four PSS design variables, the Taguchi designs for four factors have been weighed. These include 2-level, 3-level, 4-level and 5-level where all factors have 2, 3, 4 and 5 levels, respectively. Besides, another existing Taguchi designs include mixed levels but these necessarily imply that one factor has only 1-2 levels in order to include more than 4 levels for the other factors.

Among all OAs options, the most appropriate to test more and equal number of levels for all factors is $L_{16}(4^4)$. This OA consists of four factors with four levels each, as Table 1 summarizes. It is also an enough small OA that can be used to reduce the number of simulations. $L_{16}(4^4)$ 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 2 presents the 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.

Table 1 Factors and levels of $L_{16}(4^4)$

Factors		Levels			
		(1)	(2)	(3)	(4)
(1)	PP	50%	37.5%	25%	12.5%
(2)	M	12×28	9×21	6×14	3×7
(3)	S	Circular	Hexagonal	Quadrangular	Triangular
(4)	O	North	South	East	West

Once the 16 simulations are performed, the results can be tested through the Analysis of Variance (ANOVA) and the Analysis of Means (ANOM). The ANOVA is used to determine the primary order of the impact of the four PSS design variables on the annual indoor daylighting conditions. The ANOM is implemented to choose the preferable level of each variable design according to the daylighting performance target (also named 'objective function' in the OA method). The preferable levels are identified as the standard levels for listing method calculations. A key point to notice is that the ANOM tests the average performance of groups integrated by PSS that share equal levels for each factor. Thus, the achieved mean effects through the ANOM are merely the average values of the common levels but they do not display the real percentages of the space areas lighted through PSS.

2.2.2 Objective function

The goal of this analysis is to increase the area lit with useful illuminances for occupants and to reduce the area lit with excessive illuminances that can be associated with glare and thermal discomfort. Accordingly, the 'actual daylit area' must be maximized, so the 'non-daylit', 'actual partially daylit' and 'over lit' areas can be minimized.

2.3 Stage three: Listing method

Once the standard level of each variable design is identified through the OA, the listing method is utilized for further optimization for the total four to six levels listed in Fig. 3. Unlike the OA method, the listing method can include a free number of levels for comparative analysis. Thus, additional simulations are planned by the listing method, which changes the values of four to six levels of one design variable while the value of the other three design variables remains fixed at the standard level. Thus, when PP is studied, their six levels changes from 12.5 to 75%, but the levels of M, S and O keep fixed at the standard level; when M is studied, their six levels changes but the levels of M, S and O keep fixed at the standard level; similar procedure is conducted for S and O.

After performing these additional simulations, the simulation results can be described quantitatively in order to detail and compare how PP, M, S and O could influence the daylighting distribution on the workplane. By varying each of these design variables at different values, this method can identify the optimal levels. At this stage, the optimal level of each design variable is representing the highest result of the actual daylit area and the lowest result of the over lit area. Unlike the OA method, the results quantified by using the listing method properly represent the real lighted percentages of the space areas.

3. Results

This following section reports the results on how optimal design of PSS is achieved for the case study by applying the integrated method.

3.1 Identification of the standard level by the orthogonal method

Table 2 presents the daylight metrics obtained in the 16 simulations of L16(44). Table 3 provides the ANOM results, in which the Delta value is used to compare the relative magnitude of effects depending on the orthogonal design (Park, 2007). The ANOM main effects of the space areas are also illustrated in Fig. 5.

Table 2 Simulation results and ANOM of $L_{16}(4^4)$

Simulation	PSS	Factors and levels				Simulation results			
		1 (PP)	2 (M)	3 (S)	4 (O)	Non-daylit area (%)	'actual' Partially daylit area (%)	'actual' Daylit area (%)	Over lit area (%)
1	501CN	1 (50%)	1 (12×28)	1 (C)	1 (N)	0	0	89	11
2	502HS	1 (50%)	2 (9×21)	2 (H)	2 (S)	0	0	43	57
3	503QE	1 (50%)	3 (6×14)	3 (Q)	3 (E)	0	0	42	58
4	504TW	1 (50%)	4 (3×7)	4 (T)	4 (W)	0	0	47	53
5	371HE	2 (37.5%)	1 (12×28)	2 (H)	3 (E)	0	0	61	39
6	372CW	2 (37.5%)	2 (9×21)	1 (C)	4 (W)	0	0	57	43
7	373TN	2 (37.5%)	3 (6×14)	4 (T)	1 (N)	0	7	91	2
8	374QS	2 (37.5%)	4 (3×7)	3 (Q)	2 (S)	0	0	47	53
9	251QW	3 (25%)	1 (12×28)	3 (Q)	4 (W)	0	34	29	37
10	252TE	3 (25%)	2 (9×21)	4 (T)	3 (E)	0	34	36	30
11	253CS	3 (25%)	3 (6×14)	1 (C)	2 (S)	0	16	41	44
12	254HN	3 (25%)	4 (3×7)	2 (H)	1 (N)	0	40	60	0
13	121TS	4 (12.5%)	1 (12×28)	4 (T)	2 (S)	32	31	16	20
14	122QN	4 (12.5%)	2 (9×21)	3 (Q)	1 (N)	57	27	16	0
15	123HW	4 (12.5%)	3 (6×14)	2 (H)	4 (W)	47	28	12	13
16	124CE	4 (12.5%)	4 (3×7)	1 (C)	3 (E)	39	25	20	16

Table 3 Mean values obtained from ANOM of L16(44)

Factor	Main effects	Non-daylit area (%)	'actual' Partially daylit area (%)	'actual' Daylit area (%)	Over lit area (%)
1 (PP)	T1 (50%)	0	0	55	45
	T2 (37.5%)	0	2	**64**	34
	T3 (25%)	0	31	41	28
	T4 (12.5%)	44	28	16	12
	Delta	44	31	48	32
	Rank	1	1	1	2
2 (M)	T1 (12×28)	8	16	**49**	27
	T2 (9×21)	14	15	38	33
	T3 (6×14)	12	13	47	29
	T4 (3×7)	10	16	43	30
	Delta	6	4	11	6
	Rank	3	4	4	4
3 (S)	T1 (Circular)	10	10	**52**	28
	T2 (Hexagonal)	12	17	44	27
	T3(Quadrangular)	14	15	34	37
	T4 (Triangular)	8	18	48	26
	Delta	6	8	18	11
	Rank	3	2	3	3
4 (O)	T1 (N)	14	19	**64**	3
	T2 (S)	8	12	37	44
	T3 (E)	10	15	40	36
	T4 (W)	12	15	36	37
	Delta	6	7	28	40
	Rank	3	3	2	1

Note: Characters in bold indicate the preferable levels for the actual daylit area.

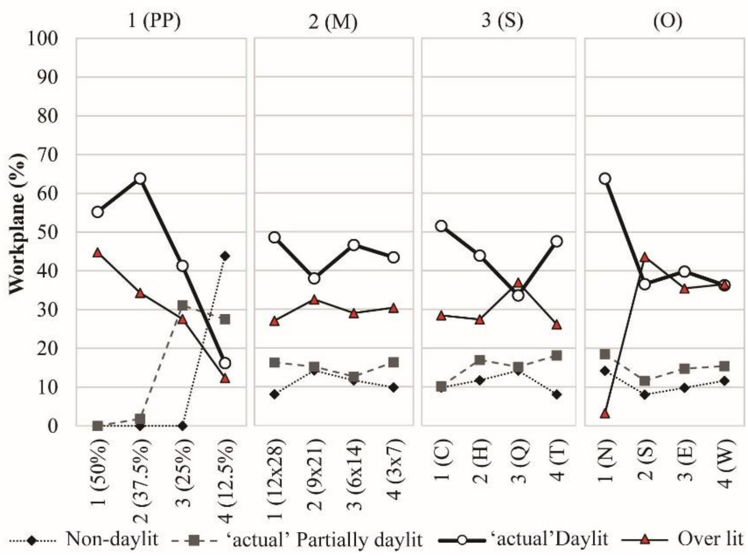


Fig. 5 Main effects for the space area means

Regarding the actual daylit area, the main effects of the factors follow the order PP (48) > O (28) > S (18) > M (11). Fig. 5 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 12×28, closely followed by 6×14. About S, the highest value is reached in the circular level and the lowest value in the quadrangular one. About O, the highest value is achieved at N and the lowest value is obtained at S.

Regarding the over lit area, the main effects of the factors follow the order O (40) > PP (32) > S (11) > M (6). Fig. 5 shows that the over lit area decreases as PP decreases. M shows fluctuations although it is observed that M 12×28 slightly achieves the lowest values. For S, the quadrangular level gets the highest values while the other three levels achieve 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 achieve more than 35%. Besides, S is the least favourable orientation because it increases this area, almost over the half of the workplane.

Table 4 presents the ANOVA results and the statistical significance (p-value) of experimental results when α=0.05. It indicates that PP and O have the most significant effects on daylighting performance since their values obtain the greatest sum of squares.

Table 4 ANOVA of $L_{16}(4^4)$

Metric	Factor	Degree of freedom DF	Sum of squares SS	Variance ratio F	Contribution *p*
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
	Error	3	83.30		

'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
	Error	3	122.05		
'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 *
	Error	3	51.80		
Overlit 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 *
	Error	3	112.35		

Basically, all factors are investigated by transverse comparisons of their average results in this stage of the methodology. To sum up, PP plays the main role on daylighting performance, where the 37.5% yields the best performance for the actual daylit area. O also plays an important role, where the North orientation yields the best performance, so it can be considered to be the most suitable orientation for designing PSS in terms of the actual daylit area. In contrast, South offers a compromise between the effects of the actual daylit and over lit areas. Of all factors, the matrix and shape exhibit the weak effects. These results provide suggestions for designers in choosing a possible strategy of PSS, especially for North orientation.

According to the objective function, the standard level of the four design variables should achieve the highest value of the actual daylit area and the lowest of the overlit area. Table 3 indicates with characters in bold these standard levels that origin the configuration 371CN. Table 5 shows the simulation results of 371CN.

Table 5 Standard level for factors

Simulation	PSS	Factors and levels				Simulation results			
		1 (PP)	2 (M)	3 (S)	4 (O)	Non-daylit area (%)	'actual' Partially daylit area (%)	'actual' Daylit area (%)	Over lit area (%)
17	371CN	2(37.5%)	1(12×28)	1 (C)	1(N)	0	7	92	2

3.2 Identification of the optimal level by the listing method

This stage focuses on further investigation of the individual factors. To optimize the four design variables, they were varied on four to six levels based on the listing method, as presented in Table 6. These results simulations are grouped by factors according to the listing method and summarized in Fig. 6. Additionally, Table 6 presents the space areas quantified in the reference models, which are included for subsequent contrasting use or non-use of PSS on façades. Besides, Fig. 7 shows all sensor points with the percentages of the working year that achieve the illuminance ranges of the daylight availability metric.

Table 6 Simulation results of the listing method and reference models

Simulation	PSS	Factors and levels				Simulation results			
		1 (PP)	2 (M)	3 (S)	4 (O)	Non-daylit area (%)	'actual' Partially daylit area (%)	'actual' Daylit area (%)	Overlit area (%)
18	751CN	6 (75%)	1 (12×28)	1 (C)	1 (N)	0	0	71	29
19	621CN	5 (62.5%)	1 (12×28)	1 (C)	1 (N)	0	0	80	20
1	501CN	1 (50%)	1 (12×28)	1 (C)	1 (N)	0	0	89	11
17	371CN	2(37.5%)	1(12×28)	1 (C)	1 (N)	0	7	92	2
20	251CN	3 (25%)	1 (12×28)	1 (C)	1 (N)	1	45	53	0
21	121CN	4 (12.5%)	1 (12×28)	1 (C)	1 (N)	59	28	13	0
22	372CN	2 (37.5%)	2 (9×21)	1 (C)	1 (N)	0	7	92	1
23	373CN	2 (37.5%)	3 (6×14)	1 (C)	1 (N)	0	5	94	1
24	374CN	2 (37.5%)	4 (3×7)	1 (C)	1 (N)	0	3	97	1
25	375CN	2 (37.5%)	5 (Random)	1 (C)	1 (N)	0	3	94	3
26	371HN	2 (37.5%)	1(12×28)	2 (H)	1 (N)	0	3	95	2
27	371QN	2 (37.5%)	1(12×28)	3 (Q)	1 (N)	0	4	94	2
28	371TN	2 (37.5%)	1(12×28)	4 (T)	1 (N)	0	3	95	2
29	376IN	2 (37.5%)	6 (Irregular)	6 (I)	1 (N)	0	1	93	6
30	371CS	2 (37.5%)	1 (12×28)	1 (C)	2 (S)	0	0	49	51
31	371CE	2 (37.5%)	1 (12×28)	1 (C)	3 (E)	0	0	61	39
32	371CW	2 (37.5%)	1 (12×28)	1 (C)	4(W)	0	0	55	45
Reference models									
REF100N		100%	-	-	N	0	0	62	38
REF100S		100%	-	-	S	0	0	8	92
REF100E		100%	-	-	E	0	0	5	95
REF100W		100%	-	-	W	0	0	14	86

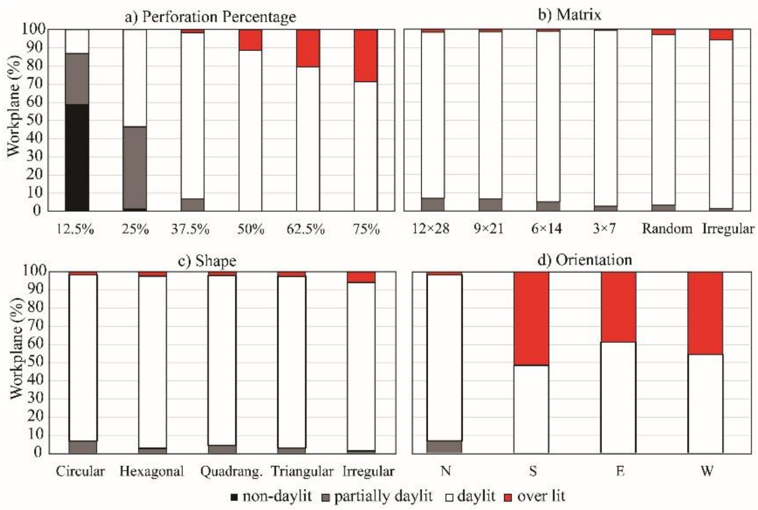


Fig. 6 Simulation results organized by factors according to the listing method

Fig. 7 Daylight availability accounted in reference models

3.2.1 Effect of the percentage perforation on daylighting performance

Perforation percentage is the main design variable due to its significance in the variation of daylighting performance, as simulation results indicate in Fig. 6a. The main findings are related to the actual daylit and overlit areas. The former shows a gradual increase as PP increases from 12.5% to 37.5% where it obtains the highest value; then, the actual daylit area shows a slight and gradual decrease as PP increases. The over lit area obtains 0% in PPs 12.5-25% and only 2% in PP 37.5%; then, it increases from 11 to 29% as PP increases. These changes can also be observed throughout the workplane in Fig. 8 where every sensor shows the percentage of the working year that achieves the illuminance range of its particular daylight availability area.

To understand the behaviour of daylight in the space with and without PSS, together with the effect of PP on daylighting performance, the six levels of this factor are investigated relative to the reference model oriented at North. Accordingly, Fig. 9 shows the absolute differences between the space areas quantified in PSS minus those computed in REF100N. In summary, the results indicate that the non-daylit area increases 59% with PP 12.5% and practically do not quantify differences in the other levels respect to REF100N. The actual partially daylit area shows a remarkable increase of 45% with PP 25%, followed by an increment of 28% with PP 12.5%; however, PP 37.5% achieves only a 7% increase while the other levels do not achieve differences with REF100N.

The actual daylit area achieves its highest increase of 29% with PP 37.5%, closely followed by PP 50% with an increment of 27%. PPs 65.5 and 75% also gets increases but these are smaller than the previous two; lastly, PPs 12.5 and 25% lessens considerably the actual daylit area meaning they should not be implemented. The over lit area decreases at a maximum of 38% with the two biggest PPs; meanwhile, a medium reduction of 36% is achieved with PP 37.5% and smaller PPs get smaller reductions.

From above, it can be confirmed that PP 37.5% yields the best performance as it increases the actual daylit area as much as possible and it reduces almost the entire overlit area from the fully glazed façade oriented at North. The second best performance is for PP 50% that achieves the second larger actual daylit area. Although the overlit area in PP 50% is larger than that accounted in PP 37.5%, it is smaller than that accounted in bigger PPs. Furthermore, Fig. 8 gives the impression that sunlight penetration through PP 50% reaches approximately 1.25 m which are less than the 2.00 and 2.50 m accounted in PP 62.5 and 75%, respectively.

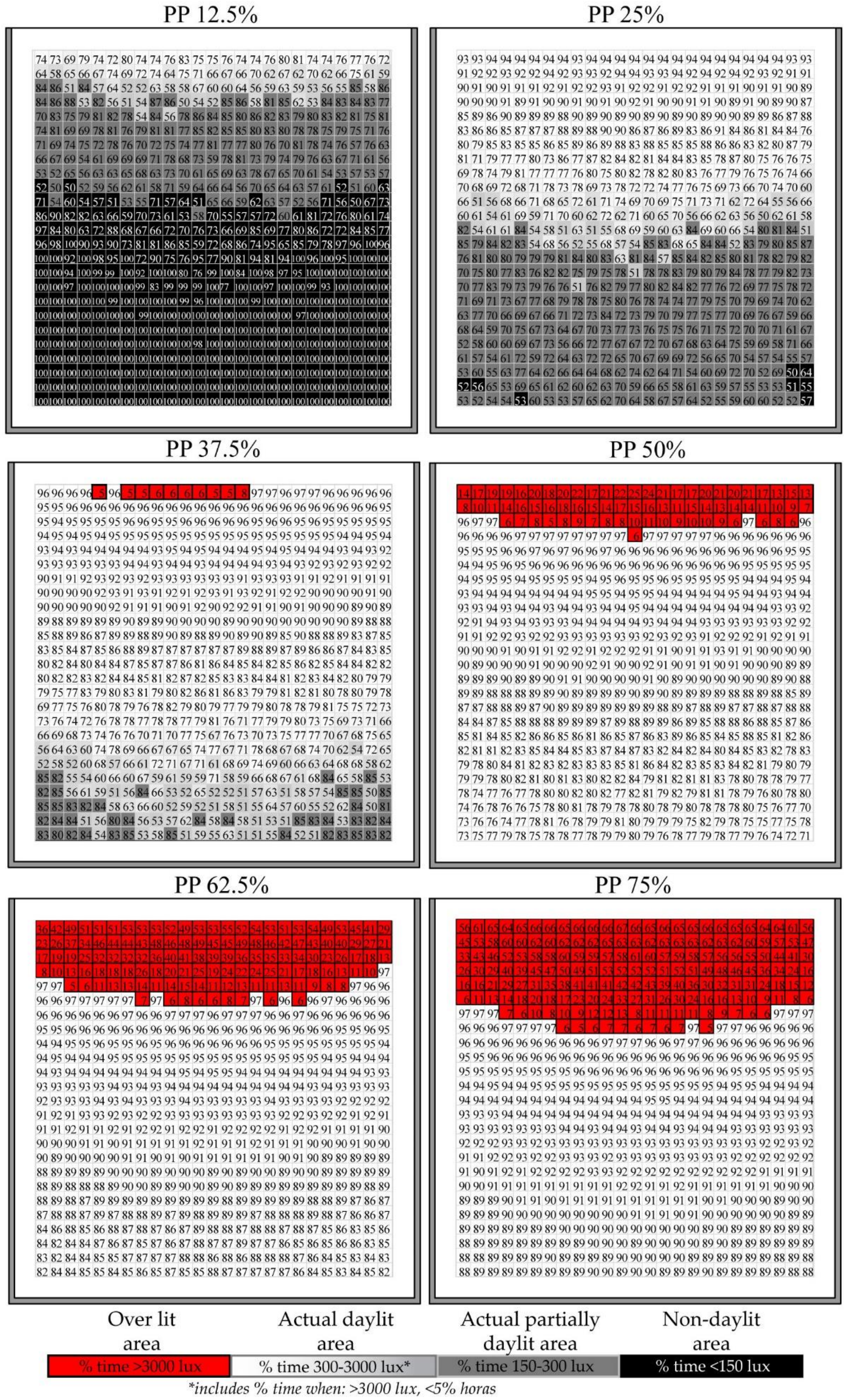
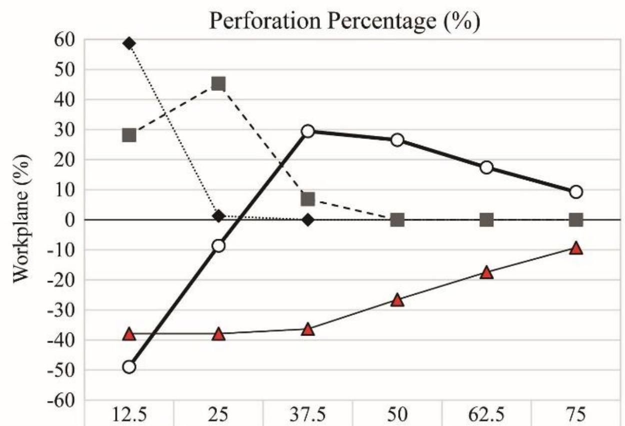


Fig. 8 Daylight availability variation attributed to changes in PP



	12.5	25	37.5	50	62.5	75
non-daylit	59%	1%	0%	0%	0%	0%
actual partially	28%	45%	7%	0%	0%	0%
actual daylit	-49%	-9%	29%	27%	17%	9%
over lit	-38%	-38%	-36%	-27%	-17%	-9%

Fig. 9 Absolute differences quantified between the six PP levels and REF100N

3.2.2 Effect of the matrix on daylighting performance

Fig. 6b indicates that the variation of M does not produce significant changes on daylighting performance. Thus, the non-daylit area is equal to zero in all levels. The actual partially daylit area obtains differences of less than 6% between levels. The actual daylit area shows differences of less than 5% between levels meaning they are no significant; however, the highest value is for M 3×7 and the lowest one for M 12×28 and 9×21. The over lit area shows fluctuations with results very close to each other; however, M irregular achieves the highest value. These changes can also be observed at all sensor points throughout the workplane in Fig. 10.

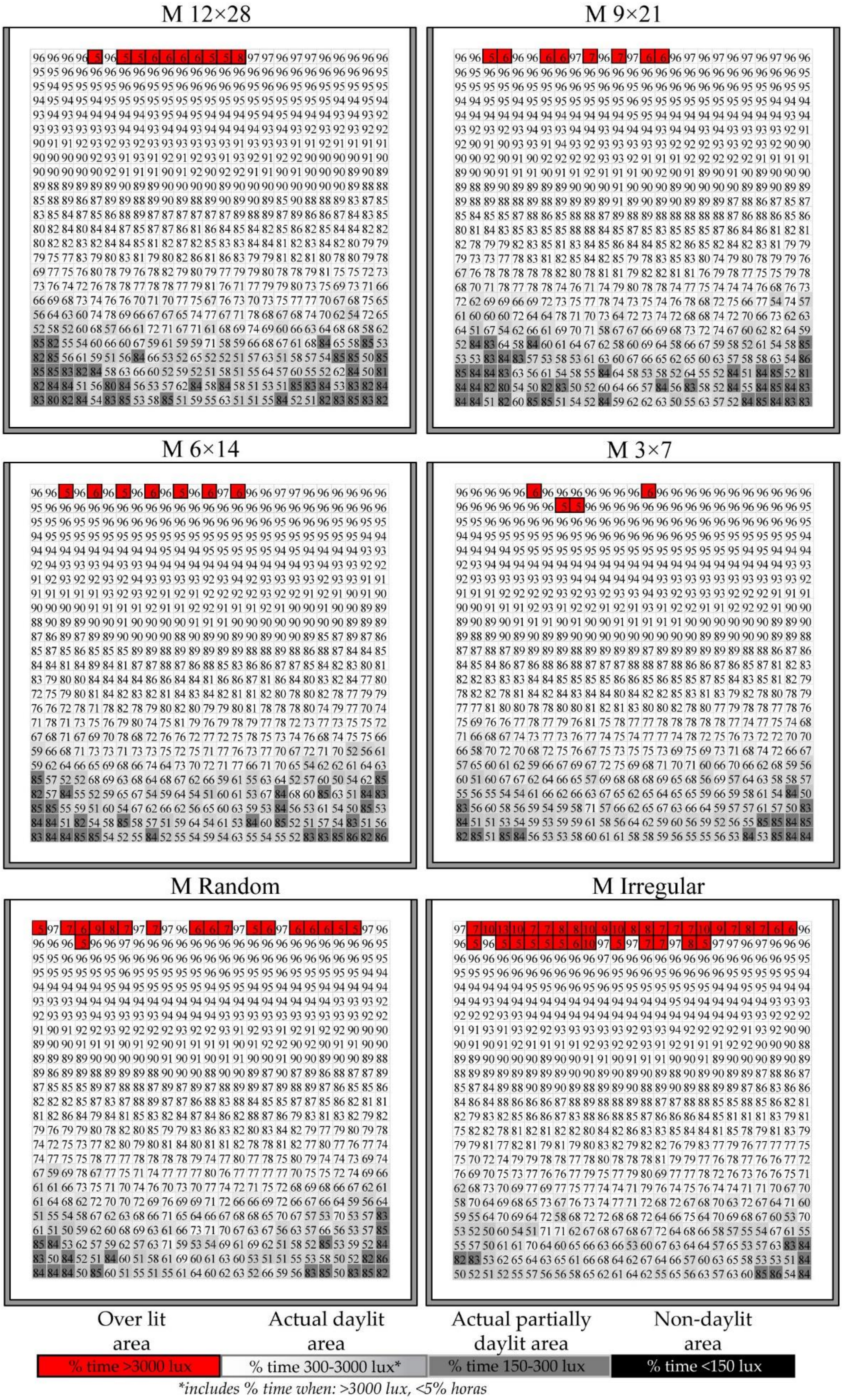
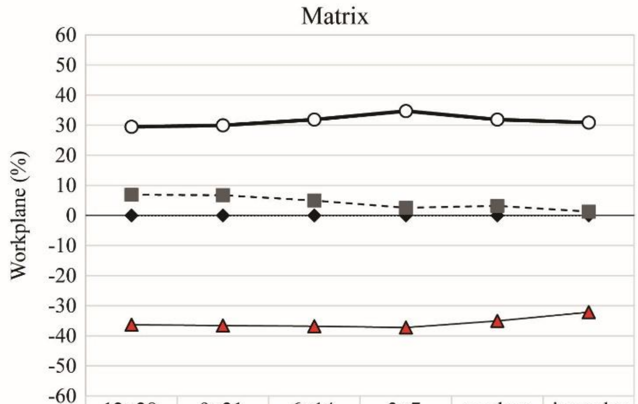


Fig. 10 Daylight availability variation attributed to changes in M

To contrast the use and non-use of PSS, together with the effect of M on daylighting performance, the six levels of M are investigated relative to the reference model oriented at North. Fig. 11 shows the absolute differences between the space areas quantified in PSS minus those calculated in REF100N. In brief, the results confirm that M is not a significant design variable. Thus, the non-daylit area does not produce any change at any level. The actual partially daylit area shows a similar increase by an average of 4% in all levels relative to REF100N, with differences between levels that do not achieve 6%. The actual daylit area is improved at all levels by an average of 31% with differences between levels that do not exceed 6%. In contrast, the over lit area is decreased at all levels by an average of 36% but the differences between levels are less than 5%.



	12×28	9×21	6×14	3×7	random	irregular
non-daylit	0%	0%	0%	0%	0%	0%
actual partially	7%	7%	5%	3%	3%	1%
actual daylit	29%	30%	32%	35%	32%	31%
over lit	-36%	-37%	-37%	-37%	-35%	-32%

Fig. 11 Absolute differences quantified between the six M levels and REF100N

3.2.3 Effect of the shape on daylighting performance

Fig. 6c shows that changes in S do not yield significant variation on daylighting performance. As a result, the non-daylit area is equal to zero in all levels. The actual partially daylit area obtains differences of less than 6% between levels. The actual daylit area obtains differences of less than 3% between levels meaning they are no significant. The overlit area shows fluctuations with results very close to each other; however, it can be observed that S irregular achieves the highest value. These changes can also be appreciated at all sensor points throughout the workplane in Fig. 12.

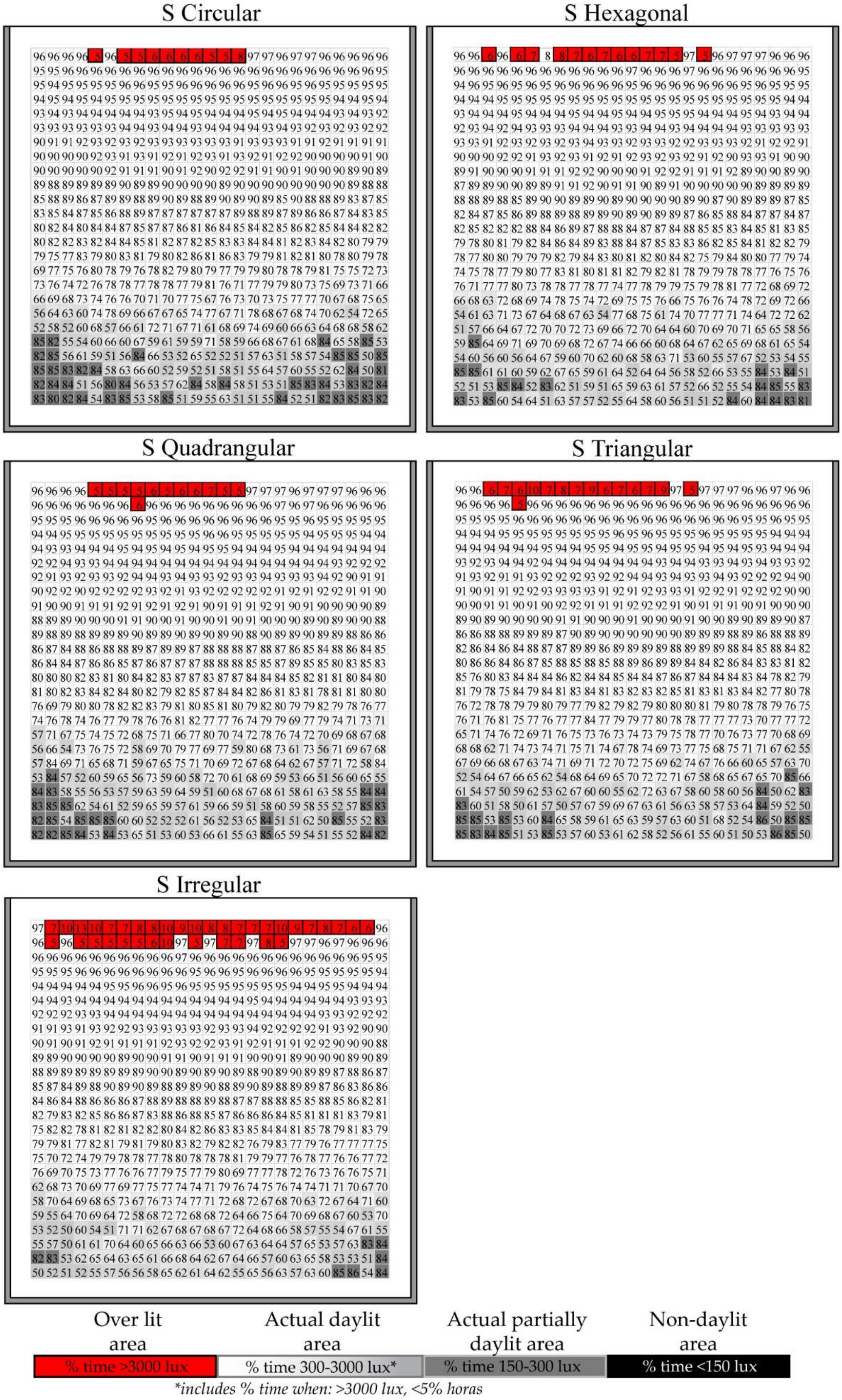
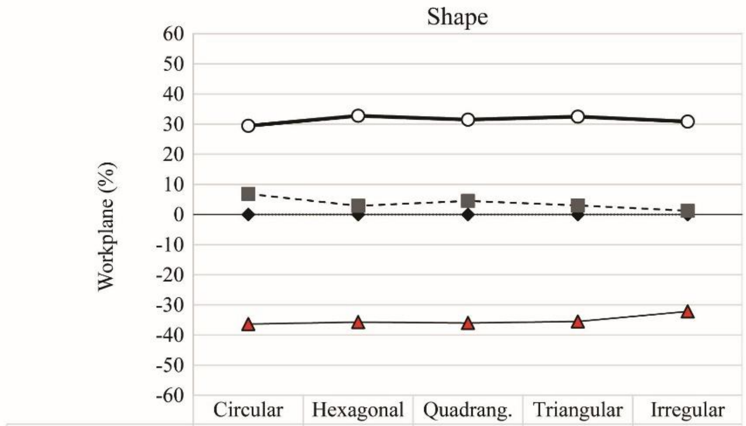


Fig. 12 Daylight availability variation attributed to changes in S

To contrast the use and non-use of PSS, together with the effect of S on daylighting performance, the five levels of S are investigated relative to REF100N. Fig. 13 illustrates the absolute differences between the space areas quantified in PSS minus those calculated in REF100N. In summary, S is not a significant design variable since the small differences quantified in the simulation results. Accordingly, the non-daylit area does not produce any change at any level. The actual partially daylit area shows a similar increase by an average of 4% in all levels relative to REF100N, with differences between levels that do not exceed 6%. The actual daylit area is improved at all levels by an average of 31% with differences between levels that do not exceed 4%. In contrast, the over lit area is decreased at all levels by an average of 35%; besides, the differences between levels are less than 4%.



	Circular	Hexagonal	Quadrang.	Triangular	Irregular
non-daylit	0%	0%	0%	0%	0%
actual partially	7%	3%	4%	3%	1%
actual daylit	29%	33%	32%	32%	31%
over lit	-36%	-36%	-36%	-36%	-32%

Fig. 13 Absolute differences quantified between the five S levels and REF100N

3.2.4 Effect of the orientation on daylighting performance

Orientation is the second most important design variable as the results differences in Fig. 6d show. Hence, it can be deduced that N yields the best performance for the latitude studied; this cardinal point increases the actual daylit area as much as possible and reduces almost the entire over lit area from the fully glazed façade. Besides, S is the worst orientation since it achieves less than half of the workplane as actual daylit area; also, it gets the highest over lit area in comparison with the other three orientations. E and W obtain intermediate values for the actual daylit area but they barely overpass the half of the workplane; besides, E and W still achieving high values for the overlit area.

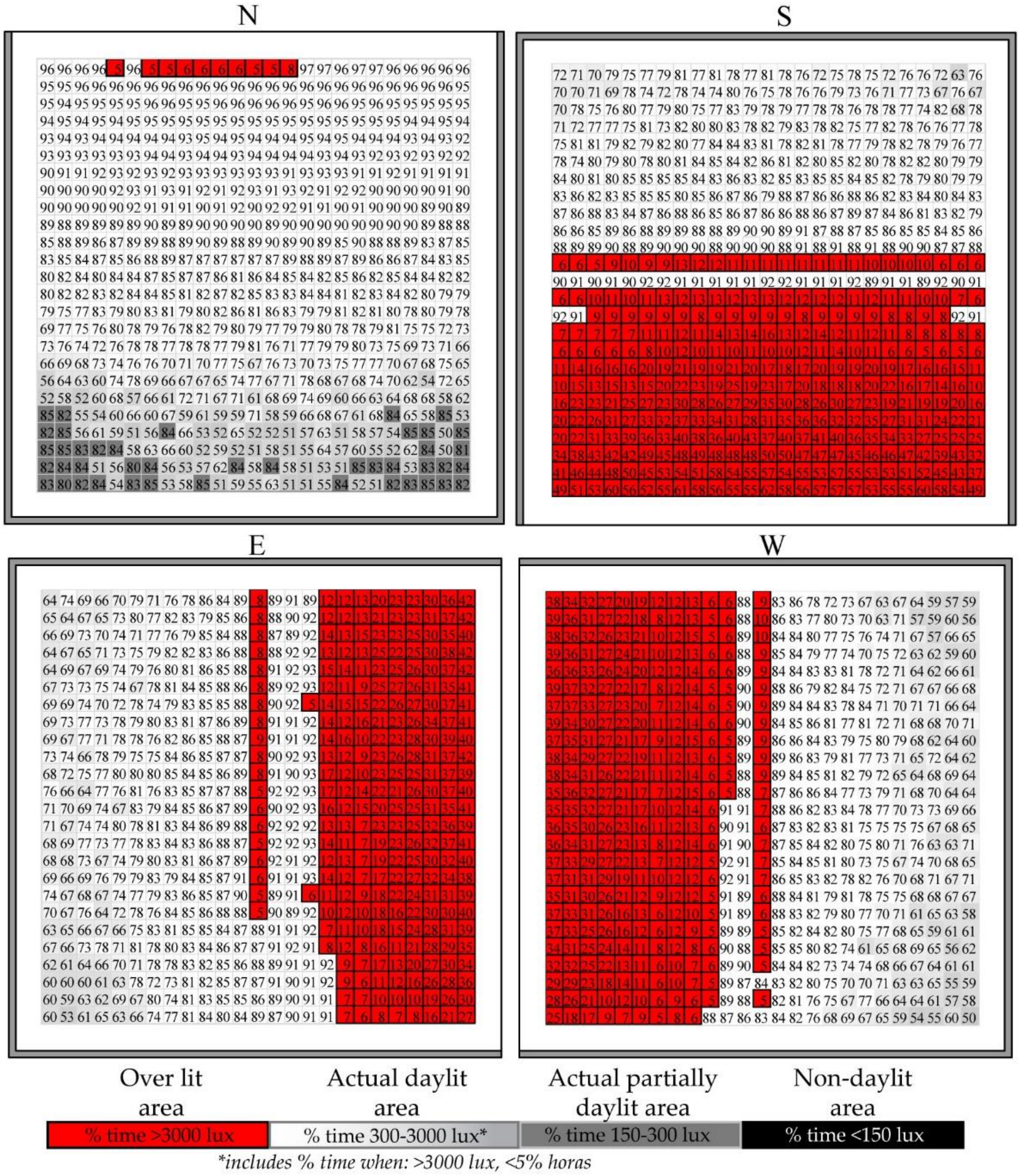
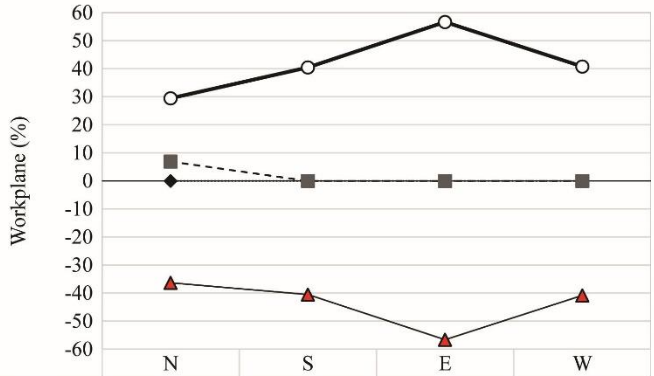


Fig. 14 Daylight availability variation attributed to changes in O

As all orientations provide certain levels of daylight, it is suitable to understand the behaviour of this resource in the space with and without PSS at every cardinal point. For this purpose, every orientation is investigated relative to its respective reference model in the following way: 371CN-REF100N, 371CS-REF100S, 371CE-REF100E Y 371CW-REF100W. Thereby, the oriented comparison is equitable and it can describe primarily the influence of using PSS and not the influence of changing the 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.

Fig. 15 illustrates the absolute differences quantified in the PSS minus those calculated in their respective oriented reference models. The results show that PSS at all orientations improve the actual daylit area, mostly at E that increases it in 57% of the workplane (from 5% in REF100E to 61% in 371CW). This effect does not mean that E orientation is better than the others, it indicates that the use of PSS on fully glazed façades oriented at E could increase the actual daylit area in a significant section of the workplane, relative to the non-use of PSS at the same orientation. For instance, the N orientation increases the actual daylit area in only 29% of the workplane (from 62% in REF100N to 92% in 371CN); however, N still accounting the highest actual daylit area among all cardinal points (See Fig. 6d). Likewise, S and W orientations can also increase the actual daylit area in 40 and 41% of the workplane, respectively.



	N	S	E	W
non-daylit	0%	0%	0%	0%
actual partially	7%	0%	0%	0%
actual daylit	29%	40%	57%	41%
over lit	-36%	-40%	-57%	-41%

Fig. 15 Improvement of the daylighting performance of PSS at the four orientations

On the other hand, PSS are also helpful for reducing the over lit area in all orientations. Hence, N reduces the over lit area in 36%, S reduces it in 40%, E in 57% and W in 41%, relative to reference models oriented at N, S, E and W, respectively. These daylight changes throughout the workplane can also be appreciated when comparing Fig. 7 and 14. For example, there is a clear reduction in the overlit area from reference models (Fig. 7) to PSS (Fig. 14). Besides, the percentages of the working year in all overlit sensors decreases considerably when using PSS. Depending on the orientation, they can reduce from 80-90% to 5-50% in the sensors near the glazing. In conclusion, there is a significant daylighting improvement derived from the use of PSS on fully glazed façades at the four cardinal points.

3.3 Design guidelines for optimal PSS

Concluding this work, the following PSS design guidelines from the integrated method:

- Perforation percentage is the variable which should guide PSS design. Although higher perforation percentage achieves higher illuminances of daylight, there is a limit in the total surface of the PSS openings that must be considered to do not reach an oversupply of daylight in the space. The optimal level of PP is 37.5%, followed by 50%. These two levels increase the actual daylit area around 27-29% of the workplane at North; both levels also reduce the over lit area in 27-36% at North. In contrast, smaller PPs can reduce until 49% of the actual daylit area and larger PPs do not obtain considerable reductions of the overlit area.
- Orientation is the second most important variable, where North yields the best performance because it achieves the highest actual daylit area together with the smallest over lit area. In

contrast, South is the less suitable orientation because it noticeably reduces the actual daylit area and increases the over lit area.

- Matrix and shape are less important as design variables. Their ANOM results exhibit weak effects for the actual daylit area since the differences quantified between levels do not achieve 6% of the workplane. However, the listing method can point better the matrix with bigger sized holes because it reduces the overlit area. In contrast, the irregular matrixes and shapes are less suitable because they increase the over lit area and sunlight penetration.

4. Discussion

This paper integrates the orthogonal and listing methods to optimize the PSS design in relation to its effect on daylighting performance. The OA method was validated in a previous research where the mean effects of different factors were successfully weighed by performing an ANOM analysis. Hereafter, some issues can be enriched. First, the ANOM tested the average performance of groups integrated by PSS that share equal levels for each factor. Thus, the achieved main effects were merely the average values of the common factor levels but they did not display the real simulation results (named as percentages of the space areas lighted through PSS). Basically, the OA method investigated all factors by transverse comparisons of their average results. Then, the orthogonal method certainly implies the selection of one OA from the Taguchi's catalog, meaning that the number of levels to be tested are restricted.

Unlike the OA method, the results quantified by using the listing method properly represent the real lighted percentages of the space areas. Therefore, the listing method can effectively complement the main effects information with a more detailed description that takes into consideration the native simulation results without any post-processing. Furthermore, the listing method can include a free number of levels for comparative and quantitative analysis. When the listing arrangement starts from the premise of the 'standard level' obtained from the OA, it still possible using only a fraction of the factorial combinations through deeper and judicious investigations.

In this paper, the integrated method allows identifying not only the statistical significance and the main effects but also the small differences that pointed better some levels. For example, the OA method assigns statistical significance to the PP, O and S factors but not to the M. Then, the less main effect is assigned to M factor since the OA just took into account the average values. However, the listing method can distinguish improvements derived from using big-sized holes and regular matrixes. Furthermore, the listing method can effectively describe the daylight distribution across all workplane and give an impression about sunlight penetration.

In brief, it is recommended to complement the orthogonal method with the listing method in order to describe in detail the real simulation results and the changes attained to the design variables; also to compare quantitatively the daylighting distribution through PSS. The main advantage of the integrated method still in reducing the number of simulations required to predict the best combination of factor levels, optimizing not only the daylighting performance of PSS but also the design and planning time for a building.

5. Conclusions

This paper aims to provide architects with methods and tools that could be applied early in the design processes. The main purpose is to find optimal solutions for two-dimensional PSS by identifying the appropriate values of different design variables through a minimum number of simulation cases. By using the orthogonal method, this paper finds that perforation percentage and orientation are prominent for the daylighting performance of PSS. The application of the OA reduces the number of simulations from 256 to only 16 for predicting the standard levels by means of statistically significance differences. This investigation further used the listing method to describe in detail how the changes in perforation percentage, matrix, shape and orientation can influence the daylighting performance. The listing method compares quantitatively the daylight distribution on the workplane and accordingly selects the optimal levels by using only 16 more simulations. In summary, the integrated method reduces the number of simulations from the 720 required to 32, so it could save time considerably when looking for the optimal solutions.

The daylight availability metric is used as the daylighting criteria. Hence, the non-daylit, actual partially daylit, actual daylit and overlit areas through PSS are investigated relative to those of the reference models with no PSS. The highest actual daylit and the lowest overlit areas are used as performance targets for identifying the optimal levels of the PSS design variables. As a general guide for all orientations, it is better to design PSS with PP 37.5% (or 50%) for maximising the actual daylit area. Among the four cardinal points, North is the best suited to the latitude studied. In contrast, South, East and West still achieving big overlit areas despite using the optimal PP. Regarding the variables M and S, the irregular levels are the less suitable and the regular ones get design flexibility. These results provide suggestions for designers in choosing a possible strategy of PSS, mainly at North since it was set as the standard level. Therefore, further investigations need to be carried out to develop specific strategies for every cardinal orientation. In short, the optimised PSS get increments of 29-57% for the actual daylit area and reductions of 36-57% for the overlit area compared to the fully glazed façades with no shading devices and oriented at the four cardinal orientations. In conclusion, there is an important difference between the use and non-use of PSS on fully glazed façades, so it is recommended to implement them.

This investigation was limited to two-dimensional PSS and only four design variables were selected for the analysis. Nevertheless, the approach here presented is worth to simplify the daylighting evaluations and allows further investigations of other design variables, such as screen thickness, cavity depth, colors, materials or even different climatic conditions. Hence, it should be highlighted the need for further research on three-dimensional screens, which are likely to impact the results across the working plane. The outcomes of this integrated methodology will help to analyse these type of screens.

As mentioned before, this work focused on annual daylight calculations. However, illuminance studies at the working plane are not suitable for all types of daylight evaluations. In particular, direct sunlight patterns and glare assessment throughout a full year need to be further explored. These evaluations need measurements taken on a specific field of view that is dependent on the occupant's position. They also imply a huge number of variable conditions, such as background luminance, source intensity, solid angle, etc. In this respect, recent researches have taken a step further to correlate the annual illuminance metrics and glare predictions (Mardaljevic *et al.*, 2012). Additionally, other considerations such as solar gains through PSS and therefore the overall energy consumption are currently ongoing (Chi, Moreno and Navarro, 2018). These studies aim to identify how the optimal levels proposed can affect the spaces in terms of energy savings.

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