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Optimization of an external perforated screen for improved daylighting and thermal performance of an office space

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Abstract

Glazed towers are predominant among commercial buildings built in recent decades. They advance the use of natural light, increase the visual contact with the outside and have a contemporary look. However, issues related to excessive daylight illuminances, glare and direct solar gains affect the visual and thermal comfort, and potentially increase the building energy demand. Passive design of protections is a key element to tackle these problems. A shading device consisting of a perforated screen is presented in this research with the aim of improving the Useful Daylight Illuminance (UDI), and reducing energy consumption and Daylight Glare Probability (DGP). The screen has been supposed to be used in an office space in Australia with windows on its north and west façades. Integrated daylight and thermal simulations have been carried out with the use of Rhinoceros/Grasshopper integrated specialist software. The geometry of the shading device has been optimized using Grasshopper integrated evolutionary optimization tool based on Genetic Algorithms. Size and distribution of the perforations in the solar screens have been chosen as optimization variables. Results, then, have been compared to a base case with no shadings and show significant improvements in UDI values, together with substantial reductions of energy consumptions and glare probability.

Keywords: Shading device; Perforated screen (PS); Optimization; Genetic Algorithms (GA); Useful Daylight Illuminance (UDI); Energy consumption; Daylight Glare Probability (DGP)

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1. Introduction

Glazed towers are predominant among commercial buildings built in recent decades, having been constructed all over the world in different types of climates and latitudes. They have a contemporary look and can increase the amount of natural light in the interior [1], which stimulates the visual and circadian systems [2]. Furthermore, they increase the visual contact between the inside and the outside of the building and the large glazed areas have a positive psychological effect because of the sense of openness of the space [3]. Evidence shows that users prefer to work in offices with daylight and visual contact to the outside, and that environments with no glare and comfortable in terms of temperature have positive effects on satisfaction and performance [4]. However, glazed façades in buildings may also cause some issues. For instance, direct sunlight in indoor spaces can produce excessive daylight illuminances, leading to visual or thermal discomfort of the occupants [4]. High levels of daylight in an office space are sometimes the opposite to optimum levels of visual conditions, being glare one of the major issues [5]. Excessive glare produce discomfort, reduction in the performance of users, and lighting changes that may increase the energy consumption [6]. In addition to daylight problems, there are also effects on the thermal performance of buildings. Daylight is just the visual component of the radiant energy that comes from the sun and, after it enters through the glass, a large percentage is transformed into thermal energy once it is reflected in the interior surfaces of buildings [7]. In Australia, office buildings are responsible for about the 25% of the total energy consumption by building type, and HVAC (43%) and lighting (26%) consume the 69% of the electricity in them [8]. Therefore, solar radiation should be controlled before it gets to the inside of buildings. This can be achieved by the use of shading devices and several examples are found in the existing literature.

A study of a Solar Screen in a desert climate was carried out in order to improve daylight, reduce glare and increase thermal comfort by analyzing its perforations [9]. Positive results were achieved and it was recommended to treat the screen of the south façade (northern hemisphere) differently in order to get better results. Another research of screens in desert climate reports that savings in energy consumption can reach values of up to 30% for west and south orientations in the northern hemisphere [10]. A research by Omidfar [11] assessed a solar screen with complex geometry in order to optimize the performance of indoor environments in terms of daylighting and energy. Results showed a reduction of annual energy use of respectively 35% and 42% in relation to the two baseline cases.

In terms of external horizontal elements, a research by Datta reported that louvres on south windows (northern hemisphere) can decrease the cooling loads for buildings in summer, while reducing the overall annual primary energy use [12]. In another research, an innovative shading device composed of tilted louvres, arranged to optimize the visual contact with the outside was studied and compared with three typical shading options (overhang, blind, and light-shelf). The new system produced better results than traditional systems, minimizing heating and cooling demand of internal spaces, and also providing maximized views of the outside [13]. External shading devices were tested in a research by Palmero-Marrero and Oliveira [14] for 5 different climates, concentrating on a typical single-zone office building with windows exposed to south, east and west. The system employed on the south façade was optimized to provide shading in summer and allow solar heat gains in winter. For east and west windows, a vertical layout of horizontal louvres was found to be beneficial in controlling light and solar gains. The developed systems were successful in reducing the energy consumption in the majority of climatic zones.

Genetic Algorithms (GA) are a powerful method in the process of finding optimized solutions for a large number of problems and have been widely studied in the field of the built environment. They mimic the process of natural selection where most powerful individuals are expected to prevail in a highly competitive environment, and a fitness value is utilized in order to assess how good these individuals are [15]. GA were part of a research to find a thermal and daylight optimized solution for placement and size of windows in a building [16]. In addition to the positive results achieved, when several runs of the same problem were done, solutions with similar environmental performance had variations. This gives flexibility to designers in order to select the preferred solution between different possibilities with very similar performance. Another research investigated an optimized shading device for a north façade window (southern hemisphere). Utilizing GA, the solution improved the daylighting illuminance levels and stopped the direct solar radiation decreasing the energy consumption [17]. A study by Karamata et. al. [18] developed an external shading, based on the Mashrabiya design principles, with a variable geometry capable of adapting to arid climates. The final goal of the research was to develop a system able to maximize the diffuse natural light and views to the exterior, block the direct sunlight and transform it to diffuse interior light. They used an optimization process as part of the methodology for maximizing the visual comfort and minimizing solar gains.

The aim of the current study is to propose an optimized perforated screen (PS) for large open-plan offices, able to improve indoor comfort conditions of a glazed building in terms of its useful daylight illuminance (UDI), its daylight glare probability (DGP), and its energy consumption based on HVAC systems and lighting. In addition, it should be transparent enough to not lose the visual connection to the exterior.

2. Methodology

This research uses a virtual model of an internal room of a building, which resembles part of an open plan office for predicting indoor visual comfort requirements. The room is a corner one and has a double orientation. The proposed perforated screens are envisaged to be placed outside and parallel to the windows. The room is part of an educational building (home of the Faculty of Architecture, Design, and Planning of The University of Sydney, NSW, Australia) and is currently used for multiple functions, hosting lectures, studio-focused tutorials, and individual study activities, with occupancy patterns and visual comfort requirements very close to the ones of an open-plan office. The room has a rectangular shape, with internal dimensions of about 9 m x 12 m and is located at the corner of the fourth floor. Its shortest side is rotated 34º counterclockwise from the north axis and it has windows on its south-east and south-west façades. The windows are partially shaded by an external overhang, cantilevering 0.75 m from the façade's plane. The room is not affected by any significant shading from neighbouring buildings.

The virtual model of the room has been built using Grasshopper™ algorithmic editor for Rhino's 3D modelling tool. Daylight and energy simulations use respectively Daysim and EnergyPlus engines, interfaced with Grasshopper through Ladybug and Honeybee plug-ins. Real time and typical statistical weather files have been imported in the energy and daylight models through Ladybug plug-in for Grasshopper [19].

The virtual model, prior to performing optimization analyses, has undergone a full calibration to check the accuracy of Radiance rendering parameters. In particular, following the protocols reported in [20], the room has been divided into three daylight zones. A regular grid of measurement points has, then, been defined. In order to avoid any interference from side walls, the last row of measurement points has been spaced out 1 m from walls. Fig. 1(a) includes a plan layout of the room, with the position of measurement points. For each point the value of horizontal illuminance has been recorded hourly from 9am to 5pm in two different days, one with clear sky conditions and the other with overcast ones. At the same time, as a point of reference, the outdoor unobstructed horizontal illuminance was measured and recorded. The measurements have been carried out by recording illuminance values with a Goldilux Lightmeter (range of measured illuminance 0-200,000 lx, accuracy +/- 3%).

As the aim of the measurements was to collect data on the natural light levels in the room, artificial lights were kept off during the entire measuring period, and the internal blinds of the windows were kept completely opened. From the values of indoor and outdoor unobstructed horizontal illuminance information, we obtained hourly values of the Daylight Factors (DF) for each point. The maximum values of the overcast day were used to be compared with the results obtained in a computer simulation of the same room.

The room has, then, been modelled in Daysim, using the following Radiance rendering parameters: ambient bounces (-ab) is 5; ambient divisions (-ad) is 1024; ambient super-samples (-as) is 16; ambient resolution (-ar) is 256 and ambient accuracy (-aa) is 0.1. These parameters have been utilized for daylighting analysis in previous researches giving accurate results in a reasonable period of time [17] [21]. Regarding the optical properties of materials, reflectivities of 0.5 and 0.8 have been used respectively for the internal surface of walls and ceiling, while a value of 0.2 has been used as the reflectivity of floor. Visible Light Transmittance of glass has been calculated as equivalent to 0.8. Fig. 1(b) & (c) show the comparison of measured values of DF, with the ones calculated from the model. For the specific comparison, the maximum DF in overcast sky conditions has been considered. As it can be noticed from the graphs, there is a good accordance between calculated and measured values, with an average error of 7.7% and a maximum error of 18.1%. Moreover, it can be noticed that the calculated and measured values of DF are almost coincident for all reference points, except A3 and A6, close to the façade's plane.

In order to define a base case scenario for the current study, some changes have been made to the model. Firstly, the room has been rotated aligning one of its axes to the true north, in order to obtain useful and replicable data by having façades oriented north and west. Secondly, the geometry of windows has been slightly modified, in order to obtain the same Window-to-Wall ratio (0.45) for both orientations. Lastly, to have a better understanding of the influence of the shading elements of both north and west façades, the room has been shrunk to a squared shape. This gives a more regular room, with back walls on south and east having the same distance from the façade. The final shape of the room is shown in Fig. 2(a).

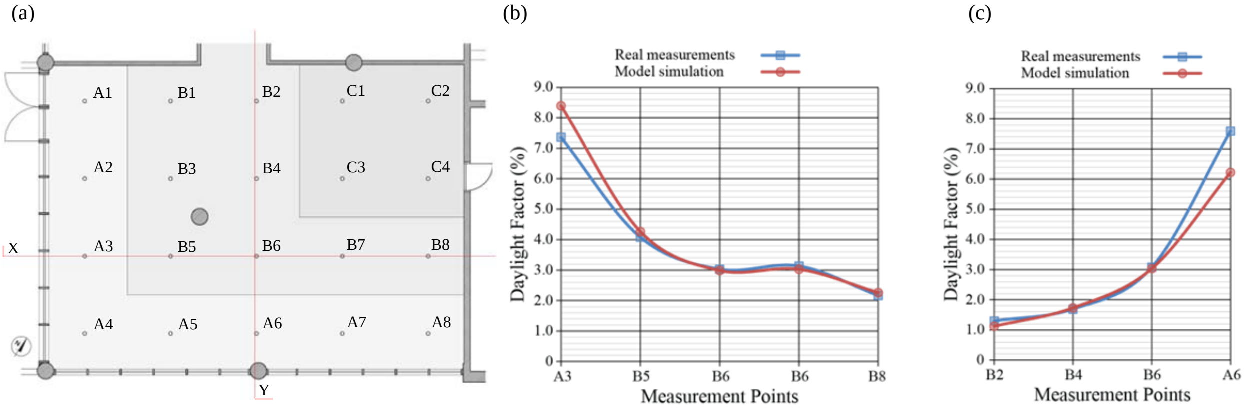


Fig. 1. (a) Grid of measurement points in Room 481. ☐ Daylighted Zone A ☐ Daylighted Zone B ☐ Daylighted Zone C. (b) Comparison between results from real measurements and the calibrated model for X axis, and (c) Comparison for Y axis.

This model has been used as a base case for the current report as it has no shading devices to control the sunlight and radiation. Analyses have been performed to assess UDI, energy consumption and DGP. As the room is representative of an open-plan office, five different reference points have been considered in the optimization (P1-P5 in Fig. 2(b)). Each of them represents the position of a potential user in the room. As it concerns glare calculations, the sensor point is located at the eye level of a seated user (1.2m from the floor) and points towards one of the windows in orthogonal direction [22]. Daylighting analyses serve also to predict the amount of artificial lighting required to meet indoor comfort requirements in the room. The schedule of operation of artificial lighting is then used as input of the energy model. In terms of occupancy, the room has been considered as fully occupied from Monday to Friday, from 8am to 6pm.

In terms of thermal properties of the model, as the space is intended to be just a portion of a bigger building, only the two walls facing north and west have been considered as exposed to the external environment. Constructions for walls and windows have been assumed to be compliant with the deemed-to-satisfy provision of the local energy code [21]. In particular the external wall has a U-Value of 0.27 W/m^{2}K, while the windows are provided with a Single-Glass Unit (SGU). All the other walls, the floor and the ceiling have been modelled as adiabatic.

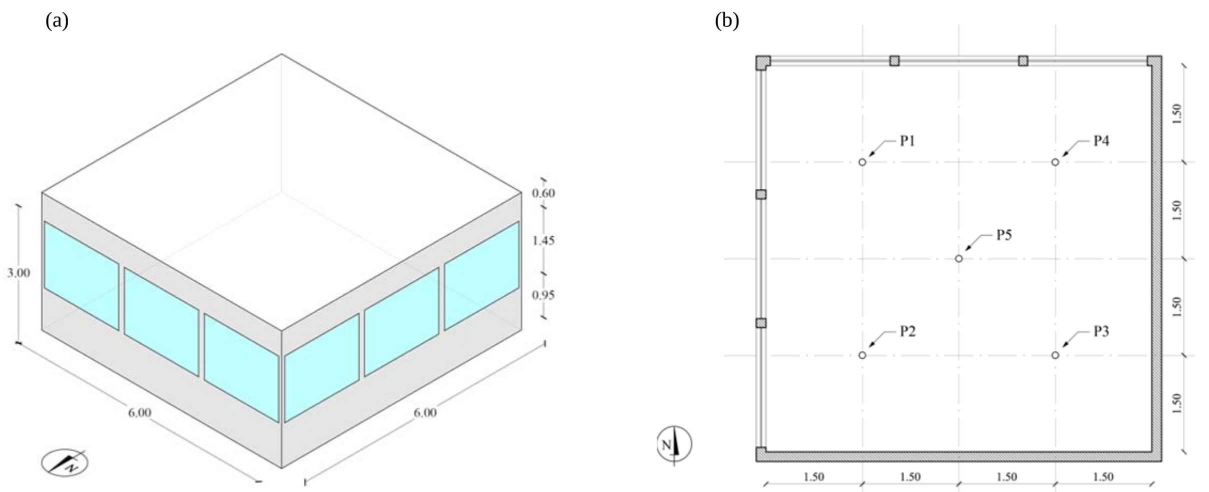


Fig. 2. (a) Case study volume, facing north-west. ☐ External walls. ☐ Windows. ☐ Adiabatic surfaces. (b) Plan of the room and its measurement points.

The office has been considered fully air conditioned to understand better the differences that solar screens might achieve in terms of energy consumption. An occupancy rate of 0.1 people/m^2 has been considered according to the Australian National Construction Code [23], while the maximum lighting density has been set 9 W/m^2, and the equipment energy density to 15W/m^2. Regarding the temperature control of HVAC systems, a heating set-point temperature of 20°C, and a cooling set-point temperature of 24°C have been considered.

2.1. Optimization Analysis

For the optimization analysis, a PS has been modelled and placed outside the windows of both façades (Fig. 3(a)). It has been modelled as a perfectly planar surface (i.e. no thickness) in order to avoid bounces of the light in the perforations, and has been spaced out from the windows of 100mm. The PS of both orientations can be modified independently to each other in terms of size and density of perforations in order to allow the optimization process to find the best possible solution.

The optimization process has been carried using the Evolutionary Algorithms embedded in Galapagos, tool included in Grasshopper. They apply the principles of mutation, selection and inheritance; populating virtually with a number of individuals that form generations. When new generations are created they keep the best individuals until their offspring gets closer to the peak values [24]. An individual is a genome, and a genome is formed by genes. Each gene corresponds to a value that can be modified. Therefore, every time that a gene changes a new genome is created. In this research, each genome consists of a gene that sets the separation between the openings (X in Fig. 3(b)) and a gene that controls the opening size (Y in Fig. 3(b)), which is given by the distance between the genes X. The subtraction Y – X gives, as a result, the perforation size.

The gene X varies between 2mm and 51mm, with steps of 7mm, while the gene Y varies between 4mm and 67mm, with steps of 9mm. Therefore, the size of the perforations varies between 2mm and 65mm. This method allows having a solar screen that can assume configurations from very transparent to very opaque. However, it can also produce results where the value of gene X is higher than the value of Y, leading to a complete opaque solar screen. In order to avoid this situation, an examination step has been added to check whether Y is bigger than X; if not, Y is replaced with a new value larger than X that allows to always have openings in the PS. As both façades can set different values for the perforations of their PS, the genomes taking into account for the optimization process are composed of X1, X2, Y1 and Y2 as shown in Fig. 3(c), allowing different transparencies for both façades.

Due to time constraints, the parameters adopted for the evolutionary solver have been limited to values that allow achieving a reliable solution in a reasonable period of time. The population has been set to 10 individuals per generation. The initial boost for the population multiplication factor in the first generation is 5. The maximum stagnant is 10 generations before the solver aborts when no improved solutions are found. The percentage of maintenance of individuals that are carried over to the next generation is 10% and the inbreeding factor is 50%.

A daylight index, UDI, has been used as fitness function for the optimization. In particular the Useful Daylight Illuminance autonomous (UDI-a), considering a comfort range between 300 lx and 3000 lx, has been assumed as main indicator [25].

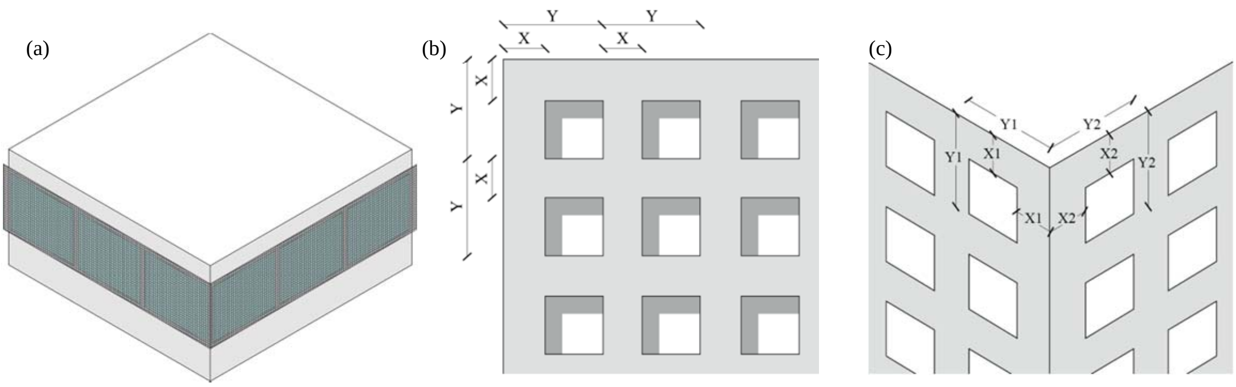


Fig. 3. (a) Perforated screens in front of windows. (b) Variables X and Y to modify the perforated screens. (c) Perforated screens of each façade can be modified independently.

Hence, five daylighting optimization analyses have been performed. Each of them taking into account just one of the measurement points as a daylight sensor, and giving as a result a perforated screen configuration (PS1-PS5 hereafter). After this, five calculations of energy consumption have been performed, one with each of these five PS configurations. Finally, five analyses of glare risk have been carried out to check the reduction of glare probability due to the use of the optimized perforated screen.

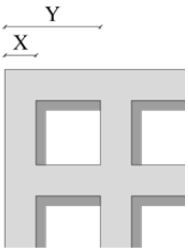
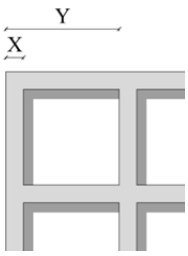
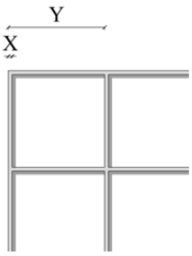
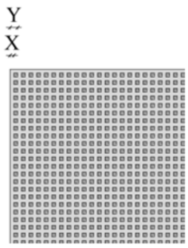
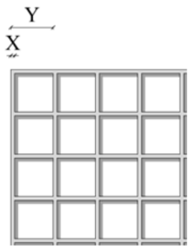
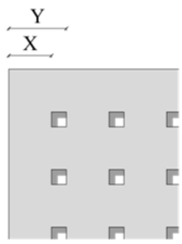
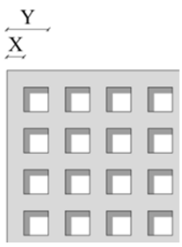
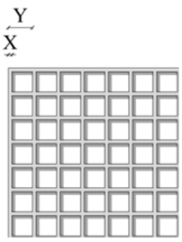
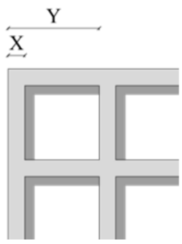
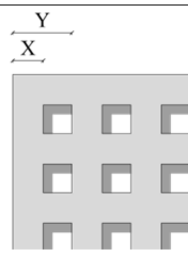
3. Results

The base case analysed shows high illuminance levels, mainly beyond the comfortable range, high energy demand and high values of DGP. Due to the double orientation of the room, the issues related with sunlight and radiation are amplified. As expected, UDI values vary across the different reference points and as the room in the base case has no protection from sunlight the points closer to windows present worst results than the ones further away from them. The inclusion of an external perforated screen produces a significant improvement in terms of UDI-a, and all the solutions present values ranging from 80% to 86%. They all achieve the goal of effectively controlling the direct sunlight that causes discomfort because of high illuminance levels. The five optimized PS are presented in Table 1. Perforation sizes and distribution for the different cases present similarities. Consistently the solar screen for the west façade is more opaque than the one for the northern one. This helps to control the direct daylight and solar radiation in the afternoon. The only exception is PS4 and this could be explained because P4 is located away from west façade; therefore, the influence of the west PS is not as relevant as for the other measurement points.

3.1. Daylight analysis results

In the simulations of the base case, the office room presented high illuminance values that exceeded the comfortable range. In Table 2 the daylight performance indicators are shown both for base case model and for the one with the optimized PS for each of the points. P1 of the base case must be compared with PS1 of the optimized solution and the same with the rest of the points for both cases. The illuminance levels of the base cases are mostly beyond the desirable levels, presenting high values for UDI-e. In terms of UDI-a values, four out of five points are below 50%, being P1 the worst case with 14% due to its proximity to both glazed façades. In contrast, P3 has an excellent result because is the one further away from the windows, receiving a reflected daylight rather than direct.

Table 1. Optimized perforated screens for each case.

	PS1	PS2	PS3	PS4	PS5
North Façade	 X=16; Y=49	 X=9; Y=58	 X=2; Y=49	 X=2; Y=4	 X=2; Y=22
West Façade	 X=23; Y=31	 X=9; Y=22	 X=2; Y=13	 X=9; Y=49	 X=16; Y=31

When the optimized PS are considered, UDI-a values are increased to 80% or above in all the measurement points, and the UDI-e values (accounting for illuminance levels higher than 3000 lx) are dramatically reduced. This ensures the decrease of uncomfortable high illuminance levels to the minimum. However, the UDI values below the comfortable range (UDI-f for levels below 100 lx and UDI-s for levels between 100 and 300 lx) are slightly increased in the new cases, making necessary to rely more on artificial lighting to maintain the minimum comfortable indoor illuminances. Nonetheless, the optimized PS improves significantly the daylight conditions of the room allowing to control it.

Table 2. Daylighting performance of simulations.

Measurement points	**Daylight performance indicators**			
Base Case	**UDI-a (%)**	**UDI-f (%)**	**UDI-s (%)**	**UDI-e (%)**
P1	14	4	3	79
P2	41	5	4	50
P3	85	9	4	2
P4	28	5	4	63
P5	48	6	4	42
Optimized Solutions				
PS1	86	7	6	1
PS2	83	8	5	4
PS3	84	10	5	1
PS4	80	11	6	3
PS5	86	9	4	1

3.2. Energy consumption outcomes

In terms of energy demand, all the optimized solutions contribute to its reduction. As observed from Table 3, the five cases achieved large savings in energy demand. By blocking solar gains, the PS reduce the cooling requirements by 27% to 63%. On the contrary, however, heating and lighting increased their consumption. In the case of heating, it can be explained by the reduction of solar heat gains in colder periods of the year. In terms of lighting, as mentioned previously, the solar screens increased the UDI-f and UDI-s values making necessary to utilize more artificial lighting to have sufficient illuminance levels in the office room. Nevertheless, the increases in heating and lighting are almost one order of magnitude lower than the reduction of cooling demand.

Table 3. Energy consumption results of simulations.

	Energy Consumption (kWh/year)				**Energy savings**	
Base case	**Cooling**	**Heating**	**Lighting**	**Total**	**kWh/year**	**%**
	4162.4	50.7	51.5	4264.6	-	-
Optimized solutions						
PS1	1529.6	195.7	56.0	1781.3	2483.3	58.2
PS2	2287.1	109.3	58.0	2454.4	1810.2	42.4
PS3	3035.8	70.2	83.4	3189.4	1075.2	25.2
PS4	1885.9	177.8	66.7	2130.4	2134.2	50.0
PS5	2201.8	100.9	66.9	2369.6	1895.0	44.4

3.3. Glare assessment

When comparing the glare analyses of the base cases with the optimized PS solutions, results show an important decrease in the intolerable and disturbing glare in every case. Comparisons between DGP of the base cases and optimized PS can be found in Fig. 4. Graphics show the values for imperceptible, perceptible, disturbing and intolerable glare. From the analysis of DGP calculations, it can be noticed that the best improvement can be achieved for reference points P1 and P4, facing the north direction, while the lowest improvement is experienced by P3, due to the already low DGP in the base case scenario (relative to the other reference points) and to the relatively large size of perforations in the optimized solution.

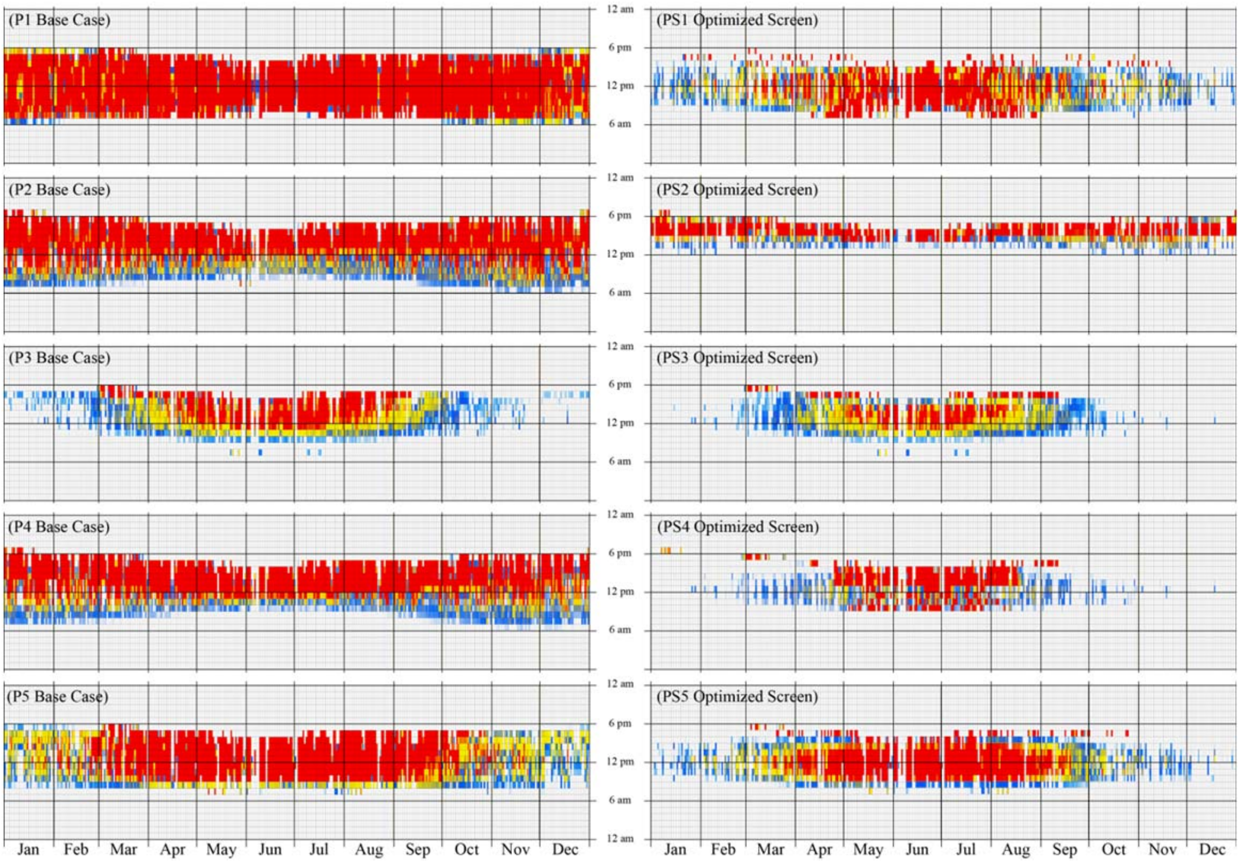


Fig. 4. Annual daylight glare probability comparison between base cases and optimized solar screens.
☐Imperceptible glare. ■ Perceptible glare. ■ Disturbing Glare. ■ Intolerable Glare.

3.4. Transparency of the perforated screens

One of the aims of this shading device is to avoid blocking the views to the outside. As the perforations are small but distributed evenly in the whole screen the eyes perceive to see with no obstructions to the outside [26]. Percentages around 50 have been considered to be perceived as semi-transparent by the human eye. In Table 4 the percentage of transparencies are presented, showing that at least one of the two façades has perforations around 50% and more in most cases. Therefore, with every solution the visual contact with the outside is possible.

Table 4. Percentage of surface of perforations of the solar screen.

	PS1	PS2	PS3	PS4	PS5
North Façade	45%	71%	92%	25%	83%
West Façade	7%	35%	72%	67%	23%

3.5. Optimized solution for the entire room

After analysing the individual results for the five different options, a single optimized solution has been selected for the entire room. Each of the optimization analysis presented previously considered the UDI-a for just one measurement point in the room, therefore each PS configuration responded to a specific condition. For this reason, an analysis has been done taking into account the 5 measurement points at the same time, for each of the 5 PS solutions. The UDI-a average of the 5 points was measured, and the solar screen PS1 achieves the best result (Table 5). In addition, this option is the one that presents the largest savings in energy consumption, as shown in Table 3. Finally, it is also effective in reducing the intolerable and disturbing glare in the DGP calculation, as it is possible to see in Fig. 5, which was measured from the centre of the room.

Table 5. Optimized solution for the entire room.

	PS1	PS2	PS3	PS4	PS5
UDI-a Average	73.8	67.2	53.6	70.0	67.6

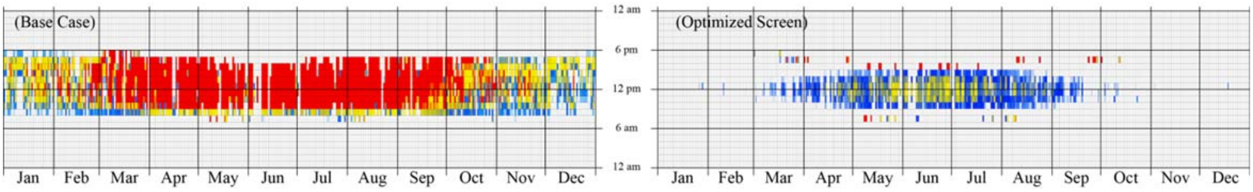


Fig. 5. Annual daylight glare probability comparison between base case and optimized solar screen.
☐ Imperceptible glare. ■ Perceptible glare. ☐ Disturbing Glare. ■ Intolerable Glare.

4. Discussion

Visual and thermal comfort in an office space is an issue of great importance for users. When it is not possible to control them passively artificial equipment is used to achieve the levels required and expected by them. This leads to a large energetic consumption and its consequential impacts on the environment. This research proposes a perforated screen that improves in a passive way the visual and thermal comfort inside an office space, north and west oriented, in order to enhance the experience of the users and to reduce the energy demand.

An optimization process has been carried out in order to try a wide range of perforation sizes and density in order to find the better configuration. Five different configurations of the perforated screen were optimized, one for each of the points analysed, producing excellent and very similar results between each other in terms of UDI-a. This is a positive outcome because notwithstanding the parameters for the optimization process considered a low number of individuals and initial boost, these results were consistently similar and with a high performance. When taking into account the large amount of possible values for perforation distribution and size in the solar screens it could have led to more varied results. In addition to the positive results in terms of UDI-a, the optimized solar screens were very effective in reducing the energy consumption of the office space. By having a vertical panel with perforations, the radiation is blocked in the outside notwithstanding the sun angle. Therefore, the solar screens consistently reduced the energy consumption for the 5 different cases. Regarding DGP, all the solutions reduced it considerably compared to the base cases. The improvement of the glare probability in the office space might be an important factor to enhance the visual comfort of users. In addition, the solar screens have different perforations distributions for each case but they maintain a percentage of transparency that allows the visual contact between the inside and the outside of the building.

From the five optimized solutions, a single option has been selected and tested. It presented the best results in terms of UDI-a value and energy consumption savings, as well as reducing considerably the DGP.

5. Conclusions

Perforated screens are shading devices that are used in the design of buildings as a continuous layer covering transparent areas. Under an aesthetic point of view, the application of perforated screens is sometimes beneficial when the designer opts for a simple and clean look, in contrast to vertical fins or horizontal louvers that extrude perpendicular to the façade. The method outlined in this paper, which makes use of Genetic Algorithms for the optimization of perforated screens, could help in defining more accurately the best distribution of the perforations and their size. Although perforated panels exist in the market and have been used in buildings, they have been usually utilized with aesthetic purposes rather than the ones intended in this research or they respond to standard solutions with perforations that have no relation with the indoor comfort needs. Non-optimized solutions could potentially improve the daylight and thermal properties of a building, but they might not be the best possible solution. This would lead to potential losses of efficiency of the shading system on the building and not the lowest possible running costs. Thus, the optimization process increases the possibilities of achieving maximum efficiency in the proposed solutions. The optimized perforated screen in this research has proven to achieve much better results in terms of useful daylight distribution compared with a base case with no shading. It has also achieved important reductions in energy demand and consequently in CO_2 emissions, and has reduced the daylight glare probability.

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