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Design optimisation of perforated solar façades in order to balance daylighting with thermal performance

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ABSTRACT

On fully-glazed building façades perforated solar screens (PSS) are often used as an outer skin in order to reduce energy consumption and to solve issues such as visual appearance. However, not only must PSS control solar radiation but they must also provide adequate daylight levels, thus requiring a balanced solution. Currently, daylighting simulation software enables us to perform efficient daylight analysis of spaces with PSS. Notwithstanding this, current energy simulation software such as EnergyPlus cannot deal well with such geometry directly, making the thermal evaluation of PSS an infeasible task. This paper presents a methodology for achieving an integrated analysis of daylighting and energy consumption of spaces with PSS during the design stage. Such methodology provides daylight analysis through DIVA, and thermal analysis through EnergyPlus via DIVA/Grasshopper/Archsim. The aim is to optimise the dual performance of a balanced PSS solution through controlling its perforation percentage, matrix and shape, by using the orthogonal arrays (DOA) statistical method. DOA method is efficient in reducing the number of simulations derived from the combination of the aforementioned variables, and in identifying the optimal PSS configuration. In comparison to a non-optimised façade located in Seville, Spain, the predicted optimal PSS achieved a 50% increase in the actual daylit area and a 55% reduction in the total energy demand.

1. Introduction

The building envelope plays an important role in controlling and/or admitting the various elements of the external environment. The building envelope can achieve about 80% of an environmental solution, creating an efficient building that interacts with its surrounding environment [1]. Present concerns with energy conservation have induced extensive studies regarding the façade's performance with the environment. There are numerous examples of buildings which have ignored their climatic conditions by extending the use of highly glazed façades in order for them to be airy, light and transparent. However, as there is a risk of high energy demand in order to maintain indoor thermal comfort [2] their energy efficiency has come into question.

Solar shading has, therefore, been an important step in energy saving control for buildings. Shading affects the energy use for lighting, heating and cooling; it also reduces yearly solar gains originating from solar radiation, as well as modifying thermal exchanges through the glazed building envelope and, moreover, it influences daylight levels within a building [3]. Perforated solar screens (PSS) are a type of shading device that have gained popularity with the shift from traditional to modern architectural styles [4,5]. Generally, PSS are flat, opaque, perforated panels forming a double skin for fully-glazed building façades. The organisation of their perforations filters out direct incident sunlight, which is prevented from directly penetrating into spaces while still allowing users to view the exterior. The opaque parts of the screen reflect sunlight and act as solar control systems [6,7]. For example, Fig. 1 illustrates a façade with a PSS.

1.1. The issue of applying the building performance simulation tools

Several works have been devoted to the study of the thermal effects of fixed shading systems, such as louvres, overhangs and vertical fins [8,9] using EnergyPlus, TRNSYS and EES software for energy simulations [3]. A few works have reviewed the impact of

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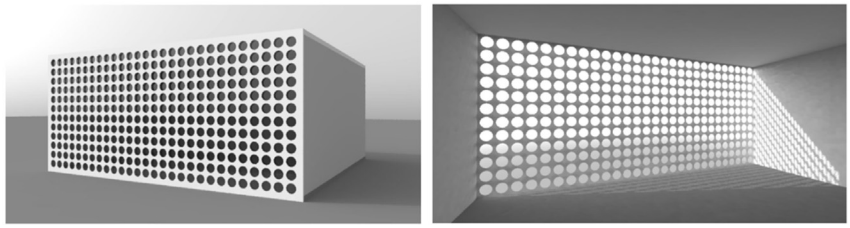

Fig. 1. Rendering of a PSS example.

perforated screens on reducing air conditioning and overheating, but these were developed for desert climates and for studying single design variables such as perforation range [10,11].

The impact of perforated façades on daylighting has, apparently, not been widely studied. There are few detailed studies regarding their effects on indoor illuminances by means of measurements on scale models [6,12,13] and computer simulations with Daysim and DIVA software [1,14,15]. Furthermore, these works addressed single design variables, such as shape [1,16], perforation rate and orientation [14] independently of each other.

A limited number of studies have addressed the balance between providing daylight and reducing solar gains derived from using solar control systems. Only a few relevant references exist [17,18]. This lack of studies addressing the integration of the daylighting and energy performances of PSS is due to the fact that such studies are complex tasks since these domains interact at many levels and simulation tools usually specialise in one domain only. The combination, therefore, of daylight and energy performance needs to employ different software packages in order to perform such detailed calculations. Moreover, to obtain accurate results building environmental performance simulation tools require a considerable amount of time and iterations. In addition, PSS usually present complex geometries, making them difficult to model in the current energy performance simulation tools and thus the design process becomes more sophisticated [19].

EnergyPlus, for example, is a whole building energy simulation program used to model the energy consumption in buildings – for heating, cooling, ventilation, lighting and other loads [20]. This software is well-suited to assessing the energy performance of conventional building systems or whole buildings, yet it is questionable whether such a tool can describe accurately the energy transfer phenomena that occur in complex geometries [21]. Furthermore, EnergyPlus has shown significant shortcomings in predicting the daylight available in a space, especially as the distance from the façade increases [22]. EnergyPlus utilizes the split flux method to model the interior reflections of light by dividing the luminous flux into two components; then, each split component is reflected by an average weighted reflectance of the surfaces above and below the window [20]. This kind of calculation often results in substantial inaccuracies that have direct consequences on electric lighting use intensity [23].

In order to overcome the simulation tools' limitations, some authors have developed methods using recent advances in software and/or in integrating the use of various software packages. Lagios, Niemasz and Reinhart [24] linked Rhinoceros/Grasshopper to Radiance/Daysim in order to evaluate key design parameters, such as window size and material descriptions. Azadeh [25] proposed a process for utilising daylighting and energy analysis software for optimising the performance of a sun-shading screen. To further understand the available daylight in the test space, a climate-based metric was calculated in DIVA. In order to model the effect of the screen on the energy consumption, the screen's hourly shading coefficient was calculated. An electric lighting schedule for the year was then generated and loaded into Design Builder for thermal simulations.

González and Fiorito [26] integrated parametric design with performance simulation tools. They used Galapagos/Grasshopper to define randomly the set of tests and then used DIVA both to calculate daylight metrics and to create an artificial lighting schedule. Finally, they used the DIVA thermal component to calculate the energy consumption and CO_2 emissions. Trubiano et al. [27] integrated the use of Grasshopper with Radiance and EnergyPlus through Matlab. Adopting genetic algorithms and a single objective function, they developed an evolutionary optimisation script to demonstrate the possibility of generating the optimal shape of atriums. Lobaccaro et al. [28] applied a similar method for optimising the geometry of a building in order to maximise the envelope's annual exposure to solar radiation. David et al. [29] applied the combination of daylight and thermal analysis for assessing solar shade efficiency. In order to rate the performance of different typologies of external overhangs, they used Radiance and EnergyPlus to calculate the shading coefficient, cooling energy demand, daylight autonomy, sun patch index and useful daylight illuminance.

1.2. The design optimisation problem

The optimisation problem, related to the design of external shadings in an office building, is linked to the time required for performing daylight simulations. This has been demonstrated to be about 35 times longer than that required for performing a full thermal dynamic analysis. Consequently, the feasibility of conducting an optimisation process for large areas or complex geometries is limited, especially when time is a constraint [26]. Furthermore, PSS design requires a wide variety of variables to be taken into consideration, so a comprehensive study of possible variable combinations requires a large amount of different models, simulations and time, something which is difficult to manage.

The Design of Experiments using Orthogonal Arrays (DOA) statistical method can simplify the interrelated study of a large number of variables, reducing the number of experiments/simulations and obtaining the maximum information which may be of use in PSS design [30]. The DOA method has been used efficiently in different fields of science, contributing valid conclusions and optimising processes [31]. It has been used to optimise building shape design in order to achieve energy savings [32] and to reduce construction costs [33]. It has also been used to optimise some window design parameters aimed at improving daylighting and solar control [34] and at maximising energy savings [35]. Chi, et al. [36] propose a methodology for applying orthogonal arrays (OA) to optimise the perforation percentage, shape, matrix and orientation of perforated screens, reducing the number of simulations from 256 to 16 and obtaining the best combination of variables for improving daylighting.