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Lighting and energy performance of an adaptive shading and daylighting system for arid climates

Luigi Giovannini [a], Valerio R.M. Lo Verso [b], *, Boris Karamata [c], Marilyne Andersen [c]

[a]*Department of Energy, Politecnico di Torino, corso Duca degli Abruzzi 24, 10129,Turin, Italy*
[b]*Department of Energy, Politecnico di Torino, TEBE Research Group, corso Duca degli Abruzzi 24, 10129,Turin, Italy*
[c]*LIPID, Ecole Polytechnique Fédérale de Lausanne, LE 1 111, Station 18, CH-1015, Lausanne, Switzerland*

Abstract

Finding the proper trade-off between blocking direct sunlight, ensuring sufficient indoor daylighting and view out is a particularly delicate task especially in arid climates, due to harsh environmental conditions. As a tentative answer to this challenge, an adaptive shading and daylighting system (Shape Variable Mashrabiya – SVM) has been developed by the authors, described in an earlier paper. In this paper, we analyze how the SVM may affect annual lighting and global primary energy performance of an office building in Abu Dhabi: the SVM was applied to east and west façades and compared to external Venetian blinds, reflective and selective glazing.

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Keywords: adaptive shading daylighting system; arid climates; mashrabiya; daylighting analysis; building global energy performance

1. Introduction

Nowadays high-rise glazed towers have become the dominant architectural typology for new buildings in Middle-East countries. However, quite obviously, this kind of building is often unsuitable for the arid and desert climates that characterize these countries, as the annual high solar radiation can transform the building into a greenhouse with major visual and thermal discomfort issues. As a result, occupants use blinds frequently, thus reducing the amount of daylight in internal spaces and increasing the energy demand for electric lighting [1-2].

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* Corresponding author. Tel.: +39 011 090.4508; fax: +39 011 090.4499.
E-mail address: valerio.loverso@polito.it

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In this context, this paper investigates the performance of a novel device which was designed and prototyped to meet as many of the requirements regarding the combination of visual and thermal comfort as possible in such a climate. The solution we came up with is an adaptive shading and daylighting system consisting of three identical opaque backscattering shields, carved with a pattern inspired by the local vernacular mashrabiya, and able to move relative to each other so as to switch between a closed position, in the presence of direct sunlight, and an open position, when skylight prevails (Fig. 1). This system, which was called *SVM* (*Shape-Variable Mashrabiya*) is able to effectively block the solar radiation in the presence of direct sunlight, thus avoiding overheating of building spaces and minimizing glare issues. At the same time, thanks to multiple internal reflections between the overlapping SVM shields, a high amount of direct sunlight is transformed into diffuse light providing more visual comfort to the users. On the other hand, when direct radiation is absent, the SVM allows important skylight penetration while restoring some view to the outside. An outstanding feature of the SVM is its ability to move without using electric energy, thanks to a specifically developed actuator that exploits the phase-changing properties of a material heated by solar radiation. The concept, design and investigation of the daylighting performance of the SVM were the object of a dedicated paper from the same authors [3]. The daylighting performance was calculated for a sample office room located in Abu Dhabi using Daysim. Results were expressed in terms of annual temporal maps of illuminances in the room using Useful Daylight Illuminance boundaries.

This paper focuses on a series of analyses which were carried out to:

- explore in more detail the lighting performance in arid climates of a sample room equipped with the novel SVM
- compare performance of SVM to the ones of other systems/technologies used to control the solar radiation, in order to reveal the SVM benefits
- assess how the SVM affects lighting and global primary energy performance (EP_{gl}) of a glazed office building.

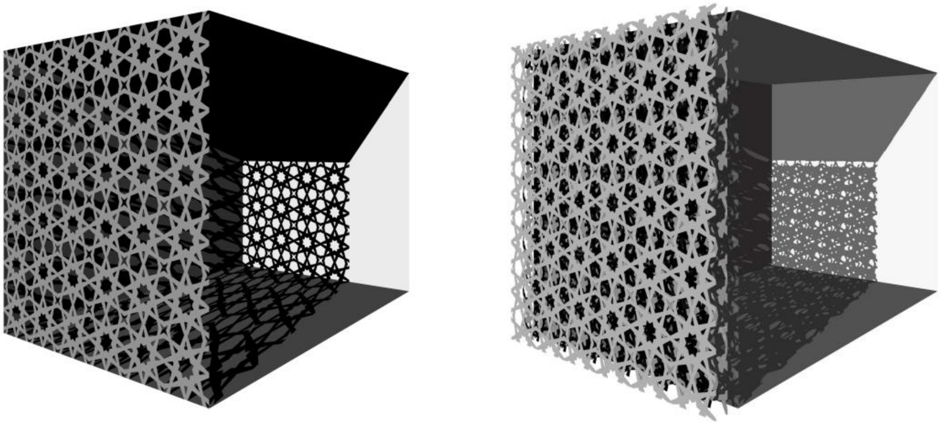

Fig. 1. Images of the SVM: opened (left) and closed (right) configurations.

2. Methodology

The present study consists of two steps. Step 1 focuses on daylight and represents an extension of results already published in [3]. The methodology followed here is the same used in the previous study. All analyses were performed for a sample peripheral cellular office located in Abu Dhabi (24.4°N, 54.7°E), a place with typical arid climatic conditions for which the SVM was designed. The office is 3.52 m large, 5 m deep and 3.04 m high, with one wall completely glazed. The light reflectance (LR) values of ceiling, walls and floor were set equal to 80%, 65% and 30%, respectively. The daylight analysis was carried out through a set of climate-based annual simulations calculating climate-based daylight metrics CBDM such as Daylight Autonomy (DA), continuous Daylight Autonomy (DA_{con}), maximum Daylight Autonomy (DA_{max}) and spatial Daylight Autonomy ($sDA_{300/50\%}$).

DA is the “percent of the occupied time throughout a year when daylight illuminance alone meets the illuminance target over a work plane E_{wp}” [4]. DA_{con} “attributes partial credit to time steps when the daylight illuminance lies below the minimum illuminance level. For example, in the case where 500 lux are required and 400 lux are provided by daylight at a given time step, a partial credit of 400lux/500lux=0.8 is given for that time step" [4]. DA_{max} is the "percent of the occupied hours when direct sunlight or exceedingly high daylight conditions are present, i.e. daylight illuminance is over ten times the E_{wp} (i.e. 500 lux for office rooms)" [4]. $sDA_{300/50\%}$ is the "percent of an analyzed area that meets a minimum daylight illuminance level of 300 lx for 50% of the operating hours per year" [5]. This analysis was coupled with the calculation of the energy demand for lighting (ED_l), assuming a typical two zoned dimmable lighting system controlled by a photosensor. Analyzing both climate-based daylight metrics and the energy demand for lighting allows the efficiency of the shading/daylighting system to be assessed extensively. Beside the SVM, some other shading technologies, currently used in Middle-East countries, were applied to the sample office to compare annual lighting and energy performances:

- double pane selective glazing (hereby referred to as SG41) with LT = 41%, solar heat gain coefficient = SHGC = 22% and thermal transmittance = U-value = 1.1. W/m^2K
- double pane reflective glazing (RG16) with LT = 16%, SHGC = 19% and U-value = 1.1. W/m^2K
- double pane low-E glazing (LT = 65%; SHGC = 41%; U = 1.2. W/m^2K), associated with venetian blinds (VBs). The VBs were assumed to be positioned outside the façade to reduce overheating of internal spaces, even though this application would be hardly feasible in a desert site, due to the aggressive climate conditions.

As the SVM is specifically conceived for east/west-facing façades, the office was simulated for both orientations. DIVA-for-Rhino was used to manage Daysim and to perform this analysis: As the novel adaptive technology developed in this study is responsive to the sun position, a Python script was specifically written to deal with the complex sequence of simple motions of the SVM and to handle the rough outcomes to elaborate the final results. In this phase, different climate-based daylight metrics, such as the spatial Daylight Autonomy, were calculated to evaluate the daylighting performance of the different technologies.

In step 2, the global energy demand for a building (including heating, cooling and equipments) was modeled by means of annual thermal analyses to investigate both summer and winter performance of the SVM. The case study of this analysis was a 5-storey office building with two fully glazed façades. The building consists of an aggregation of cellular offices identical to the one analyzed in step 1. Each floor consists of 20 different cellular offices, 10 west-facing and 10 east-facing, separated by a central hallway. Consistently with what was assumed in step 1, the building was located in Abu Dhabi. As final output of step 2, the primary energy demand for heating and cooling (EP_h and EP_c) needed to guarantee the thermal comfort over the whole year inside the building were computed (comfort temperatures set to 20°C in winter and to 26°C in summer). In order to generalize results, the heating and the cooling system were assumed to be standard systems, with efficiency values of 0.8 and 3.0, respectively. Besides, the primary energy demand consumed by equipments was also calculated, starting from internal gains (set to 14 W/m^2). To obtain the EP_{gl}, these three demands were combined with ED_l calculated in step 1, which was also converted into a primary energy for lighting EP_l. The analysis was carried out for all shading systems addressed in step 1, so as to compare the building global energy consumptions.

Three different user behavior profiles were associated to VBs according to the algorithm implemented in Daysim: *active* behavior, that is to say when occupants interact with the shades and use them appropriately when necessary; *passive* behavior, i.e. when occupants keep the shades closed and work in electric light; *equal mix active-passive* behavior, which assumes an average between active and passive behaviors. It is worth highlighting that Daysim algorithms were slightly modified to adapt them to the desert climate conditions. In the study, the shading system is moved depending on sun position in the sky, i.e. based on the presence of direct sunlight rather than on a threshold irradiance hitting the external façade. This was done because at these latitudes the direct sunlight is so strong that it must be accurately controlled to prevent from overheating and glare in the spaces. That is, the SVM gets closed when the sun is in the range -60° - +60° (azimuth angle) and 0° - 60° (elevation angle) with respect to the normal to the SVM. Higher angles were not considered because the intensity of the light would be too low, due to the cosine law, and the indoor space not enough illuminated.

The SVM was coupled with a clear glass, to maximize the amount of diffuse light collected, as in the closed position the window is completely shaded but in the open position only approximately half of the diffuse radiation is allowed in the indoor space. The SVM was tested with 3 different materials (LR = 70%, 80% and 90%) to evaluate how the variation in the reflection properties influences the performance of the device. Eight case studies were analyzed: 3 for the SVM, 3 for VBs and 2 for the two solar control glazings (selective and reflective). This set of case studies was used in step 1 and slightly changed in step 2: the equal-mix behavior was not simulated and the SVM was considered for the case with LR = 90% only. As a result, five case studies were considered in step 2.

DIVA-for-Rhino was used in step 2 as well, as it allows managing in synergy both Daysim and Energy Plus. For each case study, the annual schedule of lighting and shading systems calculated by Daysim through the Python code was imported into Energy Plus and used to calculate the values of the different energy demands. The Radiance parameters for Daysim simulations were set as follows: ab=7; ad=4000; as=2000; ar=600; aa=0.05.

3. Results, analysis and discussion

3.1. Step 1: analysis of daylighting performance

Figure 2 summarizes the CBDM results which were obtained for west-facing sample office rooms.

The $sDA_{300/50\%}$ (Fig. 2a) is an indicator not only of the frequency with which a E_{wp} criterion is met over a year, but also of the distribution of such frequency across the space analyzed. In Abu Dhabi the solar radiation is very strong throughout a year. This results in $sDA_{300/50\%}$ values often equal to 100%, for both east and west orientations, thus making a comparison between the results little informative. The only indication is that the three case studies which didn’t get $sDA_{300/50\%}$=100%, i.e. the RG16 and VBs controlled by passive and equal-mix users, seem to be characterized by the lowest daylight amount, which may result in a higher energy demand for lighting. The other metric recently proposed by the IES, the Annual Sunlight Exposure (ASE), was not calculated for this study because it does not account for the presence of any shading system. Accordingly, the ASE values would be meaningful to analyze the effect due to the type of glazing, but not for SVM nor for VBs.

As for DA results (Fig. 2b), whose minimum threshold illuminance was set to 500 lx, the SVM with LR= 90% showed a higher DA than all cases with VBs. Furthermore, all cases with SVM had a better performance than VBs controlled by equal-mix users. The SG41 obtained the highest DA while the RG16 the lowest, consistently with the LT value of these two technologies. For east-facing rooms, a different trend was observed: DA values for VBs controlled by active users were the highest, slightly above the values obtained for the SG41. Also for this orientation, all SVM cases perform better than cases with VBs controlled by equal mix users.

The DA_{con} metric (Fig 2b) also accounts for contributions of illuminance values below minimal threshold E_{wp}: compared to DA values, all trends are confirmed, different increments were observed for the different room configurations. The increase in DA_{con} values was higher for more opaque cases (the ones with lower DA values) and lower for more transparent cases (the ones with higher DA values). The SVM data showed a peculiar trend: the DA_{con} values are comparable with values for cases with SG41.

It is worth noting that high DA or DA_{con} values do not necessarily mean optimal visual comfort conditions. E_{wp} values could be excessive, such to cause glare problems to the occupants. In this regard, the DA_{max} (Fig 2c), whose threshold is ten times the one set for the DA (i.e. 5000 lx), represents an upper threshold for occurrence of E_{wp} which may create discomfort. DA_{max} values were below 3%, which is an acceptable value, for nearly all the case studies analyzed. The only exceptions are cases with SG41, whose DA_{max} value is around 15% for both orientations. Therefore, a combined analysis of DA_{con} and DA_{mx} results shows that the SVM is the technology that provides the best trade-off between amount of daylight and reduction of visual (and thermal) risks. VB controlled by active users have a similar performance to the SVM’s, but this is just an ideal situation, as VB controlled by equal-mix users are a more realistic configuration.

As far as ED_l is concerned (Fig. 2d), the results are consistent with what observed for DA_{con}, which makes sense as a photodimming control sensor was installed in all spaces. The case studies with highest DA_{con} are the ones with lowest electricity consumption for lighting, and vice versa. As expected, the values relative to the zone 1 are always lower than the values for the zone 2: actually, zone 1 is nearer to the window, and is thus reached by a higher amount of daylight throughout a year.

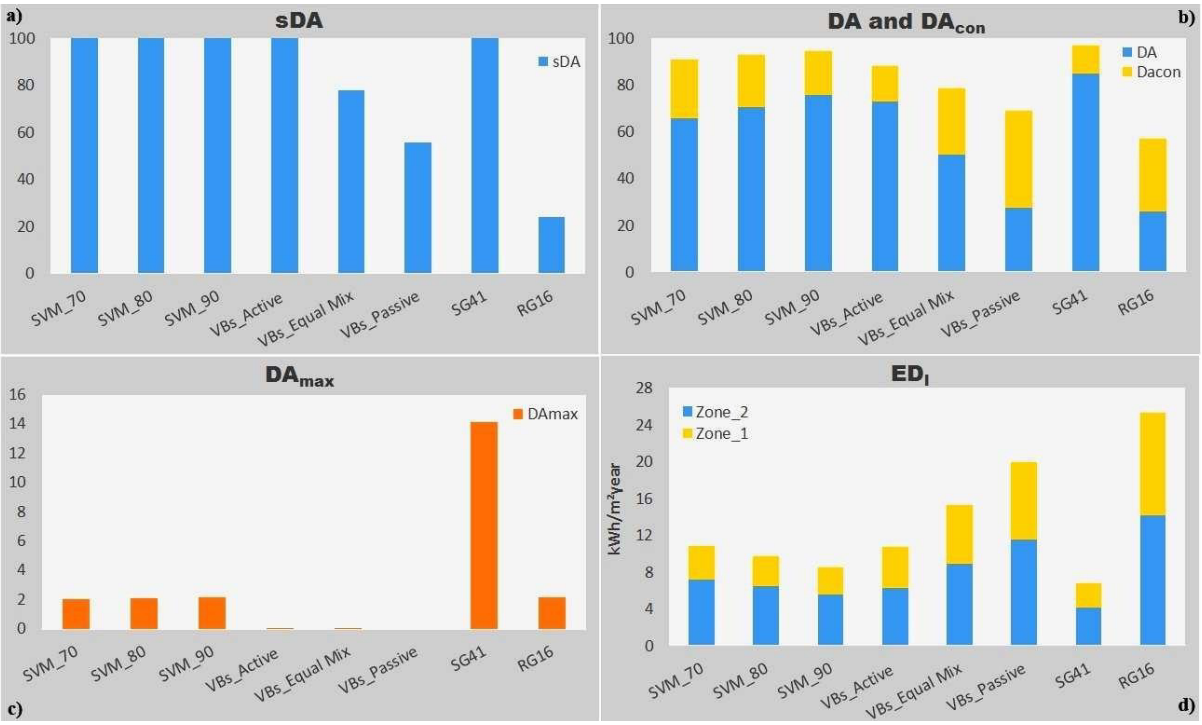

Fig. 2. sDA$_{300/50\%}$, DA, DA$_{con}$, DA$_{max}$, and ED$_l$ values found for west-facing rooms in step 1. The SG41 shows the lowest ED$_l$ but the highest DA$_{max}$, while the SVM provides the better trade-off between reduced energy demand for lighting, amount of daylight in the space and visual comfort for occupants (control of glare).

3.2. Step 2: analysis of the global energy performance

Figure 3 shows the results which were found for the different primary energy demands for the considered building: for equipments, lighting, cooling and heating, as well as the global energy demand.

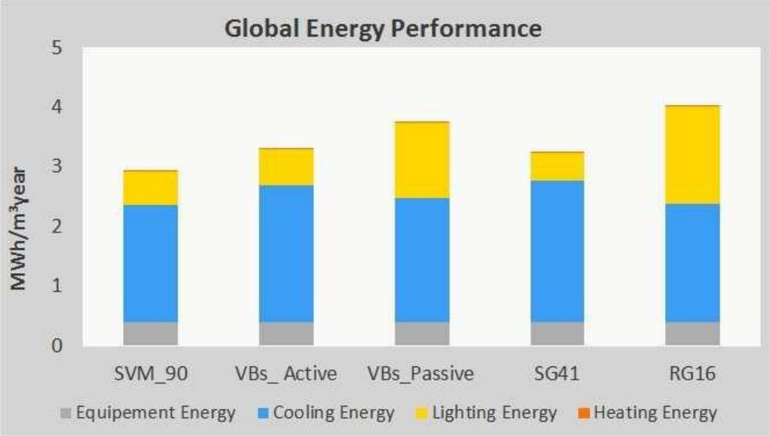

Fig. 3. EP$_h$, EP$_c$, EP$_l$ and EP$_{gl}$ values found in step 2. The SVM shows the best performance, minimizing the building global energy consumption (up to -27% compared to RG16). This is mainly due to the reduced energy demand for lighting (up to -65.7% compared to RG16) and, to a lower extent, for cooling (up to -17.2% compared to SG41).

The EP_h is negligible for all the configurations analyzed, due to the significant amount of solar radiation still prevailing in winter at the latitude of Abu Dhabi. As the energy demand for equipments is the same for all case studies, EP_l and EP_c are the key factors which influence the variation of EP_{gl}. As shown in Fig. 3, the variation of EP_c is moderate for the various case-studies, while EP_l varies more significantly. In terms of EP_{gl}, the best performance was observed for cases with the SVM: this was the most efficient technology in shading and preventing overheating of the internal ambient. Cases with SG41 showed the second lowest EP_{gl}, but with lower visual comfort for occupants. The case of VB controlled by active users has a higher EP_c value than the SVM, which means that this technology is less effective in blocking direct sunlight. Consistently with what was observed in step 1 for the daylighting results, the case with RG16 shows the least performance, with the highest EP_l, EP_c and EP_{gl} values.

3.3. Discussion and limits

Although the analyses performed were very accurate and complete, there were some limitations that could not be overcome, due to the software architecture and to the power of the computers used. The first one is related to the time-step of the weather file used, which was set to one hour because of the enormous computation required for smaller time-steps. The second limit is caused by the restriction on the number of light bounces between the SVM shields (providing the transformation of direct sunlight into diffuse light through multiple inter-reflections, in the closed configuration) that could be implemented into our simulations. Given the limited computation power, the number of bounces was set equal to eight. Thus, the performances of the SVM are reliable as for the spatial distribution but underestimated in terms of illuminance values. Quantitative figures for this underestimation will be published in a dedicated paper. It is also worth noting that, in our simulations, the VBs were positioned outside, while this would be impossible in a real harsh environment. The use of indoor VBs, a far more realistic possibility, would surely affect the internal gains of the building and, consequently, its EP_c.

4. Conclusions

The SVM proved to be a promising innovative technology for arid climates, thanks to its shading and daylighting features. It is able not only to block sunlight but also to transform a fraction of it into diffuse reflected light to provide comfortable daylighting into building spaces. Furthermore, unlike VBs that, in principle, cannot be installed outside the building façade as they would not be able to withstand the aggressive environmental conditions prevailing in arid climates, the SVM can potentially survive outside conditions. Importantly, the SVM provides a ‘pure’ (not filtered) daylighting spectrum into a room and preserves some vernacular character.

The analysis presented in the paper revealed that performances of the SVM bring substantial quantitative benefits both on daylighting and energy savings. Energy results showed that the SVM performed better than the other technologies currently used in Middle-East countries for solar control. It minimized overheating problems and consequently the EP_c values (-17.2% and -9.9% compared to SG41 and to VB, respectively). At the same time, visual comfort for users is enhanced in terms of glare control, although at the expense of a losing view to the outside in the closed configuration. It also minimized the EP_l (-65.7% and -30.7% compared to RG16 and to VB, respectively) and the EP_{gl} (-27% and -16.3% compared to RG16 and to VB, respectively).

To gain insights into the practical implementation of the SVM, we are building a real-scale prototype of the SVM, as well as of its passive solar actuator. Moreover, such a prototype will allow performance monitoring and provide insights into its potential aesthetic value.

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