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An algorithm for designing dynamic solar shading system

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Abstract

The present study aims to define and validate an analytical procedure for determining the optimal movement profile for dynamic shading system based on the horizontal mobile blinds for high level of illumination and visual comfort in indoor environments. The algorithm is developed to design a dynamic solar shading system for an office building (Ergo Tower) situated in Milan, Italy. The calculations take into account variables such as geographic location, date, time, surface orientations and geometrical and functional characteristics of shading system. In the first step the solar coordinates and the variation of solar incidence angle on the building surfaces have been defined. Using the equations of solar geometry the typical solar path (sun position e.g. solar altitude, azimuth etc.) corresponding to the specific location for the entire year and also the variation of the incidence angle with which the direct radiation affect the building surfaces are described. Based on the geometry of shading system, the optimal values of inclination of the profiles can be calculated.

Finally, due to the technical limitations of the systems, the feasible configuration has been determined corresponding to an angle close to the optimal values of inclination for ensuring appropriate shading. This test system allows the definition of the movement of dynamic solar shading systems based on a specific location and geometrical/mechanical characteristics of a certain technical solution.

Keywords: Dynamic solar shading system; horizontal blinds; optimal movement profile

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1. Introduction

Over the past decade, rapid growth of energy consumption and greenhouse gas (GHG) emissions in the building sector have made energy efficiency a priority objective in various countries by developing new building regulations and certification schemes, targeting at minimum energy performance requirements

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[1]. In this respect, the European Commission has decided to cut drastically CO_2 emissions and to increase the share of renewable sources within total energy consumption in building sector. In the European Union, the recently adopted EPBD recast [2] states that by the end of 2020 all new buildings should be "nearly zero energy buildings", i.e. with very high energy performance and their energy requirements covered by renewable energy sources to a significant extent. The further target is to achieve the goal of "net zero energy buildings" in a few years. In this context, the development of design methodologies to optimize the on-site exploitation of renewable energy sources becomes a key factor for sustainable building design.

One of the aspects, which now pose a growing focus, is the use of natural light to ensure adequate levels of illumination inside the working spaces, obtaining a higher level of visual comfort. The large variation in daylight availability and solar radiation due to diurnal and seasonal changes in sun position and cloud cover is a major cause of both high energy use and peak demand, and of occupant discomfort. However, an optimum cooling and lighting energy balance exists between the window and lighting system that can be used to reduce this energy use [3]. Daylighting can offset artificial lighting energy use and thermal loads associated with the electric lighting system, but the admission of too much daylight can increase cooling loads associated with solar heat gains. The application of appropriate strategies for the control of daylighting allows in addition to achieve high levels of visual comfort and to improve, in general, the comfort level of occupants, achieving an appropriate amount of energy savings, due to the reduction of electricity consumption for artificial lighting and solar gains through transparent surfaces of the building envelope during cooling periods. In the literature, some of the studies related to control strategies and energy savings by blind shading systems are reported [4-8].

To ensure the use of control strategies for daylighting, in Italy, some regions have enacted laws on the requirements of the use of external shading systems for the management of daylighting and the achievement of adequate standards of internal lighting [9].

The present study aims to define and validate an algorithm for determining the optimal movement profile for dynamic shading systems based on horizontal moving blinds for high level of illumination and visual comfort in indoor environments. The algorithm is developed to design a dynamic solar shading system for a case study office building (Ergo Tower) situated in Milan, Italy.

2. Case study building

The case study is represented by the Italian headquarter of a major insurance company in Milan (latitude 45° 24', longitude 9° 18' and altitude of 112 m), which lately has been transformed in a high energy performance building. Recently, this project has been awarded in the international competition Zerofootprint Re-Skinning Awards, supported by UN-Habitat and U.S. Green Building Council, with a specific mention for replication of the retrofit methodology [10].

The original structure, built in 1998, was a typical commercial building, arranged in two rectangular blocks (a low-rise structure and a tower) with a total gross volume equal to 45’500 m^3, of which 33’326 m^3 are occupied by offices and other conditioned spaces.

The building is oriented 15.56° to the south, and is characterized by large glazed surfaces, which are predominantly displayed according to the orientation of East / North-east and West / South-west.

Among the various energy retrofit strategies, a dynamic solar shading system has been placed outside all windows in order to achieve a substantial improvement in the level of visual comfort in the workplace. Such system is composed of three different technologies; the first one comprises of compact moving shades, that are profiles with an ellipsoidal section of the width of 15cm, and are placed with a spacing of 15.5cm; the axis of rotation of the blinds is in the centre with respect to profile section. These kinds of shades are located on the windows of every floor, excluding the basement floor, in the South face of the tower, in the East face of the lower block and in the West face of the lower block. The second technology consists of large moving shades: a larger blade of 40cm width is placed on top of compact shades and has and independent moving system. The main function of this shade is to deflect daylighting on the roof of working places. These blades are present in the same windows as compact blades.

The last shading system is composed of adjustable Venetian blinds, placed on the entire South façade and on the ground floor of east and west facades of the lower block; moreover they are placed on the tower block on East and West façades. The blinds can be tilted, as needed, according to one of the following positions, defined by the angle of inclination of the longitudinal axis of the elliptical cross section with respect to the horizontal plane: 0°, 37°, 45°, 70°, 0° raised and packaged (shadowing), -20° (deflecting), as shown in Fig.1.

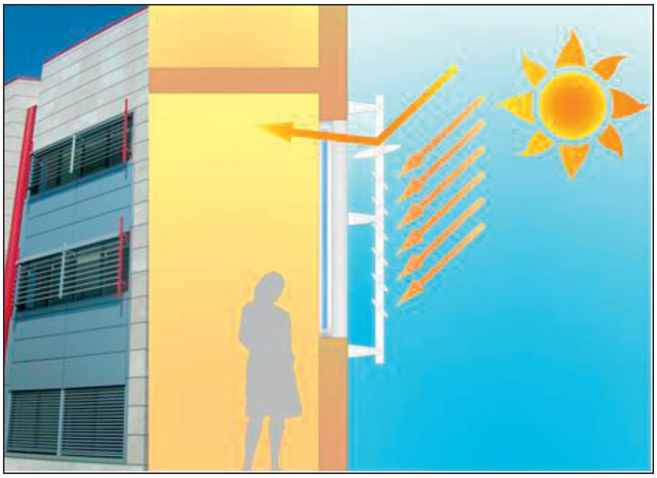

Fig. 1. Dynamic solar shading system – compact and large moving shades

Blades and blinds are controlled by an analytical-empirical logic, which calculates the position of the sun and determines the optimal hourly configuration of shading systems, such that direct solar radiation is totally blocked or effectively controlled. Such system allows optimizing daylight contribution on working areas, minimizing solar gain during cooling seasons.

3. Dynamic shading system

The shading elements are mobile blinds and consists of moving profiles with ellipsoidal section of the width of 15 cm and placed with the spacing of 15.5 cm, the rotation axis of the blind is in the centre with respect to profile section as shown in Figure 2.

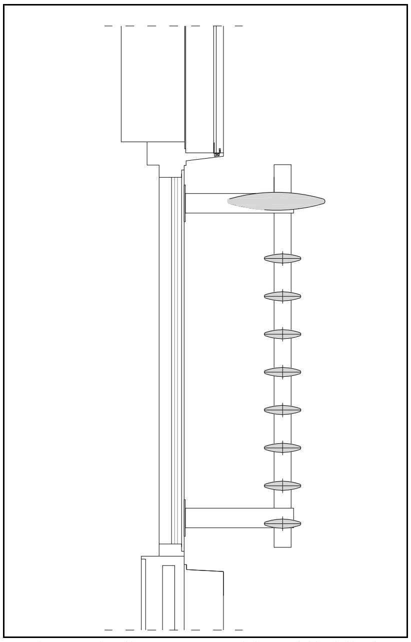

Fig. 2. Shading system with mobile blinds

This kind of shading system is located on the south, east and west facade of the complex. The shading system is designed for a number of angular movements in particular have the following possible angles of rotation: 0°, 30°, 45°, 60° -20°. These configurations are shown in Figure 3.

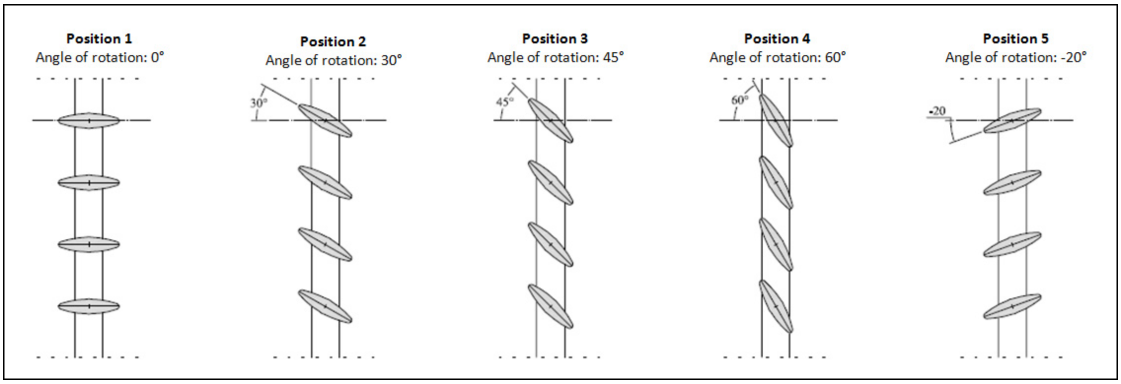

Fig. 3. Blind movement scheme

The system allows an automated management of blind movements taking into account the date, time and orientation of a specific installation.

4. Solar geometry analysis

For each orientation of the shading systems, an analysis has been made to define an optimum inclination angle, calculated for each hour from 7:00 to 20:00. For every month of the year, the calculations have been made to define the hourly positions. For the winter period (October-April), 15th day of each month is considered as reference day. All the calculations are corresponding to solar hour.

This logic implies that, from January to April, the months in which the apparent orbit of the sun in the sky tends to rise during the days ranging from 1 to 14 of each month, the angle of the shading blinds for a short period of the day results insufficient to completely block the direct radiation. The same is found in the months from October to December, when the apparent orbit of the sun in the sky tends to fall during the day ranging from 16 to the end of the month.

For the summer period, a more precautionary step is adopted for the calculations: for the months of May and June, 1st day of the month is considered as reference day, where the apparent orbit of the sun is in rise phase, while in July, August and September, the last day of the month was used as a reference day. In this way, the worst day of each month is considered, during which the apparent solar path is lower and therefore the sun's rays reach the building facades at a lower horizontal angle.

By this way, to determine the behaviour of shading systems it is necessary to define the exact hourly position of sun for each analysed day. The sun moves in its apparent motion around the planet on a trajectory that varies daily. These motions are described by algorithms that define the solar geometry. The parameters necessary for calculations and algorithms used are described below.

4.1 Declination angle

The solar declination angle is defined as the angle δ formed between the straight line joining the centre of the earth and sun and earth's equatorial plane. Its value varies during the year and has the maximum value (+23.45) in the summer solstice and the minimum (-23.45) in the winter solstice, while 0 during the equinoxes. This angle can be calculated by following expression:

$$\delta = 23.45 \times \sin\left[\frac{360}{365}(\mathrm{N}+284)\right] \tag{1}$$

Where N is the progressive number of the day of the year.

Table 1 shows the values of δ calculated for the reference day of each month.

Table 1. Annual variation of δ

Day	Month	δ (°)	Day	Month	δ (°)
15	January	-21.27	31	July	18.17
15	February	-13.29	31	August	8.10
15	March	-2.82	30	September	-3.82
15	April	9.43	15	October	-9.60
1	May	14.93	15	November	-19.15
1	June	22.04	15	December	-23.34

4.2 Hour angle

The hour angle ω is the angle between the meridian plane passing through the sun and the meridian plane of the observer. The angle has positive values in the morning and negative in the afternoon, is zero at solar noon (12:00 am) and varies 15° per hour. Its value is given by the following formula:

$$\omega = 15(t_s - 12) \tag{2}$$

Where t_s indicates the solar time between 0 and 24 [h].

The solar time t_s does not always coincide with the local clock time t_c. This difference is caused by two factors: the first one is due to the effect of rotational and translational motion of the earth around its axis and around the sun. The difference is called the equation of time (EOT) and is calculated in minutes by following expression:

$$E_t = 229.18\times\left(7{,}5\times10^{-5} + 1.868\times10^{-3}\times\cos\Gamma - 3.2077\times10^{-2}\times\sin\Gamma - 1.4615\times10^{-2}\times\cos2\Gamma - 4.089\times10^{-2}\times\sin2\Gamma\right) \tag{3}$$

Where angle Γ [°] is defined as a function of the day number N:

$$\Gamma = \frac{2\pi(N-1)}{365} \tag{4}$$

In the equation of time, it is further necessary to add the second correction factor that takes into account the location, as compared to the reference meridian. In case of Central European Time refers the meridian 15° E instead Greenwich meridian. The correction value in minutes is given by the following formula:

$$\Delta t = 4\times(L_s - L_e) \tag{5}$$

Where L_s [°] is the standard longitude, i.e. the meridian of longitude taken as reference (for Central Europe at 15 ° East), and L_e[°] is the longitude of the place.

For the present study, it is very important to precisely calculate the correction factor Δt, which is the difference between the local time t_c and the solar time t_s. It should be mentioned that all the calculations carried out in this work are with reference to solar time.

Figure 4 shows the variation of calculated hourly values of Δt for the whole year. To obtain the value of solar time t_s, the correction factor Δt should be added with local clock time t_c.

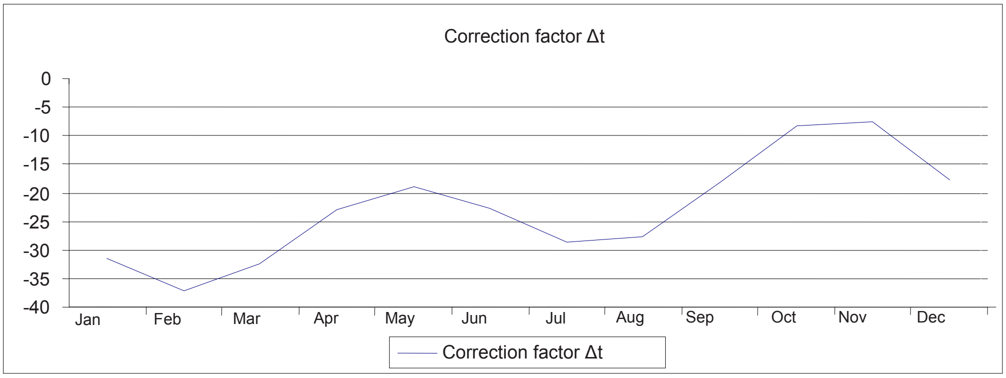

Fig. 4. Variation of calculated hourly values of Δt

4.3. Solar angle calculations

The sun's position is defined by two angles, the solar altitude angle β [°], which is the angle formed by the straight line joining the centre of the sun and the observation point on Earth's surface and the horizontal plane and azimuth angle α [°], which indicates the angle formed by the projection of the line

joining the sun-earth horizontal plane with the South. α is 0 ° when the direction coincides with the South, positive to the East and negative towards West .
The values of the angle β [°] are calculated using the following formula:

$$\beta = \arcsin(\cos\Phi \times \cos\delta \times \cos\omega + \sin\Phi \times \sin\delta) \qquad (6)$$

Where ω [°] is the hour angle and angle Φ [°] indicates the latitude of the place.
The values of α [°] are calculated using the following formula:

$$\alpha = \arccos\left(\frac{\sin\beta \times \sin\Phi - \sin\delta}{\cos\beta \times \cos\Phi}\right) \qquad (7)$$

The values of α and β are calculated from each hour between 7:00 to 20:00 for reference day of the month.

5. Blind configurations

The study aims to determine the optimal hourly position of shading systems, such that direct solar radiation is totally blocked. At the same time, it must be guaranteed the maximum opening of shading profiles and hence the maximum contribution of diffused light. The system configurations should be defined according to the specific exposition, day and hour. Therefore, the optimal configuration of the control system is such that the shadow cast by the upper blind touches the inside edge of the lower profile. To determine an appropriate algorithm, the geometry of the system components has been simplified. In this way the blind were assumed to be flat surfaces with the width equal to the maximum width of the blind and the rotation axis coincident with the axis itself, as shown in Fig. 5.

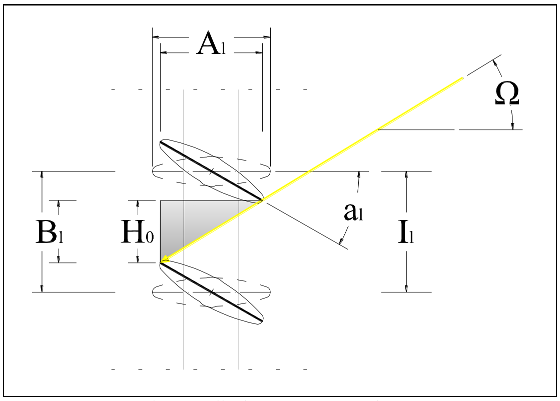

Fig. 5. Blind movements scheme

Initially it has been assumed that the height of the shadow projected on the vertical wall H_0 [mm] is equal to the projection on the vertical plane of the free space between two blinds B_l [mm] according to the following relation:

$$H_0 = B_l \qquad (8)$$

Where

$$H_0 = A_l \times \tan\Omega \tag{9}$$

Where A_l [mm] is the projection of blind to the horizontal plane and the vertical shadow angle Ω, defined as the projection of solar coordinates on the plane perpendicular to the facade and indicates the angle at which solar radiation incident on the concerned surface during the day.

The value of the angle Ω [°] is given by the following formula:

$$\Omega = \arctan\left[\frac{\tan\beta}{\cos(\gamma-\alpha)}\right] \tag{10}$$

Where γ [°] is the angle between the projection of the normal on a horizontal surface and the South; this angle is considered positive to the East and negative to the West, as shown in Figure 6.

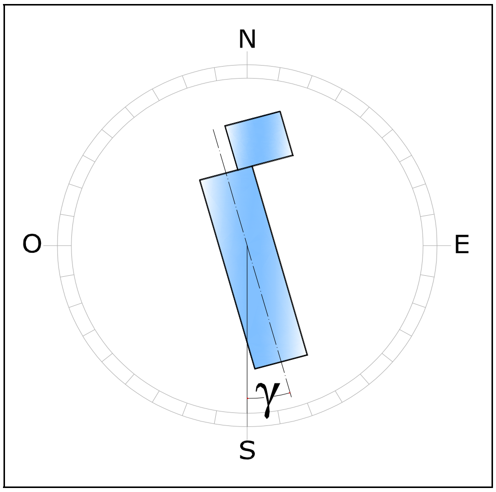

Fig. 6. Building orientation

The values of Ω are calculated for the South, East and West facades for each hour from 7:00 to 20:00 for the reference day of different months. Table 2 shows, for example, the values of Ω calculated corresponding to the facades for June 15.

Table 2. Angle Ω calculated for June 15

South facade		East facade		West facade	
Hour [h]	Ω [°]	Hour [h]	Ω [°]	Hour [h]	Ω [°]
7:00	78.70	12:00	89.25	7:00	22.77
8:00	68.46	13:00	75.27	8:00	34.08
9:00	65.00	14:00	62.67	9:00	46.80
10:00	64.30	15:00	51.48	10:00	60.89
11:00	65.22	16:00	41.41	11:00	75.84
12:00	67.44	17:00	32.03	/	/
13:00	71.11	18:00	22.79	/	/
14:00	76.73	19:00	12.99	/	/
15:00	85.33	20:00	1.43	/	/

Additionally, it must also be considered that the values of A_l [mm] and B_l [mm] are not constant but changes with the blind inclination.

The values of A_l and B_l are defined in the following formulas:

$$A_l = l \times \cos a_l \tag{11}$$

Where l [mm] and a_l [°] are the width and inclination angle of the blade.

$$B_l = I_l - l \times \sin a_l \tag{12}$$

Where the I_l [mm] is the distance between the blinds.

Substituting the value of the formula H_0 (8) with that obtained through the equation (9) gives:

$$A_l \times \tan \Omega = B_l \tag{13}$$

Substituting then in (13) A_l and B_l values previously calculated by the equations (11) and (12), the following expression is obtained:

$$l \times \cos a_l \times \tan \Omega = I_l - l \times \sin a_l \tag{14}$$

From the above expression, it is possible to calculate the optimal value of the inclination angle of the blinds as a function of Ω, the width *l* and the distance I_l.

$$a_l = \arcsin\left(\frac{I_l \times \cos \Omega}{l}\right) - \Omega \tag{15}$$

Once the optimal inclination angles are determined, it is possible to identify which of among the five possible positions provided by the system has an angle close to the calculated optimum angle. This inclination angle should be able to ensure the total shading in the time interval between two successive movements.

In must be noted that the configuration set in the system (I_l is equal to 155 mm and *l* is equal to 150 mm) does not allow its complete closure, because the value of distance between blades is greater than the width of the profiles in use. This means that in fully closed position ($a_l = 90°$) there is a slot between the profiles. Consequently the system is thus not fully effective, in particular for very low sun angles. Therefore, the limit value of solar inclination Ω was estimated equal to 15 °. This is the limit angle for which the system is capable to provide effective shading.

However it can be confirmed that for Ω values lesser than 20°, the direct solar radiation is largely blocked by the nearby obstructions comprised mostly of buildings and the surrounding vegetation.

Thus, for Ω lower than 15°, the default value of inclination angle of the blinds is fixed to 60°.

A second default is provided, in case of absence of direct radiation on vertical surfaces under consideration. In this condition, it must be chosen a configuration that ensures maximum aperture and a maximum contribution of diffused light by fixing the blind inclination to 0° (blinds are placed horizontally) in summer and -20 ° in winter.

The last default setting positions of the blinds, within the analysed time period (7:00 to 20:00), is in case the sun has not yet arisen or has already set down (for calculated values of β < 0 °): a default angle of 0 ° is fixed.

The Table 3 shows a summary of the default settings defined for each month of the year.

Table 3. Default settings for blind inclination angles

Blinds of 15 cm											
For β<0 (no sun)					a_l [°]						
Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec
0	0	0	0	0	0	0	0	0	0	0	0
For β>0 e Ω<0 (no direct solar radiation on vertical surfaces)									a_l [°]		
Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec
-20	-20	-20	-20	-20	0	0	0	0	-20	-20	-20
For Ω<Ωcritical (solar inclination not shadowable)									a_l [°]		
Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec
60	60	60	60	60	60	60	60	60	60	60	60

Table 4 shows, for example, the results obtained from the calculation for South, East and west façade for 1 June.

Table 4. Optimal blind inclination angles(a_l)

June 1									
	South facade			**East facade**			**West facade**		
Hour	**Ω [°]**	**$a_{l\ optimal}$ [°]**	**a_l [°]**	**Ω [°]**	**$a_{l\ optimal}$ [°]**	**a_l [°]**	**Ω [°]**	**$a_{l\ optimal}$ [°]**	**a_l [°]**
7:00	75.12	-59.73	0	22.43	50.35	60	/	/	0
8:00	66.12	-41.40	0	33.91	25.13	30	/	/	0
9:00	63.27	-35.57	0	46.88	-1.93	0	/	/	0
10:00	62.89	-34.81	0	61.26	-31.47	0	/	/	0
11:00	63.99	-37.04	0	76.52	-62.58	0	/	/	0
12:00	66.32	-41.81	0	/	/	0	88.31	-86.57	0
13:00	70.06	-49.43	0	/	/	0	74.15	-57.75	0
14:00	75.74	-61.00	0	/	/	0	61.45	-31.86	0
15:00	84.48	-78.78	0	/	/	0	50.20	-8.79	30
16:00	/	/	0	/	/	0	40.07	12.18	45
17:00	/	/	0	/	/	0	30.61	32.18	60
18:00	/	/	0	/	/	0	21.25	53.12	60
19:00	/	/	0	/	/	0	11.25	60.00	60
20:00	/	/	0	/	/	0	/	/	0

6. Conclusions

The developed analytical procedure for the movement of shading systems allows to define an annual movement profile of solar shading devices, which takes into account the geometrical characteristics of a specific analysed system, its orientation and the location.

This level of analysis allows to customize the behaviour of every single shading system and ensure constant control of their movements, thus optimizing the operation and maximizing the comfort levels inside buildings.

The developed methodology has been applied for designing a dynamic solar shading system based on the horizontal mobile blinds for an office building in Milan with the aim to obtain high level of daylighting and visual comfort inside the working space, reducing at the same time energy consumption.

Actually the system is operational and main working parameters are being monitored.

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