Energy and daylighting interaction in offices with shading devices

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Abstract

Office buildings represent a challenge for reducing energy consumptions due to climatization, since they are characterized by high internal loads due to electronic equipment and illumination. Furthermore they are also characterized by large transparent surface areas in order to guarantee sufficient daylighting. The combination of these factors leads to high energy costs due to both internal and high solar loads. Furthermore, to guarantee healthy work places, glare problems should also be taken into account. To avoid glare and solar radiation, fixed or movable shading devices are usually provided. Nevertheless the interaction of these devices with the heating, cooling and lighting plant is not simple, since they affect both the loads and the illumination distribution, and their impact on global energy consumption should be analysed for a real energy efficient design.

In the present paper different types of shading devices, fixed, movable and combined are analysed by means of computer codes and a comparison of the energy performance of each system has been carried.

ESP-r has been used in order to study the energy behaviour of the building, while the lighting simulation package DAYSIM has been used to predict the consumption of the artificial illumination system.

DAYSIM can provide the energy code ESP-r with internal loads due to illumination for an energy simulation. Since the deployment of movable devices is automatically controlled by DAYSIM, in order to couple the two codes, the ESP-r source code has been modified introducing a controller to activate the movable shading devices in synchronous with the daylighting analysis. The results obtained with different shading devices are compared in terms of energy required for heating, cooling and lighting and also in terms of daylight distribution using distributions of useful daylight illuminance.

1. Introduction

The energy consumption due to building climatization is becoming a major concern for industrialized countries. Therefore energy saving strategies must be sought in order to guarantee both healthy conditions and a low environmental impact. This is true especially for buildings in the Mediterranean area with extensive glazed areas and high cooling loads because of solar irradiance.

In Italy, national codes require the compulsory installation of external shading devices or glazing systems with low solar gain coatings. The choice of the external shading devices is left to the designer and no guidelines are available.

The size and positioning of shading devices depend on the orientation of the building's façade, the size of the windows and the relative importance of heating and cooling loads. Furthermore external shading devices have an impact on the internal daylight distribution. The architectural impact must also be taken into account by inserting shading surfaces as little as possible without jeopardizing energy savings.

In designing an external shading device all the energetic, daylighting and architectural problems must be taken into account at the same time.

In this paper the multiple aspects of the problem have been tackled using the software tool ESP-r (Clarke, 2001), and DAYSIM for computing illuminance levels.

In the literature a number of papers which deal with the problem of the impact of shading devices on energy consumption can be found, but only in recent years have climatization and daylight analysis problems been considered together.

A detailed comparison of solar gain models with external and internal shading screens were presented in Loutzenhiser et al. 2007. Different codes have been compared, among them the ESP-r tool used in this paper, the authors found that accurate results can be achieved when predicting the energy consumption for long periods of time for highly glazed buildings.

An insight into the coupling between daylight and thermal loads was conducted in Franzetti 2004, fourteen parameters were identified and the computations were performed using "the experience plan" method with the aim of reducing the number of simulations. Different relations linking the most important parameters with lighting energy consumption and annual energy needs were elaborated. It was found that an efficient lighting control device has a favourable impact on global energy needs emphasizing the importance of taking into account the interaction between lighting and HVAC system.

Ho et al. 2008 analysed the daylight illumination of a subtropical classroom seeking an optimal geometry for shading devices. They also evaluated the lighting power required to improve the illuminance conditions within the classroom. Gugliermetti et al. 2006 used the solar system luminous efficacies method to compute indoor natural illuminance. They introduced three simplified approaches for dealing with the effect of horizontal and vertical shading devices, comparing the obtained results with experimental data. They also included the developed methods in a building energy simulation code to compare the impact of the different methods on the heating, cooling and lighting requirements of an office building.

The interaction of shading control strategies on the whole building energy consumption were analysed by Carbonari et al. 2002 for different locations and expositions and they found that the benefit of the control is dependent on the location and orientation of the building, with in general a better solution for the case of automatic controlled shading devices. Furthermore the presence of louvers made the effect of orientation on the energy requirement inappreciable. A controlled roller shade combined with an automatic controllable lighting system was analysed by Tzempelikos and al. (2007). They found that substantial energy savings can be obtained in perimeter spaces, and they changed the window to wall ratio obtaining an optimal 30% value for ensuring a good illumination of the room for a south facing window in Montreal.

In a previous work (Manzan, 2009), one author applied Genetic Optimization to the same problem, but the daylighting calculations used daylight factors obtained with RADIANCE, thus limiting the analysis to overcast skies.

The importance of automatic light dimming sensors for an energy efficient building in Abu Dhabi was highlighted by Fawwaz et al. 2010, who tested also vertical and horizontal external louvers slats at different angles and expositions. They found that the use of static louvers is more effective when applied to glazings with high shading coefficients.

The comparison of different shading devices was performed by Nielsen et al., 2011. They performed a concurrent energy and lighting simulation in order to quantify the potential of dynamic solar shading. They also emphasized the importance of introducing design alternatives from the beginning of the design of the façades.

In the present work different shading devices, both fixed and moveable, are taken into account. An integrated thermal and daylighting simulation has been performed for a south-facing window in an office building, the different behaviour of the façade system with different shading devices has been highlighted taking into account both energy and daylighting metrics. The solutions have been obtained by using two well-known freely available codes, DAYSIM and ESP-r.

2. Problem description

In the present study an office space has been used. The room is 2.87 × 4.5 × 2.96 m (width × height × depth) with a south-facing window with a surface area of 3 m². The south-facing wall has a heat transfer coefficient of 0.31 W/(m² K), the heat

transfer coefficient of the glazing is 1.4 W/(m² K), while the light transmittance is 0.6.
The dimensions of the office with the south exposed window are shown in Figure 1

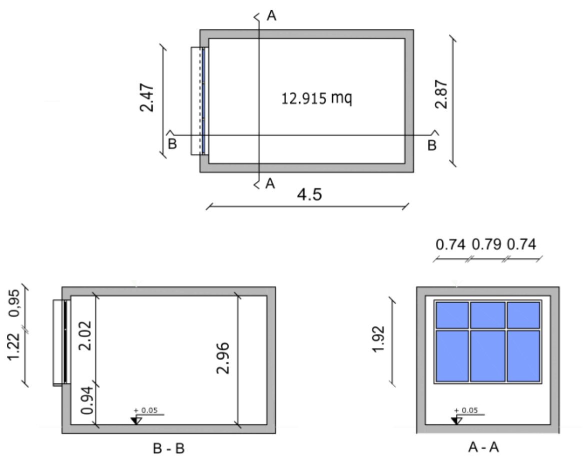

Fig. 1 – Room geometry

The office is considered occupied during workdays between 8:00 and 17:00, and the internal load due to occupancy and equipment is reported in Table 1. A maximum artificial lighting density of 12 W/m² has been considered, although the real lighting gain is controlled by a dimming sensor which varies continuously the output lighting power.
For daylight simulation the reflectances of walls, floor and ceiling have been taken as 0.4, 0.13 and 0.86 respectively.

	Equipment	Occupancy
0-8	60 W	0 W
8-17	300 W	150 W
17-24	60 W	0 W

Table 1 – Weekday distribution of thermal gains

Five cases have been analysed as reported in Table 2, while the geometry of shading devices is presented in Figure 2. Case 1, which is the window without a shading device is unrealistic, but has been reported here for comparison with the other solutions and therefore to evaluate the improving effect on energy and internal illumination patterns due to shading devices. Case 2 is a simple fixed overhang which shades the office room from direct lighting. Case 3 is an external Venetian blind system with slats at an inclination angle of 45°, which can be retracted in an upper case. Case 4 represents a similar external Venetian system, but in this case the horizontal louvers can be inclined at 0° and 45° from the horizontal. The last case is the union of cases 2 and 3.

Case	description
1	No shading device
2	Fixed overhang
3	Retractable external venetian blind
4	Controlled angle of venetian blind
5	overhang + external venetian blind

Table 2 - Cases analysed

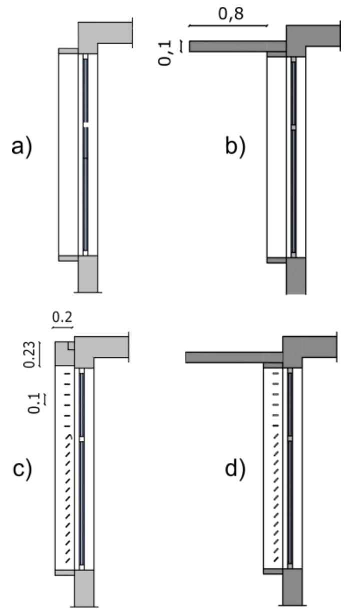

Fig. 2 – a) bare window b) overhang c) external blinds d) overhang with moveable blinds

3. Calculation procedure

Analyses were carried out using two simulation codes, ESP-r for energy simulation and DAYSIM for daylighting analysis.
The ESP-r code can cope with daylighting simulations, for instance it incorporates different coupling methods. It is possible to compute horizontal work plane daylight factors by combining analytical formula for sky component and split flux method for interreflected components, alternatively a user defined daylight

factor can be defined. More demanding computing methods are present as well: a full coupling method in which the lighting simulations are performed with Radiance at each time step and a daylight coefficient method where a set of daylight coefficients are pre-computed using Radiance.

A different approach has been adopted in this work, since the DAYSIM code has been used for daylighting analysis. In the proposed scheme the internal loads due to lighting are computed directly during daylighting simulations and then transferred to the energy computation code ESP-r by means of the ESP-r temporal data file facility. Since moveable shading devices are controlled by the lighting distribution into the room, their state has to be fed to the energy simulation code as well.

3.1 DAYSIM Simulation

DAYSIM is an analysis tool capable of calculating annual illuminance profiles. To efficiently obtain this result, it uses RADIANCE coupled with a daylight coefficient approach. For each geometrical configuration a set of daylight coefficients are computed then used to calculate internal illuminances at each simulation step with a variable sky luminance distribution. DAYSIM incorporates a user behaviour control model, called Lightswitch (Reinhart, 2002) which takes into account how occupants interact with light switches, and possible movable blinds. DAYSIM therefore is capable of computing the electric loads due to artificial illumination when no daylight is available or insufficient. The computed electrical consumption can be transferred to the simulation code ESP-r as an internal gain.

DAYSIM incorporates different methods to control the internal luminaries, in this work an efficient photo sensor-controlled dimmed lighting system with an energy-efficient occupancy sensor has been used. The photocell dims the activated lighting until the total work plane illuminance reaches the threshold of 500 lux.

Shading devices can be analysed with DAYSIM as fixed or moveable, in the latter case different sets of geometries are fed to the simulator with different positions of the devices. The code computes different sets of daylight coefficients and illuminance values.

In this work an automated blind control based system has been adopted, the blinds are fully lowered to avoid glare as soon as direct sunlight above 50 W/m² is reached in the work place, and reopened when this value is no longer met.

A set of illuminance sensors are positioned at mid room as described in Figure 3 a) in the figure two possible locations of work places have been represented, the one placed in front of the window exploits the daylighting and is intended for paperwork; the illuminance levels can be retrieved from sensors S2 and S3. Instead the other, positioned far from the window, identified by sensors S5 and S6, is intended for computer work.

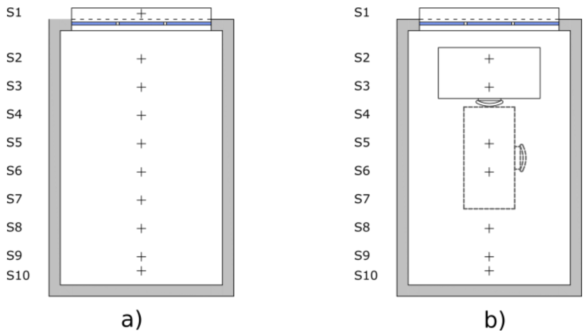

Fig. 3 – Sensors and work place positioning

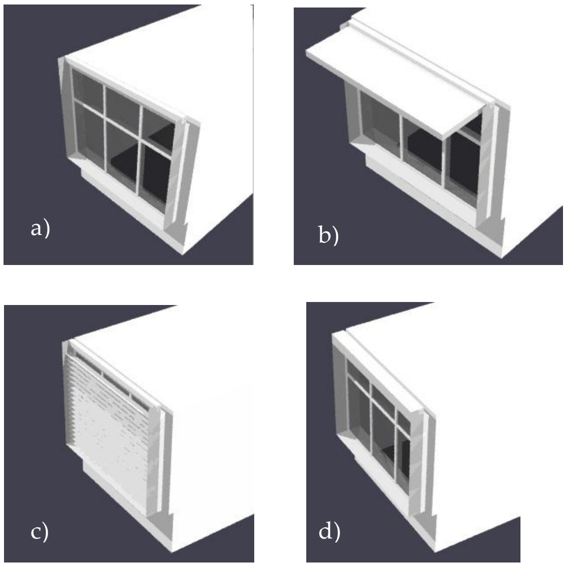

Fig. 4 – DAYSIM geometry, a) office room b) overhang c) deployed external blinds, d) retracted external blinds

The lighting simulation has been performed paying special attention to the geometric representation of the office room. For instance the authors modelled the walls' thickness, windows sills and a case container for the retracted louvers in Case 3. In Figure 4 the developed models are presented.

3.2 Simulation in ESP-r

External shading devices can be modelled in ESP-r in different ways. Fixed shading devices, such as the overhang used in this work, can be treated as an obstruction, which is a prismatic block which projects a shadow on opaque and transparent external surfaces. Shading from other buildings, horizontal overhangs, vertical fins, windows sills and reveals are examples of the obstructions that can be represented with such a model. Instead the complex interaction occurring between an external or internal blind with a glazing system can be defined in ESP-r with the complex fenestration construction (CFC). Only Venetian blinds can be modelled at the moment, controlling strategies allow us also to drive the deployment of the device or the modification of slat inclination angle. The control algorithms can be set in ESP-r and react to a number of sensors such as internal temperature or climatic data.

Unfortunately the available control methods hinder the possibility to use the control strategies implemented into DAYSIM, so for this reason the code of ESP-r has been modified.

3.3 Modification to ESP-r routines

The data exchange between DAYSIM and ESP-r has been implemented by means of a temporal file which reports for each simulation time the loads due to illumination and occupancy. This file is generated using the results obtained by the DAYSIM run. The temporal definition file is read by ESP-r and used during the simulation in order to account for the correct loads. Internal loads can be read in using the temporal definition file, but additional information is required to operate the moveable shading devices as derived from the DAYSIM run.

To achieve these results the structure of the temporal definition file has been changed by adding new parameters which represent the position of the shading device, retracted and deployed, or, if the slat angle changes, this control interacts with the CFC facility in order to synchronize the DAYSIM geometry with the ESP-r CFC model.

4. Results

Comparative data of energy demand and daylighting distribution are presented for the shading devices considered.

4.1 Energy demand

The results of the energy simulations are reported in Table 4, which represents the building's demand for heating, cooling required to maintain the internal temperature at 20 °C during heating season and 26 °C in summer conditions, and lighting. The energy carrier for heating, usually gas, is different for the one used for cooling and artificial lighting, usually electricity, therefore a primary energy consumption has been considered introducing plant efficiencies. Therefore the primary energy is computed as:

$$Q_p = \frac{Q_h}{\eta_h} + \frac{Q_c}{\eta_c} + \frac{Q_{el}}{\eta_{el}} \quad (1)$$

where the efficiencies are set as η_h =0.8, η_c = 0.8 and η_{el} =0.4, while Q_h is the heating demand, Q_c the cooling demand and Q_{el} is the energy required by luminaries.

Figure 5 shows the annual energy demand for the simulated models, while Figure 6 shows the primary energy required calculated with Equation 1.

As expected, the maximum consumption is obtained in case 1, which is the office without shading devices. For this solution the heating required is minimum, but the energy required for cooling is the highest. Since the window is unobstructed, the energy required for lighting attains a minimum. A good energy behaviour is obtained by adding a simple overhang to the window, as in case 2. In this case the energy required for cooling is substantially reduced, while the one for heating and lighting increases somewhat. This behaviour is easily explained due to the south exposure of the window and the different sun positions. In summer, when the solar elevation angle is high, the overhang is efficient in blocking solar radiation. In winter, due to the lower sun inclination angle, solar radiation is not intercepted by the shading device. However for this solution glare problems should be present, since the shading device is ineffective in blocking direct solar radiation especially during the winter months.

Case 3 is a moveable external venetian blind system. In this case the energy required for heating increases with respect to the other two cases, but unexpectedly the cooling load is higher than case 2. This behaviour can be easily explained: the blinds are activated when the direct sunlight above 50 W/m² is reached in the work place, in this case represented by sensors S3 and S6 in Figure 3. Since sensor S3 is positioned near the window, it drives the shading deployment, while sensor S6 positioned deeper inside the office drives the lighting dimming control. In this case the blinds are deployed more in winter as reported in Figure 8, so solar radiation entering the room is not blocked during the summer period, as reported in Figure 7. Case 4 represents the case with the blinds system always deployed, the control associated with sensor S3 alters only slat inclination, from 0° to 45° therefore the shading effect is always present as can be seen in Figure 7, leading to the lowest cooling load while the heating load is slightly higher than the one in Case 3. The number of hours of deployment is minimum, but it must be pointed out that the slats are always deployed and therefore only the inclination is altered.

Case 5 represents the combination of case 2 and case 3 and represents an attempt to obtain an efficient shading system reducing the hours of deployment allowing for a better unobstructed view outside the room. This effect can be confirmed by inspecting Table 3 and Figure 8. However the primary energy required is slightly higher if compared with case 2 with an increase in heating demand while the cooling load is only slightly affected. Again this behaviour can be explained by inspecting figures 7 and 8, the blinds are deployed mainly during the winter season, reducing the solar radiation with an increase of the heating load, for the same reason the lighting energy consumption shows a slight increase.

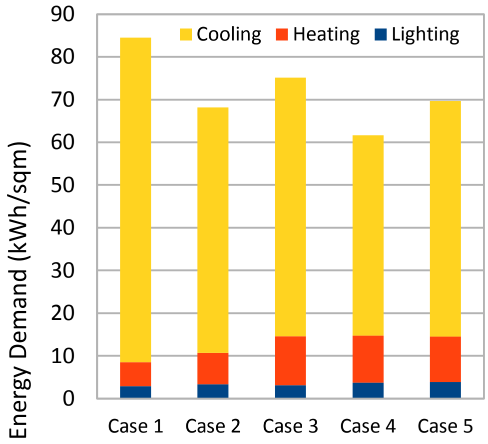

Fig. 5 – Annual energy demand

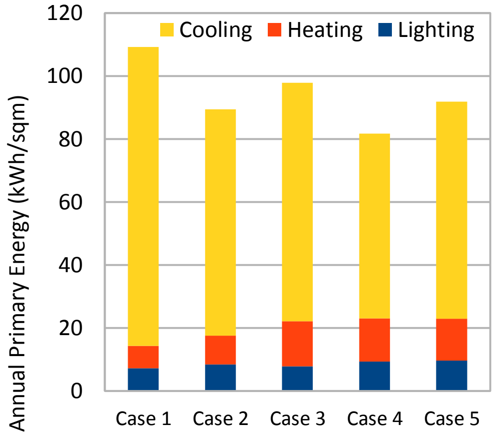

Fig. 6 – Annual primary energy required

Case	Q_h	Q_c	Q_{el}	Q_p	t_{on}
	Kwh/m²				hours
1	5.66	75.95	2.90	109.3	-
2	7.30	57.48	3.38	89.4	-
3	11.51	60.54	3.12	97.8	317
4	10.99	46.92	3.74	81.7	209
5	10.65	55.12	3.87	91.9	276

Table 3 – Energy required and blinds time of activation

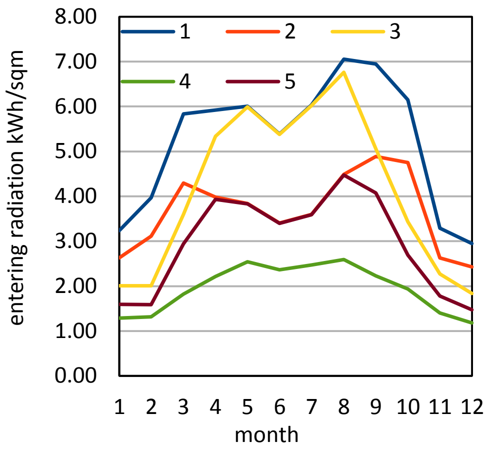

Fig. 7 – Entering solar radiation for different cases and months

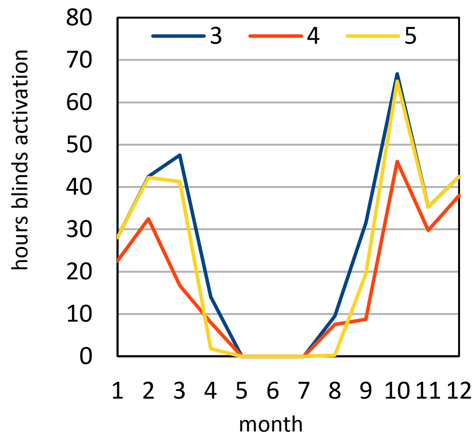

Fig. 8 – Number of hours of shading device activation per month

4.2 Daylight analysis

The amount of daylighting for the different cases is presented in terms of Useful Daylight Illuminance which is a parameter which indicates the percentage of working hours in which, in the work plane, a prescribed level of illuminantion is attained. This parameter is presented as a percentage of hours that attain three illumination ranges, 0-100 lux, 100-2000 lux, and over 2000 lux. In this work only data referring to the last two ranges are presented, since the percentages below 100 lux are always below 10% also for positions far from the window.

Figure 8 shows the distribution of UDI 100-2000 for the sensors presented in Figure 3, while Figure 9 presents the distribution of UDI 2000.

The daylighting maximum performance is obtained by case 4 witch shows the highest values of UDI 100-2000. Similar results are obtained by cases 3 and 5 until a depth of about 2 m , from this point onward the overhang increases the performance of case 5. As expected, case 1 shows a daylight illumination too strong, while case 2 although demonstrating an improvement respect case 1, results always underperforming if compared with the other cases.

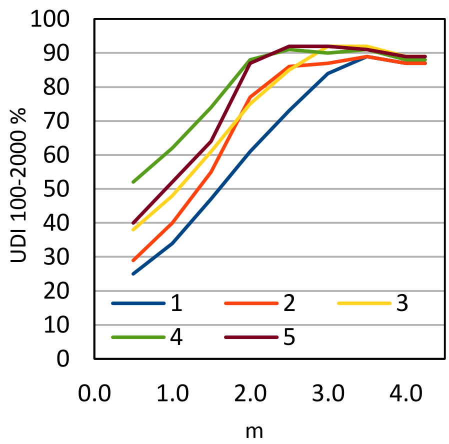

Fig. 9 – UDI 100-2000 distribution

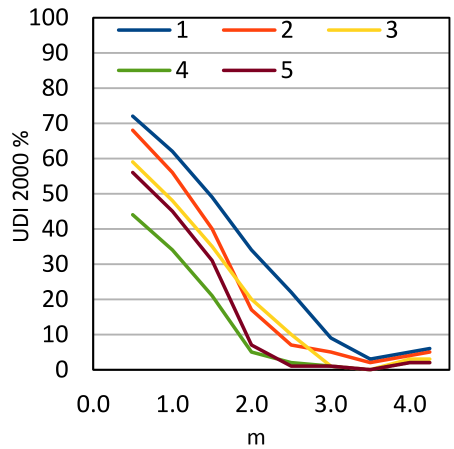

Fig. 10 – UDI 2000 distribution

Figures from 11 to 15 show the distribution of UDI 100-2000 in the work plane at a height of 0.85 m from the floor, and again the daylight distribution can be appreciated. The room always receives a sufficient quantity of daylighting as also shown in Figure 9. The low values of UDI 100-2000 near the window are due to higher values of UDI 2000. Again Cases 1 and 2 show high illuminance levels in proximity to the window. Using movable shading devices this effect is mitigated obtaining acceptable values. Case 4 gives the better light uniformity with values nearly always higher than 50%. Case 5 gives the same results from a depth of 1 m onwards, which represents a good result since the window is for most of the time unobstructed as opposed to case 4, giving a free visual outside the room.

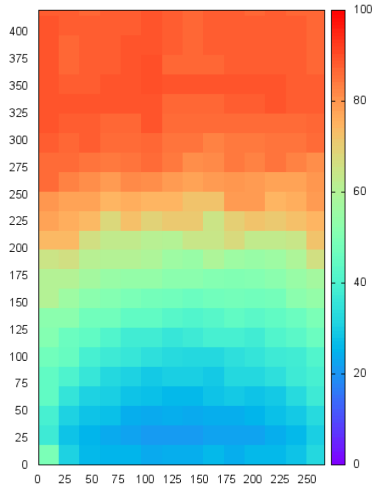

Fig. 11 – UDI 100-2000 distribution for case 1

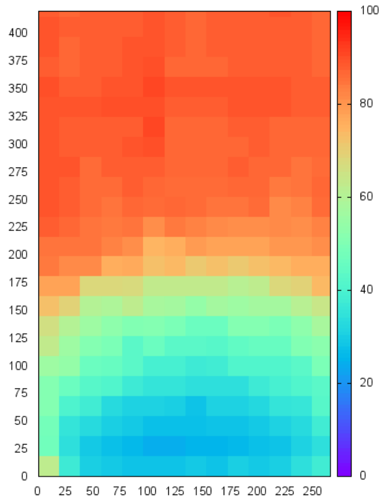

Fig. 12 – UDI 100-2000 distribution for case 2

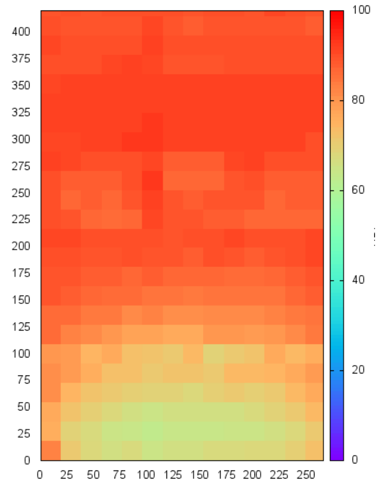

Fig. 13 – UDI 100-2000 distribution for case 3

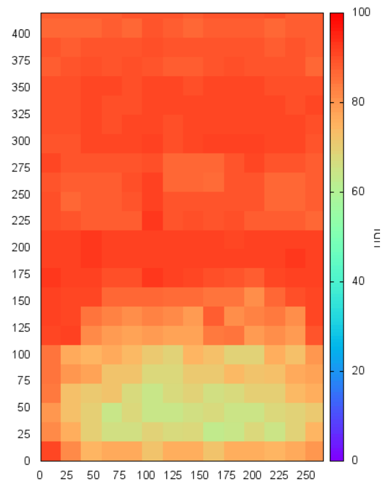

Fig. 14 – UDI 100-2000 distribution for case 4

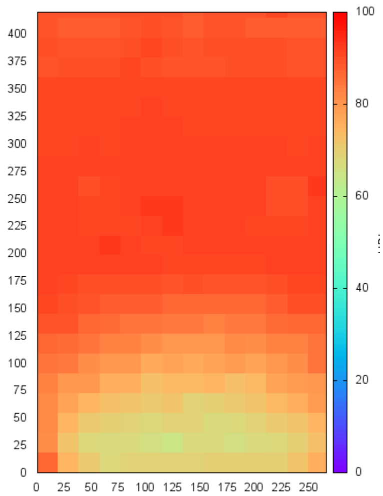

Fig. 15 – UDI 100-2000 distribution for case 5

5. Conclusions

Energy and daylight analysis have been performed for an office building with different shading devices. To obtain a dynamic simulation two codes have been used: DAYSIM for daylight analysis and ESP-r for energy analysis. The lighting analysis drives the movable external shading devices to avoid glare problems for two possible work places inside the room and computes the energy required for lighting. A new control variable has been added to the ESP-r code in order to synchronize the deployment of the shading devices with the results obtained with the daylighting analysis.

The obtained results show a good daylighting distribution and low energy consumption for the case with fixed venetian blinds with angle inclination control. Good results have also been obtained for the case with overhang and deployable devices. The fixed shading device showed good energy performance, but poor daylighting distribution with high illuminance levels near the window, this suggests that an additional analysis should be performed coupling fixed overhang with internal blinds .

The work presented demonstrates the usefulness of dynamic simulation for obtaining design scenarios which take into account different but strongly interconnected parameters such as energy performance and daylighting availability.

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