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An overview on solar shading systems for buildings

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Abstract

In recent years, different types of solar shading devices have been proposed, depending on building orientation, location, window characteristics, etc.. They can contribute to improve or worsen building thermal and lighting performances both from an energy and comfort point of view.
The present paper reports a critical analysis of some studies that investigate shading devices' effects on building thermal and/or lighting performances. This article points out the difficulty in comparing the different results given the lack of uniformity between the studies, since they analysed buildings with different characteristics, locations and using various indices. Therefore a protocol to carry out this type of studies should be developed in order to allow the comparison of the different research investigations performed all over the world. Moreover, this paper shows that thermal comfort, economic and environmental aspects related to the use of shading devices were rarely analysed.

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Keywords: buildings; solar radiation; shading devices; lighting analysis; thermal and energy analysis; HVAC systems; energy savings

1. Introduction

Incoming solar radiation in buildings has strong implications both on visual and thermal aspects. Solar shading systems influence daylight levels in a building and the view to the exterior environment; they also reduce yearly solar gains and modify thermal exchanges through the glazed building envelope. Therefore, shadings affect the building energy use for lighting, heating and cooling, and also the occupants' visual and thermal comfort. The aim of the present article is to describe and critically debate a quite large number of papers that studied this subject, considering that there is no standardized procedure to investigate the effects of shading devices. The analysed papers consider different conditions regarding climate, shading typology, orientation and characteristics of building, used methodology, etc. Shading devices allow to control daylight's entrance in buildings, thus contributing to avoid discomfort phenomena such as glare. However, the consequent reduction of daylight levels may determine an

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increase in energy consumption for electric lighting. Therefore, there is also the need for a compromise between energy saving and users' wellbeing issues. Regarding thermal aspects, articles usually performed studies referred to all the year, rarely to only summer. All the studies about the shadings' effect on yearly energy use demonstrated that shading devices decrease the cooling requirements, but at the same time they increase the heating demand given the reduction of solar gains.

After brief preliminary considerations on the examined topic, the analysed papers were grouped in categories depending on the type of shadings analysed: fixed shading systems; movable shading systems; other shading systems.

Each main category is divided in: lighting analysis; thermal-energy analysis and HVAC system energy requirements; and a more comprehensive analysis that includes both lighting and thermal-energy analysis coupled with HVAC system energy requirements.

This paper points out the need of some guidelines in order to be able to compare the different studies carried out all over the world.

Considering the very large number of published papers regarding this topic, only a limited number of them has been considered in this article, but sufficient to investigate the main problems related to this research field. Therefore, an overview on the solar shading systems for building, instead of a proper literature review, is shown.

Nomenclature

DA	daylight autonomy
DF	daylight factor
DGI	daylight glare index
E	east orientation (similarly, with reference to N, NE, NW, S, SE, SW, W)
UDI	useful daylight illuminances
WWR	window to wall ratio

2. Preliminary considerations on published papers regarding solar shading systems

In Fig.1 a possible classification of solar shading systems for buildings is reported, while the main shading types are shown in Fig.2.

The shading types object of the present papers are the following: external and intermediate devices, both fixed and movable ones. In order to avoid a comparison between too different solar shading strategies, the following solutions, as well as the related references, have not been considered in this analysis: internal solar shadings, because they depend very much on the user behaviour; self-shading buildings and solar film coatings on fenestration, because these strategy are very different from the typical solar shading devices. A few number of references on internal solar shadings and solar film coatings have been maintained only because they report also an analysis on external or intermediate shadings.

The papers illustrated in the next sections are some of the main articles on this topic.

There are few studies that performed a full scale analysis of the impact of shading systems, including thermal, energy and daylight effects [1-7].

A lack of uniformity is also noticeable, considering that there is no established protocol to perform these analysis. This means that the results cannot be compared with each other, since they differ for: characteristics of the simulated or real environment studied; methodology; software used; parameters considered to evaluate the performance of the shading system; etc. Furthermore, in some cases, the simulated environments are located in unobstructed neighbourhoods [1,2,4,7-14], which rarely occur in reality.

This lack of uniformity can also be found in studies that only performed an analysis of the impact of shading systems on daylight quality. The majority of them only evaluated the effects of shading devices on illuminances [3,15,16], others also calculated the DF [7,17], whereas only a few considered the DA and/or UDI, luminance ratios and/or glare indices [2,6,7,17-19].

Another important point regards the control systems set points (both for shadings and electric lighting). Depending on the value and type of the chosen set point, the results in terms of daylight quality, electric light use, impact on building thermal behaviour and energy savings can vary significantly [5,10,20].

The present paper also shows that some authors only studied the effects of shading systems on cooling performances [9], while others investigated these effects in both winter and summer [1-5,11-14], thus producing an assessment of both energy advantages and disadvantages. Most authors only analysed energy requirements of the building envelope, considering an ideal HVAC system or no system [4,12-14]. Other authors differently investigated the delivered energy [1-3,5], i.e. the energy required by the final user for the building needs (different from the primary energy). One reference analysed the ratio between energy demand of the building envelope and primary energy [11], another one the ratio between envelope energy requirements and delivered energy [9]. Finally, integrated shading systems for heat [8] and electricity [9] production were also studied.

Comfort, economic and environmental aspects were rarely considered. Only a few authors analysed in detail issues related to thermal comfort, as well as environmental and economic impact [8].

At today, a building designer who can dispose of this great variety of shading devices cannot rely on practical indications to understand if, given particular conditions, one system performs better than another, or rules helpful in making a choice. This is particularly true if both global comfort and energy issues are taken into account. Indeed, the parameters to be considered are too many, but until now no significant effort has been made in order to classify and characterize these devices. One of the aims of this article is to highlight this complexity and put the basis for a simple categorization from which to start.

Fig. 1. Solar shading systems for buildings: a possible classification.

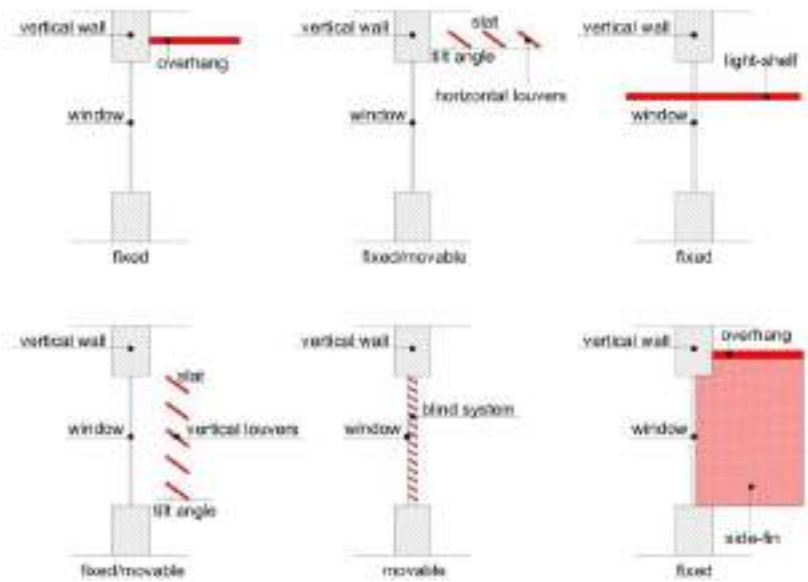

Fig. 2. Main shading types.

3. Fixed shading systems

3.1. Lighting analysis

Effects of fixed shading devices on indoor illuminances, without considering energy analysis, were studied by means of measurements on scale models [15], comparison between measurements collected in an existing building and results from software simulation [17], or software simulation [18]. In [15,17,18], an office building was considered.

A comparison of the effects of an overhang and two types of light shelves (one made of methacrylate and a mirror one) on indoor illuminances in a scale model (1:10) of an office with a S exposure in Madrid is reported in [15]. As expected, illuminances obtained in the models with light shelves resulted higher than those obtained with the overhang; between 08:30 and 11:30 the methacrylate light shelf performed better in the central months of the year.

Illuminances measured in an existing residential building in Singapore with those obtained through the simulation of the same building with Lightscape were compared in [17]. The simulation was performed using different shading systems not present in the real building: a light shelf, overhangs with different depths, combinations of overhang and two side fins. The results showed that illuminances were higher than the recommended ones except with the combination of overhang and side fins. Moreover, the shading devices analysed did not always reduce glare effects.

The authors of [18] performed a Desktop Radiance simulation of an office in Tel Aviv for all four main orientations and with different configurations: 1) no shading system and improved optical qualities of interior surfaces; 2) same case as the previous one, but with a highly reflective light shelf; 3) anidolic concentrator in place of the light shelf. The light shelf was efficient with direct sunlight on it and it is not recommended for N orientations, while the anidolic concentrator performed better in almost all the orientations, but with low solar altitude it became a possible source of glare.

3.2. Thermal-energy analysis and HVAC system energy requirements

In [10], a simulation with IDA ICE 3.0 was performed for an office building located in an unobstructed neighbourhood in Sweden. The authors studied the impact of different WWR (30%, 60% and 100%), orientations, glazing thermal transmittances. Three control set points and shading systems were analysed (fixed external louvers, internal venetian blinds, internal screens and intermediate blinds) and two plan types (open plan and cell offices). The control set points were labelled as: poor, normal and strict. A minimum level of 90% of the working hours with a PPD (Predicted Percentage of Dissatisfied occupants) lower than 15% was set as an acceptable limit regarding thermal comfort. Results showed that, for the analysed type of facade, the influence of orientation on energy use is small and that a higher glass area leads to a small decrease of the energy use for lighting. Moreover, for WWR = 100% and blinds placed inside, the cooling demand increases by 37% compared to intermediate blinds. The alternatives with the "poor" control set point and the ones with high WWR with clear triple glazing did not fulfil the minimum PPD level.

The author of [11] analysed the effects of fixed louver shading devices on the thermal performance of a building located in Italy, using TRNSYS simulation. The variations of annual solar gains through windows, the annual total energy loads with and without shadings and primary energy were calculated, Energy requirements for heating and cooling were evaluated for the whole year using three configurations of louver shading devices (while the lighting system energy was not considered). For example, considering the second configuration with a tilt angle of 30° for Rome, the primary energy of zone 2 (South exposed) was decreased by about 6.5% (9%, if only zone thermal energy needs – i.e., without considering HVAC systems - were considered).

In [12], the impact of louver shading devices on building energy requirements in the cooling and heating seasons was studied. TRNSYS and EES software were used for the energy simulation and to analyse shadings' geometry. Shading devices analysed are: overhangs on the S facing-facade (tilt angle of the slats equal to latitude of the locality) and vertical louvers on the E and W orientations (various tilt angles). The energy requirements were evaluated as a function of louver inclination angle (tilt angle), window area and location. The results showed that the use of shading devices is fundamental in cities characterized by high solar radiation and high temperature during summer (Cairo, Lisbon and Madrid), but it also reduces cooling needs in cities similar to London. For case C (windows height of 1.5 m, inclination of 20° for E and W facades), the annual energy saving, compared to the building without shading systems, was 60% for Cairo, 50% for Lisbon and 9% for Madrid. The cooling needs reduced with inclinations of 45°-70°, but the total energy demand increased in all cities given the rise of heating needs.

A study on effect of low-e glazing, overhangs and side fin shadings on transmitted solar energy and thermal loads of a residential building in Teheran (Iran) was performed in [9], by means of EnergyPlus software. Four glazing types (single clear, double clear, single low-e and double low-e) were investigated considering three combinations: windows without overhangs and side fins, windows with overhangs and without side fins, windows with overhangs and side fins. The window energy transfer and performance index (ef) of shadings were evaluated for the heating/cooling period or for the whole year. The index ef is defined as follows: ef = 100 x (Ea - Eb)/Ea

where

- Ea is the total energy that it is transferred into the building from the single clear pane glazing window without shading (reference model)
- Eb is the total energy that it is transferred into the building from the window with overhang and/or side fins.

The presence of overhangs determined an annual average ef from 29% to 51% for shadings applied to S orientation, from 11% to 33% for W, from 12% to 30% for E.

3.3. Comprehensive analysis: lighting and thermal-energy analysis coupled with HVAC system energy requirements

Comprehensive analyses of thermal, visual and energetic aspects were carried out only in few papers. The approaches, experimental or based on numerical simulation, are strongly different, and results obtained are not comparable. The effects of external fixed solar shading devices on the electric energy requirements of a standalone office building for three Italian climates were investigated in [1]. The simulations were performed by means of EnergyPlus. Energy requirements of the heating, cooling and lighting systems were analysed and two shading typologies were studied (overhangs on the S facing-facade and louvers on the E and W orientations). The analysis was carried out considering the influence of the overhang depths, climate, building height, thermal insulation, walls' thermal mass, WWR, lighting control system and building orientation. In the case of WWR=30% and 1.0 m overhangs, the global electric energy savings were 20% for Palermo (the hottest locality), 15% for Rome, 8% for Milan (the coldest locality).

In [2], the thermal and lighting behaviour of an office building in Santiago of Chile was simulated with EDSL TAS (thermal simulation) and Daysim (lighting simulation). The different variables analysed were: three types of glazing; different orientations and WWRs of the building; various types of solar shading systems. Energy demand for heating/cooling was calculated for all the combinations, and daylight quality was assessed by means of DA and UDI. The most influential factor on energy demand for heating and cooling resulted WWR, achieving the best performance with WWR=20%, overhang for N orientation and blinds for E/W.

A simplified algorithm was proposed in [3] for the assessment of illuminances in offices equipped with a lighting control system and external shading devices composed by overhangs and vertical fins. Once validated the procedure, the authors used the IENUS software to perform a lighting and thermal analysis to be applied in the early stages of the design process for offices in Rome, Bolzano, Athens, Messina, Madrid. Two different configurations were considered: an internal shading device with an automated control based on direct solar radiation levels; a fixed external shading with no indoor shading device. Heating/cooling and lighting energy demand was considered, as well as a comparison between values obtained in a scale model and the simulated ones, but no evaluation of energy saving with different configurations was made.

4. Movable shading systems

4.1. Lighting analysis

A methodology for daylight numerical simulation of an office with highly reflective louvers integrated between the panes of a double glazed windows is presented in [16]; it also allows to calculate the dimming levels for electric lights in order to optimise the use of daylight and increase energy savings. The method first determines the optimal blinds tilt angle to maximize daylight entrance, without causing glare, while allowing the maximum possible view of the outdoor environment; then, it calculates hourly daylight related illuminances at several points on the work plane for representative days in each months from 9:00 to 17:00. Subsequently, it determines dimming levels for electric light and computes the energy savings derived from blinds control and electric light dimming. The results showed a 76% energy saving for overcast days and a 92% for clear days compared to the same office where there was no control option of the electric light (while the shadings and their control system are the same for the two compared cases).

4.2. Thermal-energy analysis and HVAC system energy requirements

In [20], an efficient control strategy for shading devices is based on radiation level on the facade and inside temperature. An office in Belgium with a S exposure was analysed with TRNSYS. Energy demand was calculated as sum of direct heating demand and preheating of external air (for ensuring indoor air quality); fans and other consumptions were neglected. Two sets of simulations were performed; in the first one, an exterior screen with two positions (open/closed) and three types of management schemes were tested (the first based on irradiation level on the facade, the second on inside temperature and the third was a combination of the first two). In the second set, free cooling with three management modes and a fixed overhang were investigated. The best strategy for shading devices (first test) is based on internal temperature and solar irradiation on the façade; indeed, a control mode based only on irradiation level determines an increase in energy demand comprised between 1% and 37% compared with a control mode based on internal temperature (considering a 22° C set point).

4.3. Comprehensive analysis: lighting and thermal-energy analysis coupled with HVAC system energy requirements

Comprehensive analyses of visual and thermal comfort and energetic aspects are based on numerical simulations. TRNSYS and EnergyPlus were used in [4] to evaluate the impact of glazing area, shading device properties and control on thermal and daylight performance of perimeter office spaces in Montreal (Canada). The impact of daylight and electric lighting control on thermal performance was investigated as a function of WWR, considering an exterior roller shade. Daylight availability ratio (DAR) was calculated for each orientation. For the S facade with a 30% WWR, daylight provided 500 lx on the work plane for 76% of the annual working time. Two different types of electric lighting control were considered (passive control, i.e. electric lights switched on during working hours; active on/off control, based on occupancy). The on-off electric lighting control, compared to the case of no lighting control, determined a 16% increase in annual heating demand, 16% reduction in cooling demand, 76% decrease in lighting demand and 22% reduction in total energy. Various values of shading transmittance were considered, as well as two different types of shading control: passive control (roller shade is closed during working hours) and automatic on-off control (roller shade is open when beam solar radiation incident on the window was minor than 20 W/m^2). The first type determined poor daylight availability, whereas the on-off control of the shading during working hours increased annual daylight availability by 20%.

5. Other shading systems

In this section we have analysed the following cases: comparison or combination of fixed and movable shadings; shading device integrating a solar thermal system; building-integrated photovoltaic shading-type; combination of electrochromic windows and overhangs.

5.1. Lighting analysis

Different shading devices (overhang, a blue and a white fabric awnings, a venetian blind with different slats angle and a grey and a white fabric screens) in a S oriented office in Horsholm (Denmark) were compared in [19] by means of Radiance simulations in different days and hours under CIE clear sky. Only fabric screens are internal shading systems; the overhang and fabric screens are fixed, whereas the awnings and venetian blinds are movable. The results showed that the grey screen performs poorly in terms of work plane illuminances, illuminance uniformity and luminance ratios. The blue awning, venetian blind with slats sloped at 45° and the white screen had acceptable values for all indicators. The venetian blind with horizontal slats, the overhang and the white awning determined values that are not suitable for computer work (too high illuminance values on work plane) but acceptable for traditional office tasks. The best overall performances were those of the 45° venetian blind and of the white screen.

5.2. Thermal-energy analysis and HVAC system energy requirements

In [8], a shading device integrating a solar thermal system for water heating was analysed for a building in Portugal and Spain. A numerical model of the system with different configurations was developed; collector efficiency is also quantified. Two situations were compared: the real one with a completely sunlit louver and two shaded louvers, and an ideal one with three completely sunlit louvers. For the real case in Lisbon, shadings reduced transmitted energy by 7% (inclination of 15° on horizontal plane), 12% (30°) and 17% (45°). For the ideal case, the optimum angle was 25°. The annual solar fraction was between 83% and 52%. A payback of 6.5 years and a CO_2 saving of 8.6 tons were obtained.

In [9], the authors investigated the impact of a building-integrated photovoltaic shading-type (BIPV) with different azimuth angles on electricity generation and reduction in cooling load and energy use. The simulations were performed for Hong Kong (China). Optimal inclination of PV modules was 10° for S facing facades (maximum annual electricity generation was 76.7 kWh/m^2). The annual electricity generation decreased when the tilt angle exceeded 40°. The integrated shading on E facade had to be installed vertically. The maximum cooling load reduction for windows (S orientation) was 51.6% when the tilt angle was 50° and the wall utilization fraction (ratio of the height of concrete walls with PV modules to the total height) was 100%, while this reduction was 17,8% with a tilt angle of 80°. The SW modules with an inclination of 30° and a 20% wall utilization fraction determined an annual electricity saving of about 225 kWh (115 kWh, for an inclination of 60°). Different optimum tilt angles of integrated shading were obtained for various orientations.

5.3. Comprehensive analysis: lighting and thermal-energy analysis coupled with HVAC system energy requirements

In [5], the combination of electrochromic windows and overhangs was analysed through DOE-2, by simulating an office building with a S exposure in Chicago and Houston (USA).The window was divided in an upper and a lower part and various overhang depths were tested in two positions (above the upper part or in the middle of the window). The authors investigated different electrochromic window control strategies to determine which one produced the lowest level of discomfort glare, adequate daylight levels and lowest energy use. The best control strategy is the one where the lower aperture of the window is controlled by total incident solar radiation levels, while the upper aperture is controlled by daylight levels.

In [6], simple indices to assess the thermal and lighting performance of shading systems are proposed: solar shading coefficient, cooling energy, DA, sun patch index on work plane and modified UDI. The authors linked DA, UDI e SP by proposing new extreme values for UDI (300 and 8000 lx). The indices were applied to an office in Gillot (Reunion Island), by using EnergyPlus. A N facing window was considered with four types of solar shadings (two types of overhangs, overhang and rectangular side fins, overhang and triangular side fins).The louvers were studied with variable number of blades: from 0 to 3 blades UDI was greater than 80%, for 4-5 blades it was near 40% and below 20% for more than 5 blades.

In [7], a year thermal and lighting simulation was performed with iDbuild, for an office in Denmark in an unobstructed environment. The main orientations were tested with different window heights (1.0 m, 1.5 m and 2.0 m). Three solar shading systems were analysed: no shading, fixed horizontal venetian blind and a movable venetian blind controlled on indoor air temperature and risk of glare. Total energy demand, energy for artificial lighting, energy for heating/cooling and DF were evaluated. The best global performance was obtained by the S facing facade with a window height of 1.5 m and dynamic solar shading (total energy yearly demand of 46 kWh/m^2), whereas the worst performing facade resulted N facing one with a fixed shading system and a window height of 1.0 m (66 kWh/m^2). Facades with a window height of 2.0 m with no shading or dynamic shading provided a minimum DF of 2% in the entire working zone.

A study of the impact of four shading types (overhang; blind system; light shelf and an experimental shading device) was reported in [14]. The experimental system improves view performance for occupants and protects from direct sunlight with various adjustments of the slat angle. The cooling/heating load, the annual load and energy consumption were evaluated for a South Korean location with IES_VE code. The experimental shading determined the maximum cooling energy saving (11%), followed by the long light shelf, long overhang, short light shelf, short overhang and blind system. The analysis was conducted when the solar altitude is equal to 76°. The light shelf allows a better distribution of daylight.

6. Conclusions

The paper reports an overview on some published scientific papers regarding solar shading systems for buildings. A drastic lack of uniformity has to be highlighted, even when the research studies refer to only one aspect of the topic (for example, only an analysis on the impact of the shading systems on daylight quality).
The following further considerations can be derived from the paper:

- the need to establish a protocol in order to allow a comparison between the different research results obtained all over the word;
- the "macro - categories" by means of which shading systems were grouped in this paper, although this represents a first attempt to approach in the highlighted complexity, revealed to be insufficient: from the analysis carried out, a more complex work with a taxonomic aim is required. This work should be approached by means of the individuation of some features and suitable "performance parameters" for shading devices, based on structural characteristics of the shadings, climate and local characterization (building orientation, urban density, etc.);
- the importance to collect comparable data on existing buildings with different shading devices and from various climatic areas in the world;
- the suitability, for future research studies on solar shading systems for buildings, to perform a global building performance analysis considering both thermal and lighting issues, including energy and comfort aspects. The analysis of one or few of these aspects is not only incomplete but sometimes could be also misleading;
- the suitability of a technical-economic analysis on shading devices, as well as of a proper LCA (Life Cycle Assessment);
- the suitability of energy analyses on shading devices that take into account also the HVAC system types and efficiency, therefore evaluating primary energy requirements besides building thermal energy needs; moreover, the need that the researchers always clarify which type of energy requirements they intend (building thermal energy needs, delivered energy, primary energy, etc.);
- daylight should be studied using more reliable indices such as DA and UDI, while also evaluating glare risk. Moreover, a proper integration between daylight, electric light and shading influence should be also carefully analysed, since it can determine not only great energy savings but also relevant improvement of users' comfort;
- regarding the building design, the need to develop a design procedure that, from its early stages, takes into account with the same accuracy both comfort (thermal and visual) and energy issues.

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