A dynamic skylight for daylighting and assisting climatisation in a medium size room

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ABSTRACT: This work presents a dynamic skylight, for daylighting and assisting climatisation in a medium size room. Room's size and lighting from above are compatible with uses as show-room of art gallery or museum, class room and reading room. The device includes an heliostat with variable geometry, it can exploits direct or sky diffuse solar radiation as function of season and weather conditions. During the cold season the direct radiation, if present, is re-directed inside the room on diffusing ceiling. During the warm season device's configuration is modified to allow the entrance of the only sky diffuse radiation fraction that is required for daylighting. This radiation comes from the sky-dome's side opposite to Sun direction. The direct radiation impinging on other side of device is used to create in its interior a solar stack effect that contributes to air extraction and natural ventilation. Roof opening's size, device's geometry and its control logic have been optimised by means of computer simulations. Optimisation is aimed to minimise the total annual primary energy demand for climatisation and illumination. Room's energy balance takes into account of solar and internal gains. Device's geometry has been optimised for two Italian climates: Venezia and Trapani.

Keywords: energy, daylighting, skylight

1. INTRODUCTION

Since the beginning of Architecture's history openings in the top of building's envelope have been used with multiple purposes: indoor daylighting of buildings located in high density urban tissues, modelling and scene-light in holy and representative buildings, ventilation and smoke's evacuation [1]. In hot dry climates these openings were also used, jointly with pools, to provide ventilation, evaporative cooling and humidification [2].

On one hand daylighting from above allows to avoid discomfort glare, because the luminous sky is kept out of occupant's visual field, on the other hand it don't allows outside vision.

For these reasons lighting from above can be proposed in a room only for particular destinations as: art gallery or museum show rooms, classroom, meeting room and library reading room; not in dwellings or offices.

This work presents a dynamic skylight aimed to daylight and to assist air conditioning in a medium size reading room of 6X6 m in plan and 4 m height.

At present the proposed device is just at the planning stage, therefore all the energetic and daylighting evaluations contained in this paper are based on computer simulations.

The examined spatial module (Fig. 1) is laterally adjacent to other similar spaces, obviously they have to be situated at the last floor of a building.

In these conditions the roof is the more dispersing border. Roof and internal walls have a light metallic frame, and the envelope is assembled using sandwich panels containing insulation.

A time-averaged presence of thirteen persons in the room is supposed. According with Italian standards an air change ratio of 20m³/(h·person) is assumed. Artificial lighting plant utilises fluorescent lamps (efficiency 91 lm/W). Continuous dimming is applied to lamps in order to ensure 500 lx on visual tasks. Internal gain due to lamps corresponds to the absorbed electric power.

The building is equipped by a full air HVAC plant connected to a natural gas boilers and electric coolers. Efficiency of different plants is taken into account to calculate primary energy demand. In particular boilers and coolers instantaneous efficiency is calculated as function of loads. Moreover the global efficiency (production and distribution) of Italian electric system (35%) is used to obtain the primary energy demand related to all the electric uses.

2. OPENING'S SIZING

Any opening in the building's envelope has to accomplish several functions:

- thermal gain during the winter,
- daylighting,
- ventilation for hygienic aims and summer cooling,
- Outside vision.

These functions often conflict reciprocally, in particular climatisation and daylighting. The opening size has to mediate between different requirements with the aim of minimising total primary energy needs and achieving global comfort conditions.

Also in the case of a opening on the roof the optimal size is different in different seasons; therefore a moveable configuration can mediate the contrasting needs in a better way than a fixed one.

2.1 Optimal size of different kind of skylight.

The first step in skylight's design is top opening's sizing. The optimal size depends from the skylight's typology and from its control logic, if moveable elements are present. Therefore three different configurations have been compared. For each of them optimal size has been defined.

1) Simple horizontal skylight, without any control for Sun radiation, only an internal diffusing curtain to avoid glare phenomena is present.
2) The same skylight of previous point with addition of external movable louvers in order to avoid overheating.
3) Dynamic skylight incorporating a heliostat.

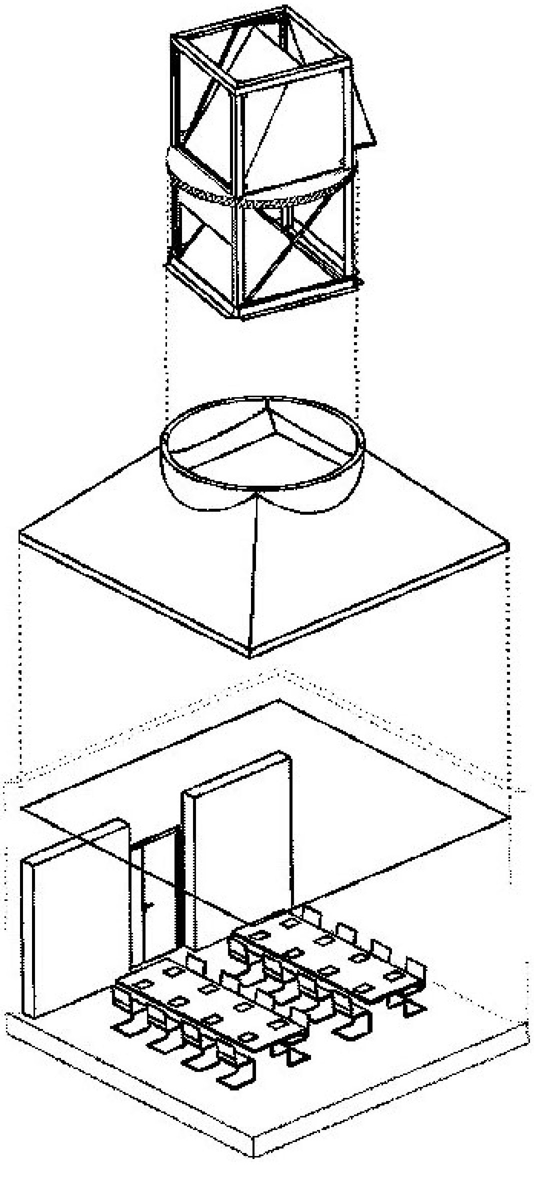

Figure 1: Exploded axonometric projection of the module with the dynamic skylight. The moving part is the upper double-cube

Position of movable elements, in the second and third cases, is defined according to a control logic that can be resumed as follow: at any moment the device has to consent the entrance of the useful solar radiation only. This is a fraction of available radiation corresponding to:

1) a thermal power not bigger than requested for heating;
2) a luminous flux not lower than requested for lighting, in order to exploit the better quality of natural light and to contain thermal load from lamps.

2.2 Software and calculations.

Size of aperture on the roof, device's geometry and its control logic have been optimised by means of computer simulations

The utilised software is a particular version of *Ener_lux* [3]. It calculates: energetic and luminous solar radiation entering in the room throughout the skylight, the level of internal illuminance and executes a simplified energy balance of the building module by hourly steps. This balance takes into account solar and internal gains (occupants and artificial lighting).

Calculating total energy demand, electric consumption for air circulation, air extraction and HVAC operation are considered.

More detailed lighting analysis have been performed by means of software 3D Studio Max, that use Radiosity algorithm [4].

Three Italian climates have been considered, they are situated respectively in the North (Venezia 44.5° N), in the centre (Roma 42° N) and in the South (Trapani 39° N). For each of them device's geometry has been optimised.

2.3 Simulation's results.

In figures 2 and following are reported the behaviours of total primary energy demand vs top opening's size, for each of three types of skylight. Data are referred to the climate of Venice.

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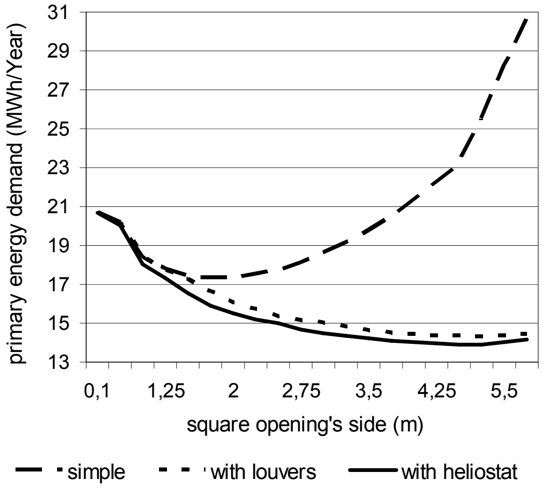


Figure 2: Venice, room's total primary energy demand as function of top square opening's side length, for three different kind of skylight .

Increasing opening's side length all the curves present a first descending part, due to energy saving in artificial lighting, which increases with opening's width.

Beyond the minimum point the energy demand raises as a consequence of climatisation needs. In fact heat losses in cold periods (without significant solar gains) and cooling in warm periods are rising with opening's width.

Comprehensively this trend is very remarkable for the skylight without any radiation control, whereas it is moderate in the other two cases, particularly for skylight with heliostat, which trend is almost flat after the minimum. The control of entering radiation reduces energy demand related to climatisation, especially during the warm season.

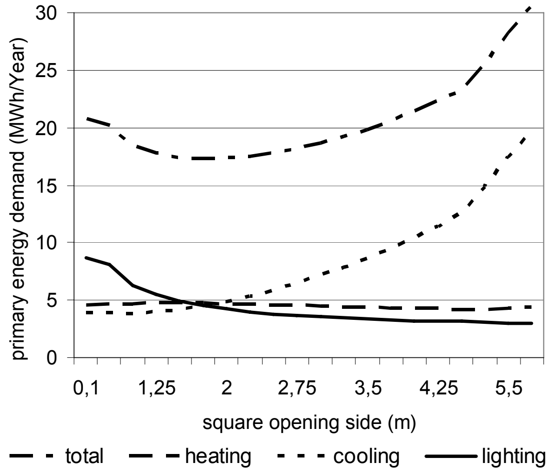


Figure 3: Venice, simple horizontal skylight, room's primary energy demand related to different final uses as function of top square opening's side length.

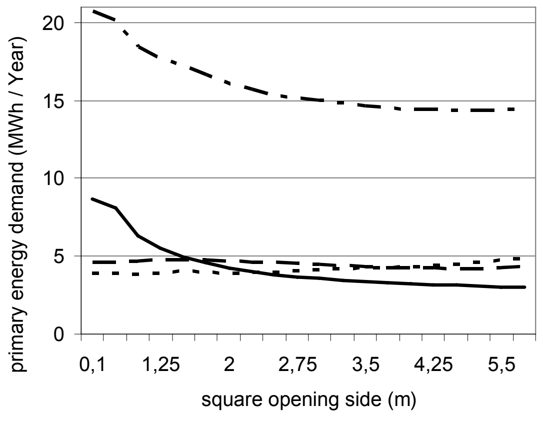


Figure 4: Venice, skylight with heliostat, room's primary energy demand related to different final uses as function of top square opening's side length.

The different position of the minimum point for each configuration is evident. Opening's optimal size is relatively small for skylight without control devices. In this case the length of square opening side is 1.5 m in the climate of Venice and 1.25 m in Trapani. Presence of control devices consents bigger side length values (almost double): less or more 3 m in Venice, 2 in Trapani. This allows to obtain a higher level of daylighting for longer periods and a more uniform illumination inside the room (Fig. 13-14).

Some considerations can be made analysing different components of energy demand.

a) Energy demand for heating is the less important component. Its entity is remarkable in Venetian climate only. This demand is bigger for device incorporating heliostat, in fact the bigger entering luminous flux provokes a lower internal gain from lamps.
b) Simple daylight presents the bigger energy demand for cooling, the other two configurations show less or more the same values. Comparing daylight with louvers and that incorporating heliostat, the second consent a small further economy due to the smaller thermal load from lamps, but only for little opening's size values. This difference disappears for bigger size values.
c) In presence of radiation control devices the entity of lighting energy demand is comparable with that one of cooling, but it presents an opposite trend: it decreases with increasing of opening's size. Differences between different configurations are appreciable only for reduced opening's size values. In fact the adopted control logic always allows the entrance of a luminous flux not lower than request.

For all the configurations, referring to the optimal size, the minimum value of total energy demand is situated in March, whereas the maximum one is between August and September (Fig. 5).

Because of internal gains, energy demand for cooling is present less or more during the entire year, except for January if we consider the simple skylight and January-February if we consider the other two configurations. Maximum cooling need is observable in July.

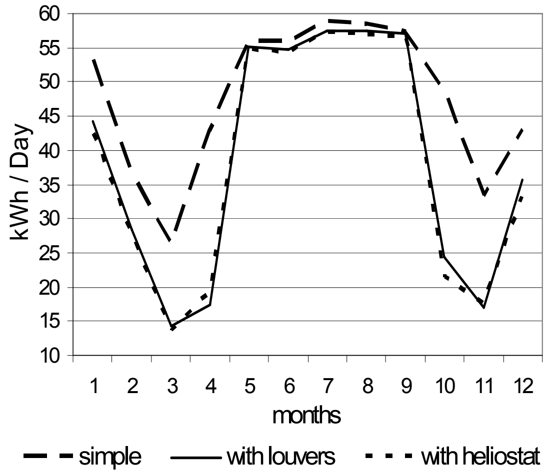


Figure 5: Venice, annual profile of room's daily total primary energy demand referring to the optimal size of each skylight typology.

Comparing device's behaviour in different Italian climates we can observe that total energy demand increases proceeding from North towards South. This is due to the greater consumptions for cooling that are the more influencing one. Referring to the opening's optimal size this consumption in Trapani are 7% bigger than in Roma and 30% respect to Venice. Contextually opening's optimal size decreases, as already observed.

From energetic point of views not big differences between configurations two and three are remarkable. Only for a reduced opening's size the heliostat allows a small economy respect to louvers: 1% in correspondence of common optimal size value, until 6% for smaller size. This economy is due to a smaller energy demand for illumination.

The bigger advantages of heliostat are due to the better quality of lighting: internal illumination is more uniform, as shown in the rendering (Fig. 14-15), and natural lighting is exploited for more time.

Considering the monetary costs of operating energy, rather than primary energy demand, the optimal size results a little reduced, but only in Venetian climate. In facts, except for heating, which is relevant only in Venice, the other two energy demand components require electricity.

3. THE PROPOSED DEVICE

The proposed device includes a heliostat with variable geometry and other reflecting surfaces, it allows to exploit direct or sky-diffuse solar radiation as function of season and weather conditions.

The entire metallic frame, supporting heliostat and other reflectors, can rotate around vertical axis to follows solar azimuth [5,6].

This structure is represented in upper part of Fig.1, in Fig. 6 and followings.

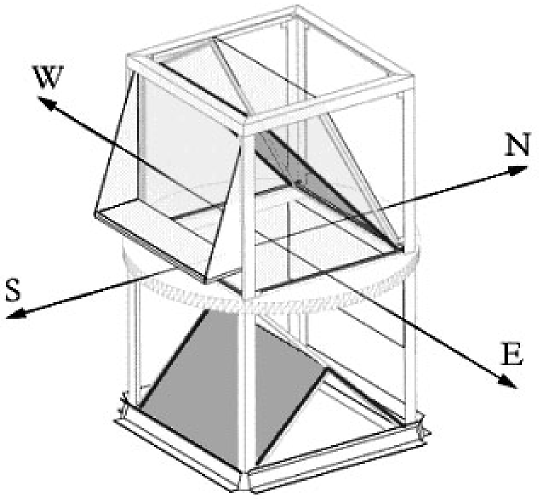


Figure 6: The moving frame, supporting heliostat and other reflectors, in Winter configuration (Venice. 21 Feb. 12:00 a.m.). The upper dark-grey surface is the heliostat's specular reflector, whereas the lower dark-grey surfaces are the diffusing/reflecting elements

The heliostat, that is the first reflector, is external to the room and it is contained in a double glazed envelope, this is composed by two clear glazing, 6 mm thick, spaced by 4 mm thick interstice. The profile of this envelope is evidenced in Fig. 13.

During the cold season the direct radiation, if present, impinges on the heliostat's specular reflector, and it is re-directed downward inside the room.

In the lower part of rotating frame two other plane surfaces redirect horizontally a rate of the radiation to the diffusing ceiling, and diffuse the rest downward over the visual tasks.

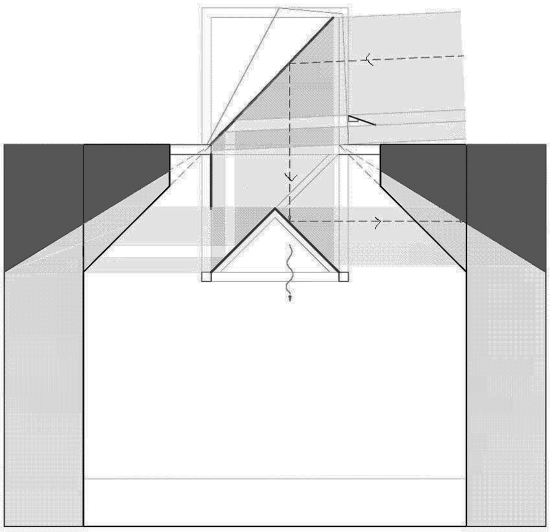


Figure 7: Venice. 21 February, 7:00 a.m.

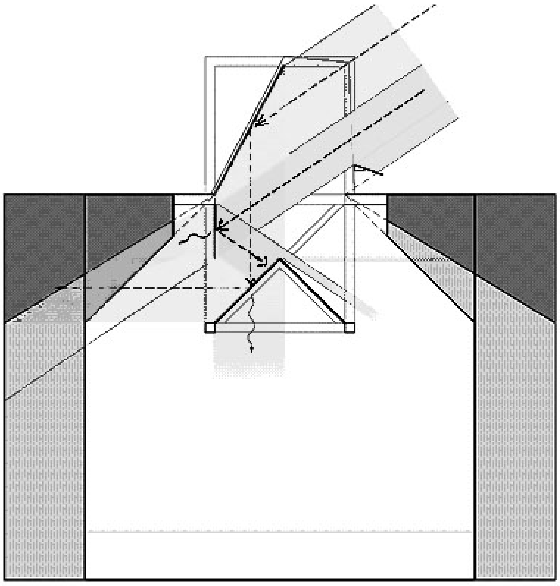


Figure 8: Venice. 21 February, 12:00 a.m..

The first reflector is a textile, reflecting on one side (reflection coefficient: 0.9) and absorbing on the other side. Its slope and its extension are adjustable, by means of movement of one extremity, as shown in Fig. 9-10.

The second reflector is a micro-perforated fabric, reflecting on its upper side (reflection coefficient: 0.8). The micro-holes allow a diffuse transmission of a rate of radiation to the other side (transmission coefficient:

0.12). From room's interior it appears translucent. It is composed by two surfaces with fixed inclination of 45° as shown in Fig. 6-7-8 and 11.

All these plane reflectors can by wrapped-up around one extremity when their presence is not requested. In cloudy days it is necessary to exploit the sky diffuse radiation, for this reason the two reflecting surfaces that would obstruct the opening are rolled up and they "disappear".

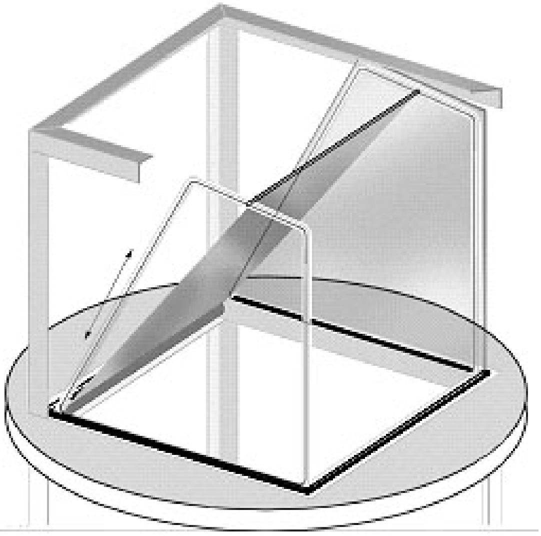


Figure 9: The guides allowing slope variations of the first reflector.

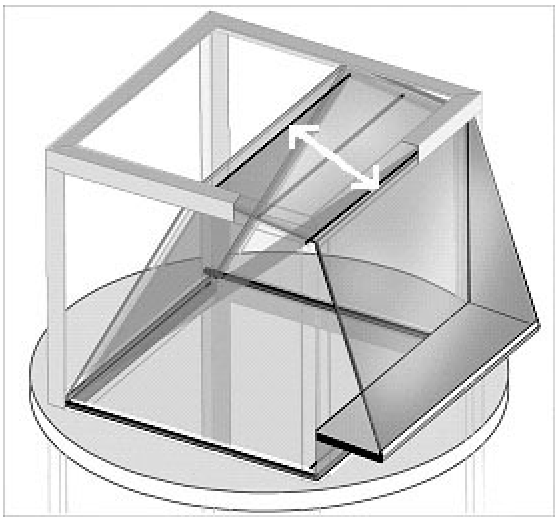


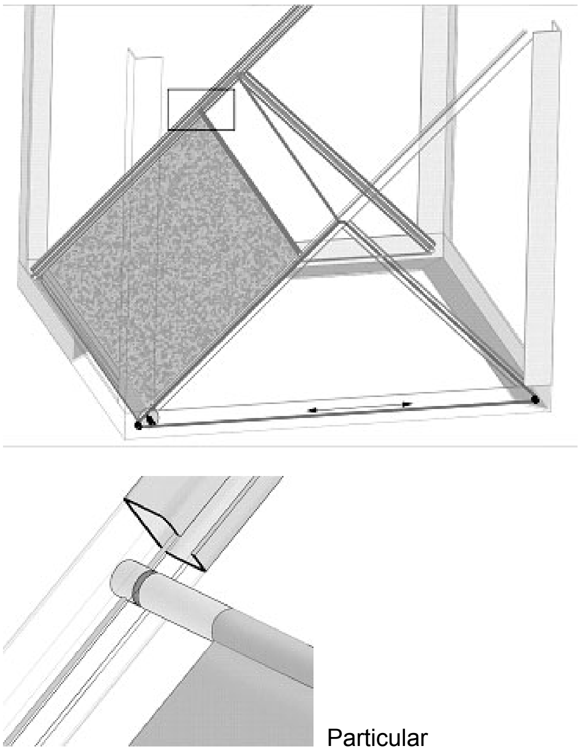
Figure 10: Slope variation of the first reflector.

During the warm season the device modifies its configuration rotating of 180° around its vertical axis. This way it exposes to the direct radiation an internal absorbing surface: the other side of the heliostat's reflector, and transforms itself in a plane air solar collector (Fig. 12).

The direct radiation impinging on the device is used to create a solar stack effect that can contribute to air extraction and room's natural ventilation. Warm exhaust air is purged throughout an opening on the device's top.

The opposite side of the absorbing surface (facing the interior of the room) is low-emissive (specular reflecting), this characteristic reduces the infra-red re-irradiation forward room's interior.

Device's side opposite to Sun direction, is transparent and allows the entrance of sky diffuse radiation.



Particular

Figure 11: Roll-up surfaces of second reflector

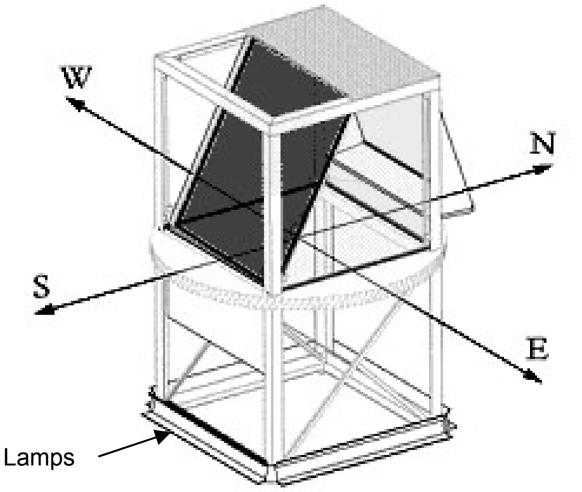


Figure 12: Device's summer configuration. (Venice 21 June 12 :00). The upper black surface is the backward side of the heliostat's reflector, that become the absorber. The lower reflecting/diffusing surfaces are rolled-up

Integrating lamps are disposed at the bottom of internal rotating structure of the heliostat and exploit the same diffused reflection on ceiling's plaster.

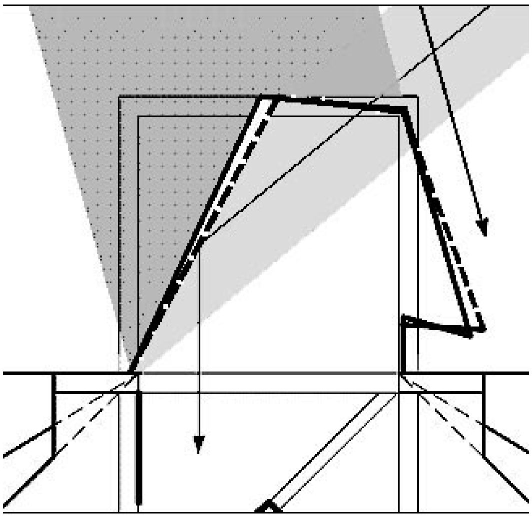


Figure 13: Optimal slope of external glazed surfaces for the climates of Venice (continuous line) and Trapani (dashed line).

The device is relatively simple from geometric point of views, being composed only by plane surfaces without concentrators. The aim of exploiting either direct or diffuse radiation requires a variable geometry; in this case it is obtained by using plane wrapable surfaces.

5. CONCLUSION

Devices controlling the entering solar radiation allow a sensible reduction of operating energy demand respect to a simple horizontal skylight.

Figure 14: Venice 21 February at 9.00 a.m. Internal luminance distribution with simple plane skylight

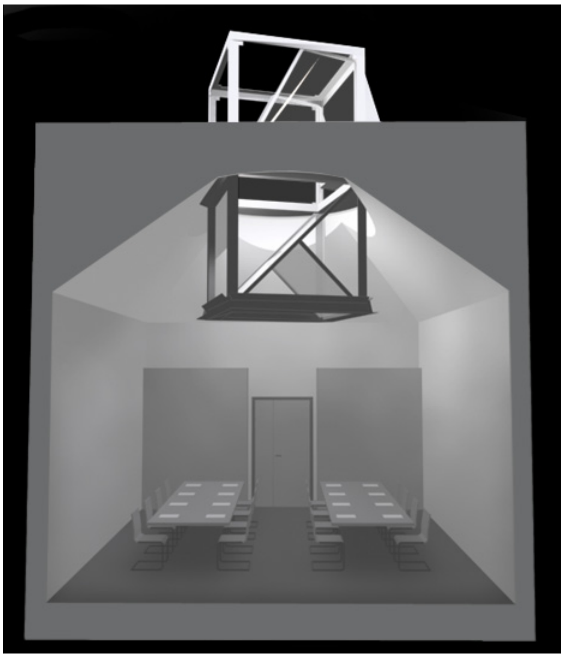


Figure 15: Venice 21 February at 9.00 a.m. Internal luminance distribution with skylight incorporating heliostat / proposed device

The energetic advantage of a device including a heliostat respect others more simple devices, like louvers, is not remarkable. The bigger advantage of the heliostat consists in a longer time of utilising daylighting and in a better quality of internal visual field.

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