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The approach to daylighting by scale models and sun and sky simulators: A case study for different shading systems

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Abstract

At the Daylighting Laboratory of the Politecnico di Torino a facility, which consists of a sun simulator and a sky scanning simulator, allows daylighting simulations to be made inside scale models for both research and design purposes. Photometric data and digital images of the luminous environment are the results that are obtained. The "sky" covers one-sixth of the vault, while the "sun" is fixed: therefore the model is rotated to reproduce the entire vault and rotated and tilted to reproduce the relative sun–Earth position.

In the paper the different components of the structure are shortly described, the possible fields of application are presented and, as an example of daylighting assessments, the results of a case study are reported. This latter is concerned with a comparative evaluation of different typologies of shading systems for South orientated façades for a sample high-school classroom: overhangs, external and internal + external light-shelves, horizontal fins are analysed, taking the effect of specular, semispecular and matt finishing also into account. For this purpose, reference conditions were assumed, both for sky conditions and sun positions, and repeated so as to compare environment performance which were obtained with the different shading systems.

Keywords: Daylighting; Sun simulator; Sky scanning simulator; Scale models; Shading systems

1. Introduction

The use of daylight in non-residential buildings has become an important strategy to improve environmental quality and energy efficiency by minimising artificial lighting consumption, heating and cooling loads. Daylighting design and building design should always be linked to each other, in one only creative process aimed at generating appropriate architectural and technical solutions while reducing building energy consumption [1].

In spite of this, daylighting strategies are seldom considered by architects or designers in the early stages of a building design: this is often due to a poor diffusion of daylighting simulation tools and also to a lack of simple tools, that are able to accurately predict the performance of daylighting systems exposed to lighting conditions, which vary continuously in distribution and intensity, according to the seasons, to hours of daylight and to specific climate conditions.

Two different approaches can usually be followed for accurate daylighting simulations: the use of computer simulations and simulations using scale models analysed either under real sun and sky conditions or under an artificial sun and sky. This paper is focused on the scale model-based approach and presents a facility which was realised for this purpose by the authors at the Politecnico di Torino: this consists of a sun simulator and a sky scanning simulator, which allow daylighting simulations to be made inside scale models for both research and design purposes. As a result, a prediction tool for both schematic design and design development is available for designers. Scale models, originating from design culture, are often used by architects to analyse design solutions in a three-dimensional physical representations, and provided that spaces are correctly modelled (as far as both the geometry and the photometric properties of the surfaces are concerned), they allow photometrically correct daylighting

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evaluations to be made as no scaling corrections are required for daylight [2–6].

Daylighting assessment can be carried out either under real sky or under artificial sky and sun conditions. If scale models are used under an artificial sky and sun (properly designed structures that enable daylighting conditions to be reproduced with artificial lamps and luminaires), it is possible to simulate the dynamic behaviour of daylight to allow a comparison of the environmental performance of different daylighting systems to be made: it is actually possible to maintain constancy and repeatability of the luminance distribution of a sky vault and the apparent movement of the sun, assessing a daylighting system with reference to the same daylighting conditions [7].

As far as the software-based approach is concerned, different kinds of simulation codes have been developed, able to both predict daylight quantities and also (usually) to produce renderings of a daylit environment [1,8–13]. The computer programs that are available are characterised by different levels of simulation accuracy and given output and range from simple ones to very accurate ones, which use radiosity and ray-tracing algorithms for the simulation of the interaction between light sources and surfaces [1,14–16].

Both computer simulations and physical simulations offer different possibilities and drawbacks which vary according to the characteristics of the code or the artificial sky/sun that is used, to the goals and to the characteristics of the case studies, etc. Various discussions on the topic have been presented by different authors in several publications [16–27].

The use of scale models under artificial skies offers the opportunity of using real materials, of having a visualisation of the real luminous environment (a possibility that is particularly appreciated by architects) and of simulating a greater number of sky conditions (when dome or scanning sky simulators are used) [4,14,28,29]. In general terms some of the drawbacks of this approach are related to:

- the costs involved in the construction of the model (when a detailed model is required) and in the transport of the model to centres where artificial skies are available,
- the time necessary to obtain a detailed model of a complex building and
- the difficulty of scaling some innovative materials (laser cut, prismatic panels, etc.).

Other drawbacks are connected to the type of artificial sky and sun and they can result in possible simulation errors [6,7,21,29].

The following sections are focused on the scale model-based approach and present the facility achieved for this purpose at Politecnico di Torino. Its potential applications as daylighting design tool are also presented, as well as a case study, concerned with a comparison of environment performance provided by different daylighting systems.

2. The sun and sky simulator facility at the Daylighting Laboratory of the Politecnico di Torino (IT)

Different types of artificial skies have been created in the past: mirror skies, dome skies, spotlight sky simulators or scanning skies, each of which is characterised by different advantages and disadvantages [21,30–39].

Comparing the potentialities and limits of each type of artificial sky, at the Daylighting Laboratory of the Politecnico di Torino, it was decided to design and build an artificial scanning sky, supplemented by an artificial sun. The facility was conceived not only for research purpose, but also (and especially) as a tool for designers (architects, engineers, lighting designers) to predict what way daylight can characterise outdoor and indoor environments, since it allows both physical quantities to be determined (illuminance and daylight factor (DF) values, spatial distribution of daylight over an indoor room) and to reproduce how a daylighted environment appears as well as the dynamic behaviour of sun penetration.

The components of the structure are described in the following part; further details on the technical features, as well as on the calibration and testing procedures, are reported in previous papers [22,40–42]. The facility consists of:

- *A sky scanning simulator*: This is based on the subdivision model of the sky hemisphere proposed by Tregenza for sky luminance measurements and which is assumed by the CIE in the IDMP (International Daylighting Measurement Programme) [43,44].

According to the model, the dome is subdivided into 145 circular areas, each of which is considered of uniform luminance. In the scanning sky simulator, the areas are simulated by means of circular luminaires located on a hemispherical surface according to the angular coordinates established by Tregenza. A structure with 25 luminaires, corresponding to one-sixth of the whole hemisphere (diameter equal to 7 m) was constructed (Fig. 1); real illuminance values inside models are obtained by adding the partial values measured for a six-step scan of the scale model situated in the centre of the hemisphere. The luminance distribution of the whole sky is obtained by opportunely varying the luminance of each luminaire for each rotation. This way, different sky conditions can be reproduced (overcast, clear and intermediate conditions) according to both standard models and real luminance values recorded at IDMP measuring stations.

Only one-sixth of the sky dome was physically constructed, so as to reduce both construction and maintenance costs, calibration problems and energy consumption. Furthermore, not having an overall dome reduces the error that is obtained when simulating the desired sky condition due to undesirable reflections on the opposite luminaires. For this reason, the walls are all

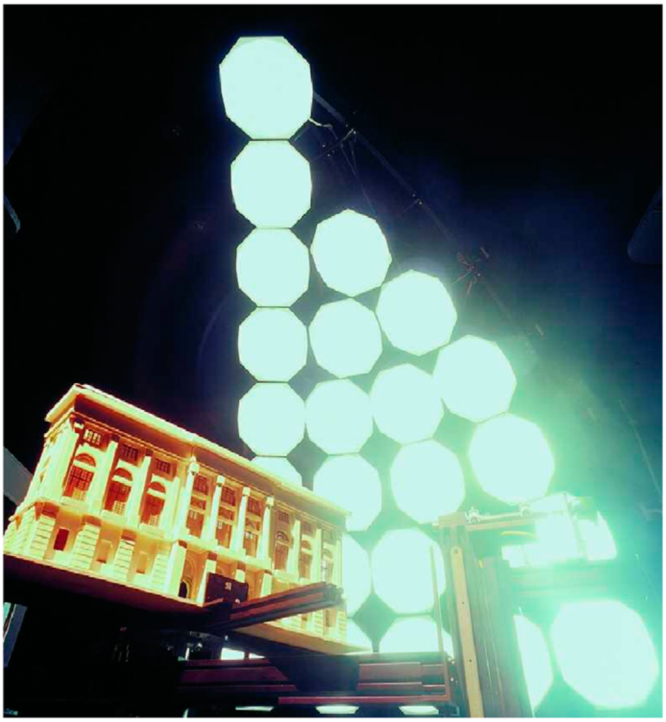

Fig. 1. The sky scanning simulator at the Daylighting Laboratory of the Politecnico di Torino.

painted black. Each luminaire is 0.67 m in diameter and is equipped with ten 26 W compact fluorescent lamps that are radially positioned, while the optics is composed of a specular aluminium reflector, a central specular aluminium cone and an opal polycarbonate diffuser, to increase the luminance uniformity of the luminaire surface. The light output fits a Lambert distribution and a uniform luminance distribution on the diffuser (standard deviation of the luminance values with respect to the mean value of less than 8%). Five electronic ballasts allow the light output to be controlled in the 100–3% range, therefore the corresponding average luminance approximately ranges from 6300 to 200 cd/m^2.

- *A sun simulator*: The sun is simulated by a theatre luminaire positioned 8 m away from the stand of the model. The optics was adequately modified so as to reproduce as much as possible the principal photometric characteristics of sunlight: a luminous beam characterised by parallel rays and a uniform value of illuminance on the plane of the model. A specific optic system was designed, which consists of two lenses with different bending (a 5 diopter condenser lens and a 2 diopter frontal lens). The projector is equipped with a 1200 W halogen lamp. As far as the model stand surface is concerned, the luminaire features an illuminance distribution that is characterised by a standard deviation to the mean value ratio of less than 8%. Furthermore, no significant shadows were observed on the same surface for the zenith sun position.
- *A structure to rotate and tilt the stand of the model*: A stand was located in the centre of the artificial sky vault to support and move the scale model. It is equipped with two step motors, which produce a rotation around the vertical axis (reproduction of the sun's azimuth angle) and a rotation around the horizontal axis (reproduction of the sun's elevation angle). Another movement is manually carried out by the user: this concerns the vertical translation of the plane on which the models rest, a movement that is useful to align the upper lintel of the window with the horizon line of the vault in order to reduce the error relative to the simulation of the horizon line.
- *A photometric data acquisition system*: A quantitative assessment of the lighting conditions is made by measuring illuminance values through 17 miniaturised probes (one of which is placed outside the model to measure the external unobstructed horizontal illuminance), which were specifically conceived to measure inside scale models. Each illuminance-meter is characterised by a reduced sensitive surface (3 mm in diameter) to minimise the scale error, a $V(\lambda)$ match lower than 3% and a directional error (cosine correction) lower than 1.5%.

Apart from quantitative measurements, the acquisition of digital images is also carried out, by means of a video camera that is placed inside the model and which is connected to the control unit. This instrument allows a qualitative analysis of the luminous environment.

- *A control unit*: A specifically developed software governs all the functions and procedures that are necessary to simulate sunlight and daylight: rotating and tilting the model, according to solar geometry equations that have been implemented in it; calculating the luminance values of the 145 circular areas into which the sky vault is subdivided; dimming the luminous flux output for each of the 25 luminaires; acquiring and elaborating photometric data and digital images.

Due to its characteristics, an artificial scanning sky presents some drawbacks:

- Because of the finite distance between the stand of the model and the portion of the dome, some scale errors may occur, especially when dealing with large models:
  - horizon line error [16,21],
  - parallax error, since different parts of the considered model receive different quantities of daylight and sunlight [45].
- Long time needed for carrying out a simulation with the sky scanning simulator, because of the six-step scan and the time of stabilisation (up to 15 min) taken by fluorescent lamps when dimmed passing from one vault's sector to next one.

3. Possible uses of the sun/sky simulator facility

The sun simulator and the sky scanning simulator built at the Daylighting Laboratory constitute a useful and user-friendly tool for daylighting design [22]. Main advantages for designers can be summarised as follows:

- Good adherence with real situations, since even complex buildings or interiors can be reproduced with great accuracy and hence analysed.
- Possibility of simulating different sky conditions, referring to both standardised daylighting models and real skies, experimentally measured.
- Possibility of getting out of the dynamic behaviour characterising a real sky. Actually, a particular luminance distribution and a sequence of sun positions may be repeated to allow comparing performance of different daylighting systems.
- Possibility to carry out an objective measurement of photometric data (quantitative evaluation).
- Possibility of carrying out a perceptive assessment of the daylighted environment (qualitative evaluation), by taking photographs of the indoor simulated environment.

Besides studies with different aims and on different scales can be carried out:

- *Site planning*: The dynamic variation of shadow patterns related to a particular site or a group of buildings can be studied.
- *Indoor environment*: Both the dynamic of sun penetration and the quantitative and qualitative aspects of the diffused luminous environment can be studied.
- *Daylighting systems*: Environmental performance of daylighting systems such as windows, skylights, shading devices, light pipes, etc., can be assessed (quantitative and qualitative evaluation) and their performance can be compared under the same daylighting conditions [41].

Since 2002, a number of different studies have been carried out at the Daylighting Laboratory, ranging from site planning to single indoor environments or daylighting components analysis.

Most studies carried out in the facility refer to one of the following categories:

- comparison of environmental performance of different daylighting systems (openings, glazed surfaces, shading devices),
- optimisation, during the design stage, of a specific daylighting system.

The different goals of the studies belonging to the two categories imply different procedures in the use of the scanning sky simulator.

For the comparative evaluation of different daylighting systems, models reproducing sample environments are used. Besides, reference conditions are assumed, both for sky conditions and sun positions, and repeated in order to compare environmental performance of the assessed systems. At present, for this category, most studies have been carried out to evaluate the performance of different shading systems (overhangs, vertical fins, Venetian blinds,

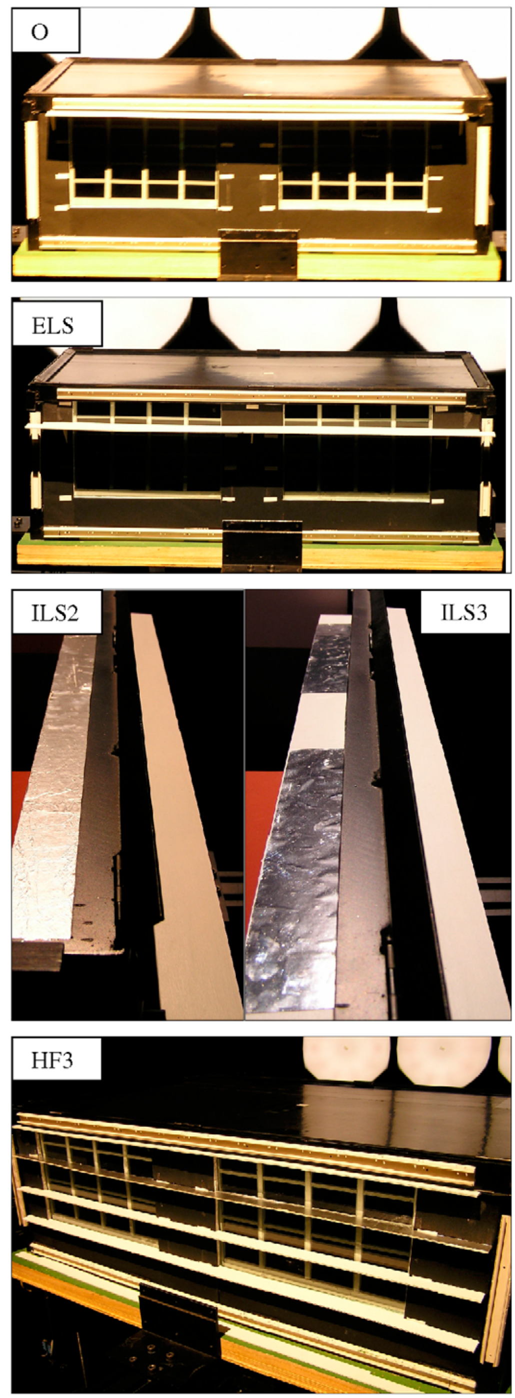

Fig. 2. Scale model reproducing a sample classroom equipped with different shading systems. From above to bottom: overhang, external light-shelf, external internal + light-shelf, horizontal fins. See Table 1 for legend.

light-shelves, PVC, wood or aluminium louvered screens) for both residential and non-residential environments (e.g. attics, offices, classrooms, etc.) [46–49].

The optimisation of a specific daylighting system is carried out during the building design stage and it is related to the distributive and photometric characteristics of the space for which the system has been conceived. At present, for this category, most studies have been carried out to optimise the design of shading systems such as mobile or fixed, matte or specular, continuous or micro-perforated louver shades [50,51].

4. Example of use of the sun/sky simulator facility: comparison of environment performance provided by different daylighting systems

As an example of application of experimental researches carried out by means of scale models under the sun and sky simulator facility, a specific case study, concerning the assessment of environmental performance of simple shading devices, is presented. To analyse daylighting conditions a scale model was achieved so as to reproduce a sample classroom, representative of typical real environments with regard to sizes, exposure, optical and chromatic internal surface properties and daylighting system typologies (unilateral side-lighting through vertical windows). For artificial sky and sun experimental activities purpose, the achieved model was 1:10 scale, featuring (Fig. 2):

- *Sizes*: Reproduced classroom is 9 m long, 6 m wide and 3 m height. Such sizes were determined according to technical specifications prescribed by architectural design handbook and guidelines for high school: resulting floor area ($54\,m^2$) and volume ($162\,m^3$) are representative a series of typical real classrooms.
- The 2 windows in the south wall, each of them 3 m wide and 2 m height, sill being 0.9 m from floor level; the openings have a clear 6 mm glass and a grey frame similar to the one characterising some real classrooms.
- *Internal surface colours and luminous reflectance values* (r_l): The ceiling is white painted ($r_l = 0.72$), walls have a lower part light blue painted ($r_l = 0.48$) and an upper part with an ivory-coloured finish ($r_l = 0.61$), while the floor is made of red brick ($r_l = 0.33$)
- *Internal surface optical properties*: All materials were assumed as Lambert diffusers.

Among all possible solutions, shading devices which were chosen for the south-oriented glazed wall consisted of both external and internal screens. Tested configurations are described in Table 1 and shown in Fig. 2. In particular, the performance of a simple overhang was compared to the

Table 1
Description of analysed shading system configurations

No.	Code	Description	SF[a]	
			Summer, June 21st	Winter, December 21st
1	O	Overhang – matt diffusing Reflectance = 0.7; depth = 0.6 m	55	88
2	ELS	External light-shelf — matt diffusing Reflectance = 0.7; positioned 0.55 m away from window's lintel Depth = 0.7 m	55	87
3	ILS1	Internal light-shelf — matt diffusing Reflectance = 0.7; positioned 0.55 m away from window's lintel Depth = 0.55 m	Not applicable	Not applicable
4	ILS2	Internal light-shelf — semispecular Reflectance = 0.9; positioned 0.55 m away from window's lintel Depth = 0.55 m	Not applicable	Not applicable
5	ILS3	Internal light-shelf — specular Reflectance = 0.9; positioned 0.55 m away from window's lintel Depth = 0.55 m	Not applicable	Not applicable
6	E+ILS1	External light-shelf + matt internal light-shelf See cases ELS and ILS1	55	87
7	E+ILS2	External light-shelf + semispecular internal light-shelf See cases ELS and ILS2	55	87
8	E+ILS3	External light-shelf + specular internal light-shelf See cases ELS and ILS3	55	87
9	HF1	Horizontal fins — matt diffusing Reflectance = 0.7; fins' spacing = 0.67 m; fins' depth = 0.2 m	53	88
10	HF3	Horizontal fins — matt diffusing + 1 specular Reflectance = 0.7/0.9; fins' spacing = 0.67 m; fins' depth = 0.2 m	53	88

[a]SF = Shading factor, defined as [52]: $SF = \frac{F_{s,b} \cdot I_b + F_{s,d} \cdot I_d + I_a}{I_b + I_d + I_a}$ (–). $F_{s,b}$ = sunlight fraction of the window in presence of direct radiation (–). $F_{d,b}$ = skylight fraction of the window in presence of direct radiation (–). I_b, I_d, I_a = direct irradiance, diffuse irradiance and irradiance reflected from the albedo incident onto the glazed surface (W/m^2).

one of other fixed screens (like external light-shelf, internal light-shelf, External-internal light-shelf and horizontal fins). The goal of improving daylight penetration in the rear part of unilateral side-lighted classroom was one of the criteria used to define the tested configurations. For this reason, different materials (matt, semispecular and specular) were tested as finishing on the upper part of internal light-shelves. The same were applied to one of the horizontal fin (finished in both a matt and a semispecular material).

Screens' size and position were determined in order to assure a comparable shading effect. For this reason, assumed configuration were characterised calculating the shading factor (SF) value [52] and the final geometry was set so as to have similar SF values (Table 1 and Fig. 3) and an efficient shading effect with respect to sun's position during the year. The SF values were determined both for the summer time (referring to June 21st and for winter time (referring to December 21st), based on monthly average irradiance data measured for the town of Turin [53].

As far as the experimental activity is concerned, two sets of measurement were carried out for each shading configuration.

The former involved the use of the artificial sky, aimed at quantitatively assessing the illuminance and DF values in correspondence of 16 points on the classroom's work plane (positioned at a height of 0.8 m from the floor) (Fig. 3).

Measurements were repeated referring to different sky conditions and different daylight availability: both a CIE clear sky and a CIE overcast sky were assumed as reference standard sky conditions, while to take daylight variation during the year into account both a winter condition (identified in December 21st, at noon) and a summer condition (June 21st, at noon) were simulated.

The latter experimental set involved the use of the artificial sun, aimed at qualitatively evaluating the dynamic penetration of the sun into the classroom for different periods of the year and within a single day. The analysis was carried out for two "extreme" sunlight

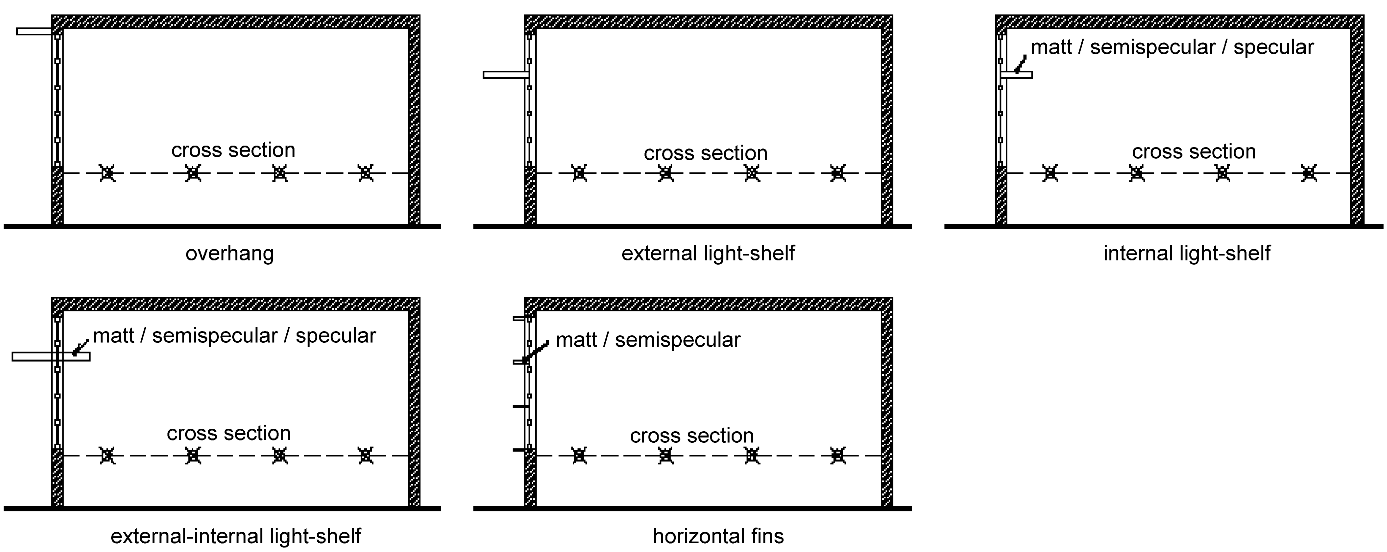

Fig. 3. Geometry and position of analysed shading systems.

Table 2
Average daylight factor, uniformity of distribution over the horizontal plane and relative difference of daylight quantity over the cross section (CIE overcast sky)

CIE overcast sky	O	ELS	ILS1	ILS2	ILS3	E + ILS1	E + ILS2	E + ILS3	HF1	HF3
DF_{av} (%)	2.54	2.68	3.46	3.51	3.56	2.45	2.52	2.54	2.86	2.96
$U = DF_{min}/DF_{av}$ (–)	0.33	0.40	0.30	0.31	0.31	0.38	0.39	0.38	0.39	0.38
Distance from window (m)	DF relative difference (referred to the overhang) (%) [a]									
0.75	0.00	0.02	51.47	53.04	53.19	−3.39	−1.67	−1.34	2.11	4.39
2.25	0.00	16.78	29.29	32.36	34.51	4.26	7.30	9.82	28.89	32.81
3.75	0.00	6.44	9.06	12.55	15.20	−11.74	−8.46	−5.73	17.56	20.26
5.25	0.00	27.76	21.47	23.75	26.84	10.54	12.72	15.64	29.98	30.82

[a]Daylight factor relative difference with respect to the overhang are calculated through the formula: $(DF_i - DF_O)/DF_O$. DF_i = daylight factor measured for each shading device. DF_O = daylight factor measured with the overhang.

Table 3
Average Illuminance, uniformity of distribution over the horizontal plane and relative difference of daylight quantity over the cross section (CIE clear sky – December 21st)

CIE clear sky December, 21st—noon	O	ELS	ILS1	ILS2	ILS3	E+ILS1	E+ILS2	E+ILS3	HF1	HF3
E_{av} (lux)	4089	3883	4564	4625	4669	3535	3704	3752	3932	4023
$U = E_{min}/E_{av}$ (–)	0.54	0.62	0.54	0.52	0.53	0.59	0.57	0.58	0.60	0.59
Distance from window (m)	E relative difference (referred to the overhang) (%) [a]									
0.75	0.00	−11.06	13.36	14.89	15.09	−11.96	−10.18	−9.99	−12.90	−10.17
2.25	0.00	−3.99	13.37	15.76	17.23	−10.18	−8.04	−6.35	1.58	3.81
3.75	0.00	−8.22	1.96	3.71	5.57	−19.30	−17.53	−15.57	−3.02	−2.88
5.25	0.00	9.64	10.19	9.96	12.06	−4.78	−5.04	−2.94	7.84	8.26

[a]Illuminance relative difference with respect to the overhang are calculated through the formula: $(E_i - E_O)/E_O$. E_i = illuminance measured for each shading device. E_O = illuminance measured with the overhang.

Table 4
Average Illuminance, uniformity of distribution over the horizontal plane and relative difference of daylight quantity over the cross section (CIE clear sky—June 21st)

CIE clear sky June, 21st—noon	O	ELS	ILS1	ILS2	ILS3	E+ILS1	E+ILS2	E+ILS3	HF1	HF3
E_{av} (lux)	1682	1637	2142	2174	2203	1472	1552	1571	1715	1748
$U = E_{min}/E_{av}$ (–)	0.43	0.50	0.38	0.39	0.39	0.49	0.48	0.48	0.48	0.48
Distance from window (m)	E relative difference (referred to the overhang) (%) [a]									
0.75	0.00	−9.91	40.35	41.53	42.44	−14.08	−12.19	−11.78	−6.46	−4.62
2.25	0.00	2.79	17.50	20.07	21.73	−8.06	−3.92	−2.10	10.48	13.92
3.75	0.00	−2.31	4.47	6.07	8.06	−13.90	−12.01	−10.06	4.16	6.06
5.25	0.00	11.90	12.08	12.85	14.87	−1.22	−0.05	1.77	12.34	14.70

[a]Illuminance relative difference with respect to the overhang are calculated through the formula: $(E_i - E_O)/E_O$. E_i = illuminance measured for each shading device. E_O = illuminance measured with the overhang.

conditions: a winter day (December 21st and a summer day (June 21st), respectively, characterised by lowest and highest sun's elevation angles with respect to the annual solar dynamic behaviour. For both days, sunlight penetration was assessed at different hours: 9 a.m. noon (solar radiation coming from east), noon (solar radiation coming from south) and 4 p.m. (solar radiation coming from west).

4.1. Results

The luminous environmental performance of tested shading devices were assessed by means of different quantitative and qualitative information elaborated from the data collected during the simulations carried out using separately the diffused and direct daylight components.

4.1.1. Daylight diffused component

Positioning 16 illuminance detectors over an horizontal plane 0.8 m from the floor allowed calculating different daylighting metrics: average DF (DF_{av}), average illuminances (E_{av}), uniformity of illuminance distribution U (determined as DF_{min}/DF_{av} and E_{min}/E_{av}) and profiles along a cross section of the horizontal plane. The results which were obtained, referred to considered sky conditions and periods of the year, are shown in Tables 2–4 and in Figs. 4, 5. The following considerations and trends could be drawn from result analysis:

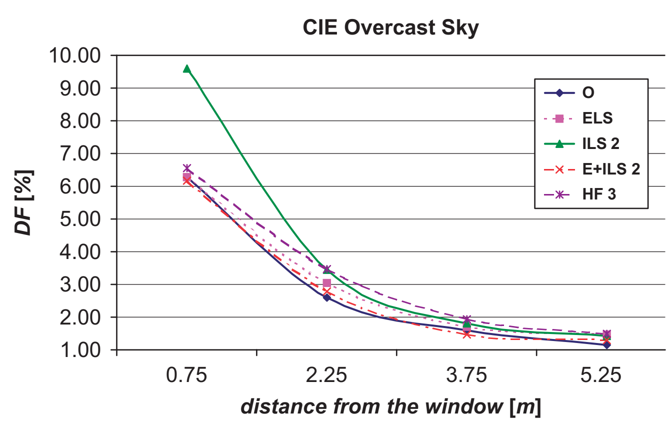

Fig. 4. Daylight factor values measured along a cross section (reference condition: CIE Overcast Sky).

- Although the shading devices were designed to have the same SF, they necessarily led to different internal daylight availability (average DF value) and distribution.

The internal light-shelf only ensured an average DF higher than 3%, while for the other devices a DF_{av} within 2.45% and 2.96% was found, with a better performance for the horizontal fins and a worse for the overhang and the external + internal light-shelves.

- In clear sky conditions, the highest average illuminance values were observed with the internal light-shelves, intermediate and similar values with the overhang and the horizontal fins and lower values respectively with the external light-shelf and the external + internal light-shelves.
- The uniformity of daylight distribution over the horizontal plane was quite similar for the external light-shelf, the external + internal light-shelves and the horizontal fins, while it was reduced if the overhang or the internal light-shelf were used.
- The light penetration towards the rear part of the classroom and the uniformity of distribution along the cross section (assessed for each point along the section in terms of Daylight Factor or illuminance relative difference with respect to the performance of the overhang—Tables 2–4—and by observing the graphical representation of Fig. 4, 5) were higher for the horizontal fins and the external light-shelf, and respectively, lower for the external + internal light-shelves, the overhang and the internal light-shelves.

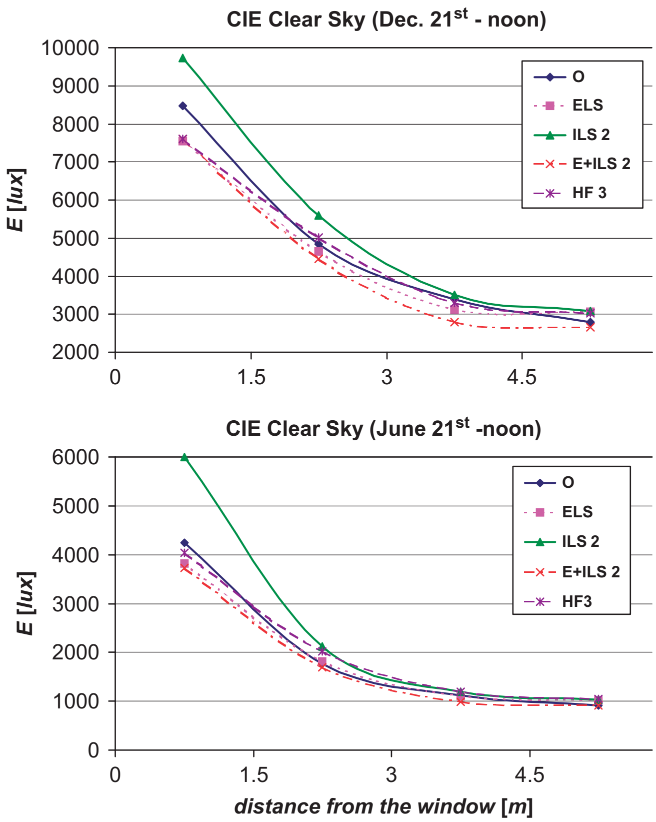

Fig. 5. Illuminance values measured along the cross section (reference condition: CIE Clear Sky).

Even if similar trends of performance can be observed for the different sky conditions and periods of the year, different absolute values emerge due to the different luminance distribution of the sky vault (Tables 2–4 and Figs. 4, 5).

4.1.2. Sunlight direct component

Digital pictures taken inside the model to analyse the sunlight presence and position within the room were the

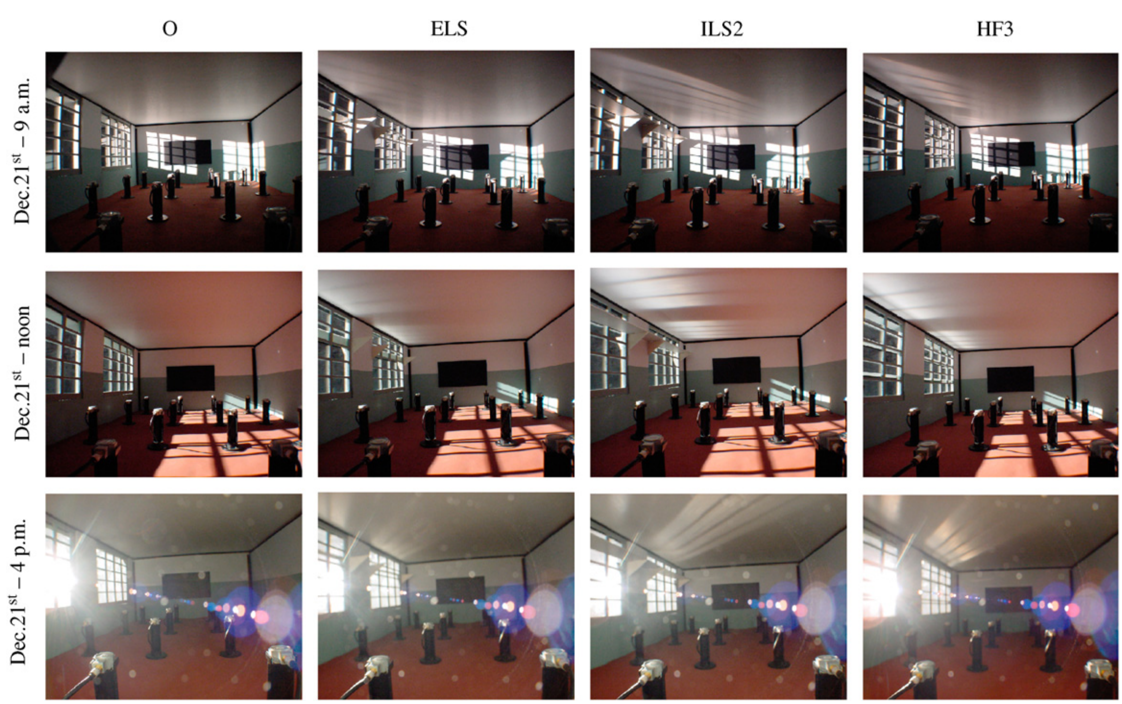

Fig. 6. Example of direct sunlight penetration.

Fig. 7. Effect on light distribution on the ceiling produced by different finishing of the internal light-shelf.

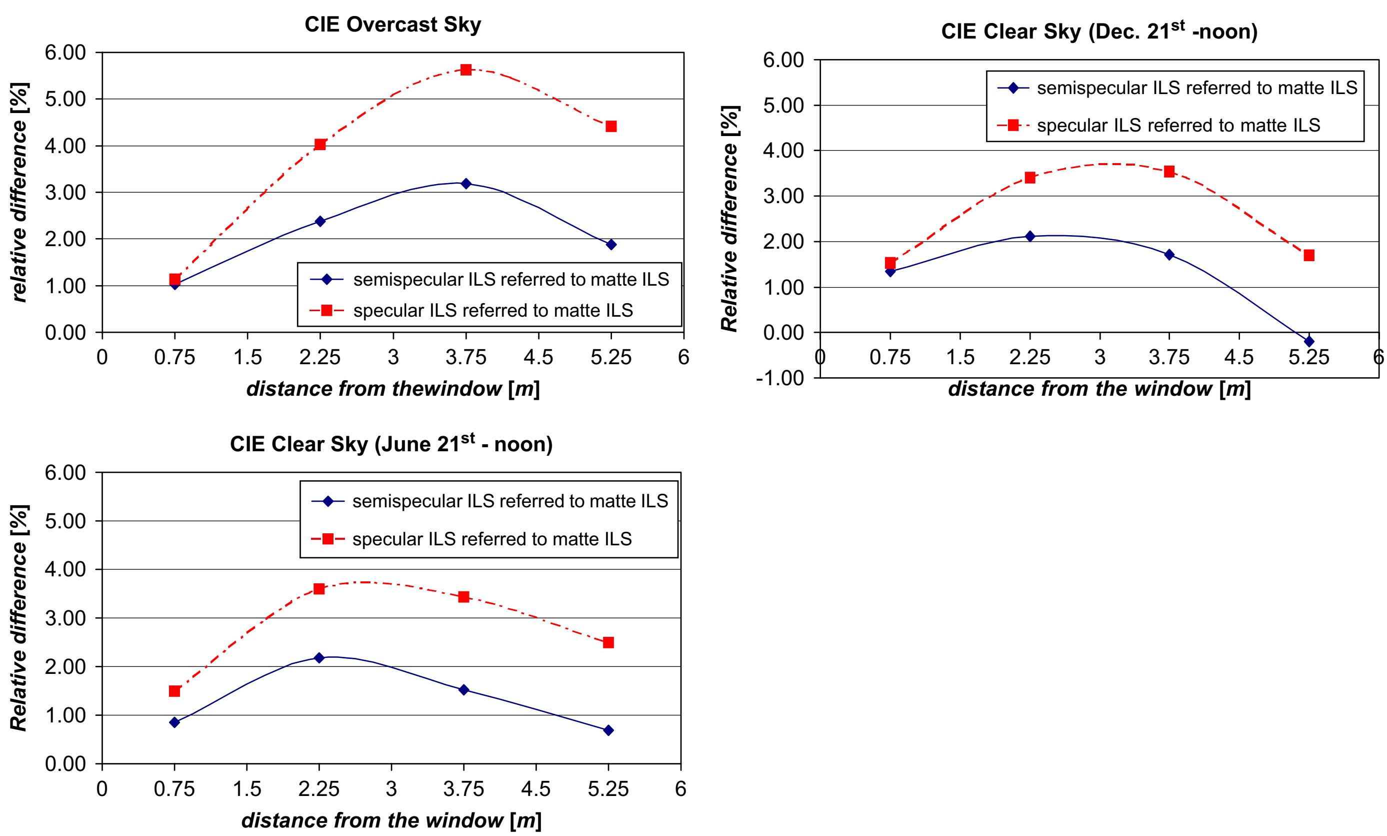

Fig. 8. Illuminance relative difference obtained with semispecular and specular finishing referred to matt finishing.

collected results. A sample of sunlight penetration produced by the different shading devices during the 21st of December at different hours of the day is presented in Fig. 6. With the exception of internal light-shelves the images which were taken showed that tested shading devices provide an effective protection from direct sunlight in summer period (June 21st) (no direct sunlight observed inside the model).

The use of specular or semispecular finishing for the upper part of internal light-shelves and horizontal fins seemed to produce a general increase of illuminance on the horizontal plane inside the model (Tables 2–4). Furthermore, it differently contributed to increase daylight penetration in the centre and rear part of the model, as shown in Fig. 7.

The effect of different finishing was also perceptible in the images taken during sunlight simulations (Figs.7, 8).

5. Conclusions

The paper describes the potential applications of a facility, which consists of a sun simulator and of as sky scanning simulator, for daylighting design and research through scale models. Accurate simulation of different daylight conditions (both standard or experimental), quantitative and qualitative evaluations of lighting environmental performances and definition of daylighting systems' geometric and photometric characteristics can be carried out through this approach. This is therefore conceived as an alternative prediction tool to a numerical simulation-based approach for daylighting design.

An exhaustive example, concerning the comparison of lighting environmental performances of different traditional shading devices, is presented. These were designed to ensure an equal energy performance (similar SF values for both summer and winter period) and applied to the model of a sample classroom and tested under the artificial sun and sky facility. Results obtained through the simulations of different sky conditions and sun paths show the differences in the lighting performances, emphasising in particular best results for the horizontal fins and the external light-shelf (considering daylight quantity, daylight penetration and uniformity over the cross section as evaluation criteria).

The features of the simulation facility allowed also the assessment of the quantitative and qualitative effect of different shading finishing. Specular and semispecular finishing used for internal light-shelves always produced higher illuminances and contributed to increase daylight penetration towards the rear part of the room. Nevertheless, the pictures which were taken during the sunlight simulation showed that such finishing, and in particular the specular one, created high luminance areas on the ceiling when reached by direct sunlight, hence resulting in a potential cause of discomfort glare.

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References

[1] IEA (International Energy Agency). Daylighting in buildings. IEA SHC Task 21/ECBCS Annex 29 Final Report, 2000.
[2] Hopkinson RG, Petherbridge P, Longmore J. Daylighting. London; Heinemann; 1966.
[3] Moore F. Concepts and practice of architectural daylighting. New York: Van Nostrand Reinhold Company; 1985.
[4] Robbins CL. Daylighting-design and analysis. New York: Van Nostrand Reinhold Company; 1986.
[5] Cannon-Brookes SWA. A study of the use of scale models in the daylighting design of museums. Proceedings CIBSE national lighting conference, Cambridge; 1994. p. 238–46.
[6] Cannon-Brookes SWA. Simple scale models for daylighting design: analysis of source of errors in illuminance prediction. Lighting Research & Technology 1997; 29 (3): 135–42.
[7] Littlefair P, Lindsay CR. Scale models and artificial skies in daylighting studies. Technical Note 90/3, BEPAC (Building Environmental Performance Assessment Club); 1999.
[8] Erhorn H, De Boer J, Dirksmoller M. ADELINE—An integrated approach to lighting simulation. Proceedings of international daylighting conference "Daylighting '98", Ottawa, Ont., Canada; 1998.
[9] ⟨http://eetd.lbl.gov/btd/tools/superlite/superlite2.html⟩.
[10] Ward Larson G, Shakespeare R. Rendering with Radiance: the art and science of lighting visualisation. San Francisco: Morgan Kaufmann; 1998.
[11] ⟨http://www.lightscape.com⟩.
[12] ⟨http://lesowww.epfl.ch/anglais/Leso_a_frame_sof.html⟩.
[13] ⟨http://www.lighting-technologies.com⟩.
[14] Baker N, Fanchiotti A, Steemers K. Daylight in architecture. A European reference book. London: James and James Ltd, for the Commission of the European Communities; 1993.
[15] IEA (International Energy Agency). Validation of daylighting computer programs. IEA SHC Task 21/ECBCS Annex 29 Final Report; 1999.
[16] Roy GG. A comparative study of lighting simulation packages suitable for use in architectural design. Perth: Murdoch University, School of Engineering; 2000.
[17] Ubbelohde MS, Humann C. Comparative evaluation of four daylighting software programs. At ⟨http://www.coolshadow.com/downloads/ACEE%20daylighting.pdf⟩.
[18] Khodulev AB, Kopylov EA. Physically accurate lighting simulations in computer graphics software. Moscow; 1996.
[19] Galasiu AD, Atif MR. Application of daylighting computer modelling in real case studies: comparison between measured and simulated daylighting availability and lighting consumption. NRC (National Research Council Canada) document NRCC-42862, in IEA (International Energy Agency) Task 21/Annex 29; 1998.
[20] EPFL (Ecole Polytechnique Fédérale de Lausanne). Laboratoire de lumière naturelle. Ecole Polytechnique Fédérale de Lausanne, Lausanne; 1998.
[21] Pellegrino A, Lo Verso VRM. La simulazione dell'illuminazione naturale mediante cieli artificiali: rassegna delle strutture esistenti. Proceedings AIDI (Associazione Italiana di Illuminazione) national lighting conference, Genoa, November 1999. p. 25–6.
[22] Filippi M, Aghemo C, Pellegrino A, Lo Verso VRM. Realisation and testing of a portioned dome artificial sky. Proceedings CLIMA 2000 world congress, Napoli, September 2001. p. 15–8.
[23] Mardaljevic J. Validation of a lighting simulation program under real sky conditions. Lighting Research & Technology 1995;27(4):181–8.
[24] Mardaljevic J. The BRE-IDMP dataset: a new benchmark for the validation of illuminance prediction techniques. Lighting Research & Technology 2001;33(2):117–36.
[25] Maamari F, Fontoynont M. Analytical tests for investigating the accuracy of lighting programs. Lighting Research & Technology 2003;35(3):225–42.
[26] Reinhart CF, Fitz A. Key findings from an online survey on the use of daylight simulation programs. NRC (National Research Council Canada) document NRCC-46897; 2004, at ⟨http://irc.nrc-cnrc.gc.ca/fulltext/nrcc46897/⟩.
[27] Reinhart CF, Fitz A. Findings from a survey on the current use of daylight simulations during building design. Energy & Buildings 2006;38(7):824–35.
[28] Michel L. Méthode expérimentale of évaluation des performance lumineuses de bâtiments. PhD thesis no. 2042, Département d'architecture. Ecole Polytechnique Fédérale de Lausanne, Lausanne; 1999.
[29] Navvab M. New developments in scale model photometry techniques for interior lighting. Proceedings CIE session "Daylight and solar radiation measurement", Berlin, Germany, October, 1989. p. 9–11.
[30] Littlefair P. Design with innovative daylighting. Building Research Establishment Report, Garston (UK); 1996.
[31] Bietry J. Division Eclairage et Colorimetrie. CSTB (Centre Scientifique et Technique du Bâtiment) Report, Nantes; 1986.
[32] ⟨ http://www.northwestlighting.com/daylighting/index.html⟩.
[33] ⟨http://eande.lbl.gov/CBS/NEWSLETTER/NL4/Skysimulator.html⟩.
[34] ⟨http://taz.tamu.edu/energy/daylight.html⟩.
[35] Szerman M. Daylighting model measurements within the IEA Task XI Project. Proceedings CIE session "Daylight and solar radiation measurement", Berlin, October 1989. p. 9–11.

[36] ⟨http://www.lichtlabor.com ⟩.
[37] ⟨http://www.cf.ac.uk/uwcc/archi/research/sky.html⟩.
[38] ⟨http://www.bartlett.ucl.ac.uk/sky/sky.htm⟩.
[39] Michel L, Roecker C, Scartezzini JL. Performance of a new sky scanning simulator. Lighting Research & Technology 1995;27(4):197–205.
[40] Filippi M, Aghemo C, Pellegrino A, Lo Verso VRM. Daylighting design through the use of an artificial sky. Proceedings of light 2001 Slovak international conference, Strbske Pleso High Tatras (Slovak Republic), October 2001. p. 10–12.
[41] Aghemo C, Pellegrino A, Lo Verso VRM. Scale models under an artificial sky as tool for daylighting design: possible applications. Proceedings of CIE light & lighting 2002 international conference, Bucuresti (Romania), November 2002. p. 28–30.
[42] Lo Verso VRM. La simulazione dell'illuminazione naturale mediante cieli artificiali. PhD thesis, Faculty of Engineering, University of Genoa, Genoa, Italy, 2002.
[43] Tregenza PR. Subdivision of the sky hemisphere for luminance measurement. Lighting Research & Technology 1987;19(1):13.
[44] ⟨http://www.idmp.entpe.fr⟩.
[45] Mardaljevic J. Quantification of parallax errors in sky simulator domes for clear sky conditions. Lighting Research & Technology 2002;34(4):313–32.
[46] Manco P. Valutazione di sistemi di controllo della luce naturale su modelli in scala. Sperimentazioni con sole e cielo artificiali. Degree thesis, Department of Energetics, Faculty of Architecture, Politecnico di Torino; 2001.
[47] Blaso L. Il progetto della luce naturale in modelli in scala in cieli artificiali: applicazione alla tipologia edilizia delle mansarde. Degree thesis, Department of Energetics, Faculty of Architecture, Politecnico di Torino; 2003.
[48] Ravasio I. La tipologia ''mansarde'' nell'architettura del passato e del futuro: analisi tipologica e prestazionale. Degree thesis, Department of Energetics, Faculty of Architecture, Politecnico di Torino; 2004.
[49] Aghemo C, Pellegrino A, Lo Verso VRM. La progettazione dell'illuminazione naturale mediante l'uso di modelli in scala in cielo artificiale: possibili applicazioni. Proceedings of AIDI (Italian Association on Lighting) international lighting conference 2002, Perugia, Italy, December 2002. p. 4–6.
[50] Capoccetti F. La simulazione dell'illuminazione naturale: utilizzo del cielo artificiale per il progetto di una biblioteca. Degree thesis, Department of Energetics, Faculty of Architecture, Politecnico di Torino; 2004.
[51] Aghemo C, Filippi M, Pellegrino A, Lo Verso VRM. Il progetto di sistemi di illuminazione naturale attraverso l'uso di un cielo artificiale. Frames 2004;108:40–5.
[52] CEN (Comité Européen de Normalisation), European Standard EN ISO 13790, Thermal performance of buildings—Calculation of energy use for heating; 2004.
[53] CNR-PFE (Consiglio Nazionale Ricerche—Progetto Finanziato Ricerca). Dati climatici per la progettazione edile ed impiantistica. CNR, Roma; 1982.