

INDOOR DAYLIGHTING: ASSESSMENT OF THE PERFORMANCES OF DIFFERENT WINDOW OPTIONS

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Summary. The article shows the results of a case study dealing with indoor daylighting concepts and practice. The analysis evaluates the performances of different window options taking into account quantitative and qualitative aspects such as daylight factor, uniformity ratio of illuminance, and daylighting glare index.

1. Introduction

Architectural daylighting can be investigated under several aspects.

Windows are often considered a mere architectural element of the building envelope regarding to compositive and technological aspects rather than a design feature modelling daylight, allowing view, and dealing with psychological and economical aspects (fig. 1).

A correct use of apertures can be a powerful vehicle for determining indoor environment. Daylight moves, changes character and varies with the weather providing building a living quality unachievable with any other design element. It can also be used as a minor design element adding visual impact to a corner, highlighting a piece of sculpture etc.

Architectural daylighting changed through centuries responding to functional requirements, technological opportunities and cultural influences. Throughout most of architectural history, daylight has been the primary source of light, supplemented by burned fuels. The quantity of light and the aperture dimensions are influenced by the need to moderate the outdoor environment by means of a sealed building envelope.

In addition to illumination, daylight has been symbolic of cleanliness, purity, knowledge, haven, and thus suitable for religious purposes. [1]

The Pantheon in Rome, is a typical example of open dome construction which allows daylight to enter the inside through an unglazed opening in the dome (fig. 2).



Fig. 1 - Gaudí. Batllò House, Barcellona (1905 -1907)

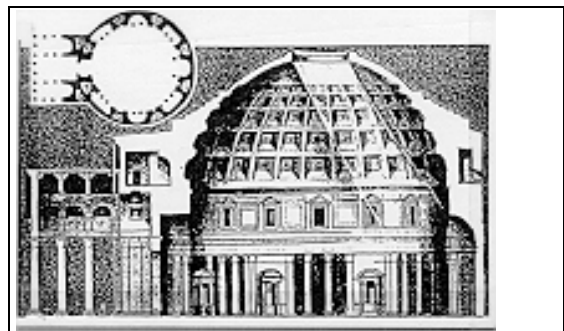


Fig.2 - The Pantheon, Rome: the unglazed skylight

It was the industrial revolution that brought the most rapid changes in both requirements and solutions for daylighting. With the innovations developed during this period, buildings became free from the constraints that had forever determined their forms. The larger openings permitted by the use of a structural high-strength steel frame increased access to daylight illumination around the perimeter of the building. On the other hand this fact was accompanied by the potential for increased glare, winter heat loss, and summer solar gain. The thermal qualities of the earlier, more massive construction were lost.

Considerable advances in artificial lighting and new heating and cooling systems allowed a free use of the window element not always rational.

In recent years a great deal of recognition has been given to the contribution that daylight can make to energy conservation in buildings. The interest in efficiency, social and behavioural issues lead to a detailed daylighting project.

Energy conscious design, should consider daylight both as an art and a science, a design element

and an environmental system (fig. 3). As a design element daylight can enhance aesthetic and qualitative aspects of a building; as an environmental system it should be subjected to a rigorous quantitative analysis.

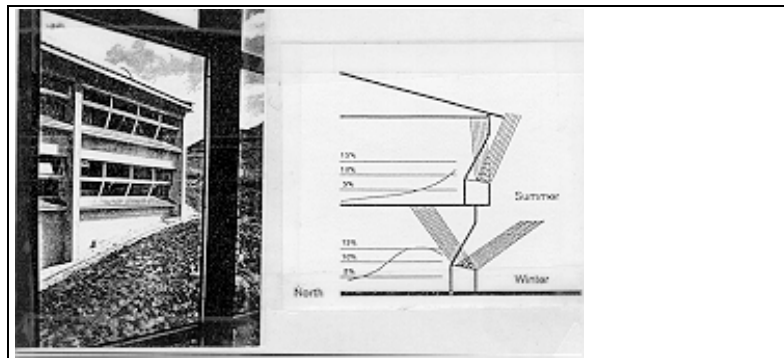


Fig.3 - Advanced daylighting system [2]

2. Daylight project

There are many reasons that justify considering daylighting as a useful light source in almost every type of buildings. Primarily because of:

- the quality of light
- the importance of daylight as a design element
- the communication channels to the outside provided by daylight apertures
- the energy conservation resulting from the use of daylight as a primary or secondary illuminant
- the psychological and physiological benefits not obtainable with electric lighting or windowless buildings. [3]

Hence, a daylight system choice should be related both to quantitative and qualitative issues. To make a rational use of daylight it is necessary to ensure that enough light is allowed to enter the window taking into account visual comfort requirements and psychological and emotional aspects.

The daylight illumination in an interior can be expressed either in absolute terms as an illuminance value in lux, or better, because of the variability of external daylight conditions, as a percentage of the total daylight availability available from the whole unobstructed sky. This percentage is called daylight factor.

Introduced in England in the sixties as a performance index of a daylighting system, Daylight Factor has been defined by Hopkinson, Petherbridge and Longmore as “the ratio of the daylight illumination at a point on a given plane due to the light received directly or indirectly from a sky of assumed or known luminance distribution, to the illumination on a horizontal plane due to an unobstructed hemisphere of this sky. Direct sunlight is excluded for both values of illumination. (...) The definition also accepts any distribution of luminance of the sky and therefore refers to the ratio of the internal to the external illumination at a given point in time”. [4]

Daylight factor may consist of three components:

$$DF = \frac{SC + ERC + IRC}{E_o}$$

DF = Daylight Factor

SC = Sky Component; light reaching a point in a room directly from the sky

ERC = Externally Reflected Component; light reaching a point directly after reflection from an external surface

IRC = Internally Reflected Component; light reaching a point after reflections from surfaces within the room

E_o = External horizontal illuminance from an unobstructed sky without direct solar radiation

Many methods exist for finding the components for a specific given point, though they are checking procedures rather than ones which generate a daylighting design.

Partly for this reason, an average daylight factor has been proposed as a design parameter. It represents the three components calculated simultaneously and it can be made the basis of window sizing, enabling daylighting to take a place in the overall design process.

Technical recommendations and Standards defining daylighting design parameters and minimum values have been drawn up independently for each country.

For example, British Standards settle minimum average daylight factors related to different activities and to supplementary electric lighting (tab. 1). They also give recommendations for checking daylight uniformity (tab. 2).

Tab. 1 - Daylighting recommendations in some workplaces [5]

Activity / Space	Type of daylighting (*)	DF (%)
Teaching	A	5
	B	2
General offices	A	5
	B	2
Laboratories	A	5
	B	2
Drawing offices	A	5
	B	1 (in supplemented area)

(*) A - Full daylighting / B - Supplemented daylighting

Tab 2 - Recommendation on daylight uniformity [6]

BS 8206/92	<p>a) no significant part of the working plane shall lie beyond the no-sky line</p> <p>b) in an interior with one or more windows on one wall only room depth shall not exceed window height and width</p> <p>c) in an interior with rooflights, the spacing/height ratio should not be too great</p> <p>d) in an interior with rooflights, ceiling and floor reflectances should be high enough</p>
BS CP 3/64	$DF_{\max}/DF_{\min} < 2$

The following expression is recommended for estimating average daylight factor [7] [8]:

$$DF_m = \frac{A_w \cdot t \cdot \theta}{A_{\text{tot}}(1 - r_m^2)}$$

where: DF_m = average Daylight Factor
 A_w = total glazed area of windows
 t = glass transmittance
 θ = angle of visible sky
 A_{tot} = total area of all the room surfaces
 r_m = area-weighted average reflectance of room surfaces

In 1967 an Italian Regulation defines average daylight factor as a unique daylight project parameter using the following formula [9]:

$$DF_m = \frac{A_w \cdot t \cdot \varepsilon}{A_{\text{tot}}(1 - r_m)}$$

where: DF_m = average Daylight Factor
 A_w = total glazed area of windows
 t = glass transmittance
 ε = window factor
 A_{tot} = total area of all the room surfaces
 r_m = area-weighted average reflectance of room surfaces

The recommended minimum average daylight factors for residential and non-domestic buildings suggested in [10][11][12][13] are listed in the table below (tab. 3)

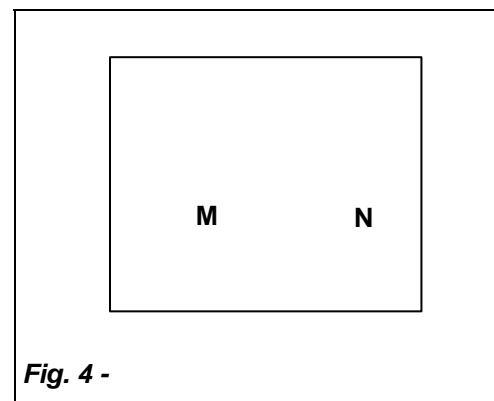
Tab. 3 - Recommended average daylight factors for residential buildings, schools and hospitals [14]

	$DF_m \geq 1\%$	$DF_m \geq 2\%$	$DF_m \geq 3\%$
Residential buildings	-	all rooms	-
Schools	offices, stairs, toilets	gym and refectory	classrooms, laboratories
Hospitals	offices, stairs, toilets	gym and refectory	wards, diagnostics, laboratories

Italian average daylight factor recommended values provide a partial checking of daylighting quantitative aspects; but it is inadequate to evaluate qualitative aspects such as natural light distribution, luminance ratio and view.

Besides, average daylight factor is a single, broad measure of daylight for the whole room and it does not give any detailed information about distribution.

In the example presented in fig. 4 average daylight factor seems to be acceptable but the distribution of light inside the ambient room is not uniform. Global illuminance for M position is the sum of beam and diffuse components, while for N position it is given only by the diffuse component [15].



It is necessary to take into consideration the different performances of a daylighting system with respect to light distribution and uniformity ratio as they play an important role in architectural daylighting, in particular speaking of office buildings; schools; libraries; hospitals.

Average daylight factor has other limitations not being able to predict glare and luminance ratio. Besides, because of the absence of specific Standards, it is often necessary to make use of further daylight control elements to satisfy user requirements.

In the Fifties the glare from large light source, such as window, has been studied at the Building Research Establishment in England and at the Cornell University in the United States. Based on a relationship between source and background luminance, the degree of glare caused by any individual light source can be expressed as a glare constant [16]:

$$G_i = k \frac{L_s^{1.6} \Omega^{0.8}}{L_b + 0.07 \omega^{0.5} L_w}$$

where: G_i = glare coefficient for each of the component parts of the view through the window (sky, obstruction, ground)

- L_s = luminance in cd/m^2 of the patch of visible sky, of the obstructions and of the ground seen through the window
- Ω = solid angle subtended by the source, with weighting factors for different areas depending on their direction with respect to the occupant line of sight
- L_b = average luminance in cd/m^2 of the interior surfaces of the room which contribute to the visual field of an occupant of the room
- ω = total solid angle in steradians subtended by the window
- L_w = average luminance of the window weighted according to the relative areas of sky obstructions and ground
- k = constant depending on measurement units and source

The glare constants for all sources are then summed to determine the Daylight Glare Index [16]:

$$\text{DGI} = 10 \log \sum_{i=1}^n G_i$$

Since glare is a comfort sensation, the DGI is based on how groups of people have responded to various levels of brightness, both from daylight and electric light, with the glare sensation scored as each individual perceived it. Testing in this manner has led to the establishment of glare criteria based on the mean glare index generated from the responses of people tested for various lighting situations. Glare criteria have been grouped into several categories, ranging from “just imperceptible” to “just intolerable”.

Daylight glare criteria have been defined and compared to those ones for artificial sources (tab. 4).

Tab.4 - Comparison between artificial source glare indices (IES GI), daylight glare index (DGI) and glare criteria [2][3]

MEAN SUBJECTIVE ASSESSMENT OF GLARE	IES GI	DGI
just imperceptible	10	16
	13	18
just acceptable	16	20
	19	22
just uncomfortable	22	24
	25	26
just intolerable	28	28

International recommendations settle maximum artificial source glare indices related to specific types of interior and occupants activities (tab. 5).

Tab. 5 - Artificial source glare indices recommendations in some workplaces and relative daylight glare index [2] [7]

Activity / Space	IES GI	DGI
Factories	25 - 19	26 - 22
Corridors	22	24
Teaching spaces	19	22
General offices	19	22
Laboratories	19	22
Drawing offices	16	20

All the above mentioned considerations require for an experimental study showing lighting performances of different window options in order to evaluate the relationship between window shape and position and light distribution related to both spatial uniformity and luminance.

Sizing windows it has considered the importance of taking into account qualitative aspects such as view. The communication with the outside is considered to provide a more interesting and dynamic indoor environment even for a small ambient.

3. The case study

In 1996 Department of Energetic - Polytechnic of Turin - in collaboration with Municipal Energetic Society (AEM) of Turin carried out a lighting laboratory for the study of natural and artificial lit environment.

The laboratory is an office room situated on the 6th floor of a recent construction building owning to AEM company (fig. 5).

The office room is 8m long, 6.2m wide, and 2.97m high.

Its north and east facades are completely glazed in their upper parts.

Windows are double-glazed with low-e and reflective coating on the exterior surface. Measured glazing transmission factor is 0.37, compared to manufactured data of 0.41.

The laboratory has white internal wall partitions, light-grey ceiling and pillars, and a brighten dark-grey floor. Internal surfaces measured reflectances are respectively 0.77, 0.68, 0.3.

Dealing with furniture, in the laboratory there are a desk, a working table, some chairs and a cupboard, all dark in colour and with a measured reflectance of 0.1.



Fig.5 - The office room turn into a lighting laboratory

4. Adopted window options

In order to have useful information about light distribution related to window position and shape, only one glazing facade has been analysed. East glazing facade has been completely covered by white panels with a reflectance (0.77) equal to the other two internal walls. Using the same panels five different window options have been created for the North glazing facade.

The choice of the North facade is due both to the fact that it does not involve direct solar radiation and that it is positioned on the office room main axis.

The choice of the five different window options considers lighting requirements combining with architectural concepts and psychological aspects.

The five window options evaluated are the following:

1. A high horizontal window 0.84m high (fig 6a)
2. A low horizontal window 0.84m high (fig 6b)
3. Three vertical windows 1.84m high and 1m wide (fig 6c)
4. Two horizontal windows each 0.47m high, positioned respectively 1.46m and 2.38m from floor level (fig 6d)
5. A mixed window, made by horizontal elements in the upper part and by lower vertical elements decreasing to 1m from floor level (fig 6e)

All the options have the same glazing area (5.4 m^2) in order to compare directly their different performances.

5. Methodology

For each option the following parameters have been measured: illuminance outdoors, illuminance indoors on horizontal working plane, and luminance for glazing and adjacent room surfaces seen from a frontal point of view.

A 12 points grid, 2m wide and 0.75m high, coincident with the working plane, has been used for carefully measuring indoor illuminance. Simultaneously, in conformity to daylight factor formula, external illuminance, without direct solar radiation, has been measured on the building roof, which is an horizontal plane seeing the sky dome. For this measurement a photometer head covered with a shadow band was used. (fig. 7)

Luminance has been measured for several points taking into account visual field dimensions and a seated mean of 1.2m in order to calculate daylighting glare index.

For each option illuminance and luminance measurements have been done for different hours and with clear sky, partly cloudy and overcast conditions.



Fig. 7 - Photometer head with shadow band

6. Obtained results

Daylight factor has been measured for each of the grid points, as a percentage of the illuminance outdoors, then average daylight factor has been calculated.

For all the adopted options average daylight factor is quite low due to office room dimensions, to very reduced window area and glazing low transmission factor (0.37) (tab. 6).

Not being of primary interest the quantitative analysis of the phenomenon illuminance distribution has been obtained for the whole ambient, and for the main office room axis.

Tab. 6 - Average daylight factor for all the different window options

	DF _m (%)
initial condition (2 glazing facade)	5.5
option 1	1.06
option 2	1.09
option 3	1.15
option 4	1.17
option 5	1.03

For each option uniformity ratios of illuminance have been calculated (tab. 7):

- DF_{min}/DF_{med} = ratio of the minimum to the average daylight factor on the plane
 DF_{max}/DF_{min} = ratio of the maximum to the minimum daylight factor on the plane
 DF_{max A}/DF_{min A} = ratio of the nearest to the farthest window point daylight factor along the main axis

Tab. 7 - Comparison between uniformity ratios of illuminance

	DF _{min} /DF _{med}	DF _{max} /DF _{min}	DF _{max A} /DF _{min A}
option 1	0.48	4.0	3.5
option 2	0.32	7.7	7.1
option 3	0.3	8.3	6.25
option 4	0.4	5.2	4.7
option 5	0.37	6.6	6.25

Measured internal illuminance distributions have been graphically represented (fig.8).

Daylight glare indices have been calculated for all the different adopted options.

Experimental data from international researches [15] found daylight glare index varying with sky luminance rather than in relationship to window dimensions.

The comparison between the different options proposed during this study is related to equal glazed area and luminance in order to determine how much DGI is influenced by position and shape of the window.

The obtained results for all the proposed options are represented in the table below (tab. 8).

Tab. 8 - Measured daylighting glare indices for different options

	DGI
option 1	20.3
option 2	21.7
option 3	22.0
option 4	21.0
option 5	21.8

7. Conclusion

For daylight design and analysis the average daylight factor is the quantitative parameter generally used. However it is not sufficient for a complete characterisation of lit environment.

The aim of this study has been to undertake a more comprehensive analysis of daylighting in interior spaces, and in particular to verify the performances of different daylighting systems with respect to those indexes and parameters concerned with qualitative characteristics of luminous environment.

Five different window options with the same glazing area but different shape and position on the facade have been realised.

Since the glazing area is the same, and internal and external conditions don't change, it can be considered that each option provides to the room the same quantity of daylight. This is confirmed by the elaboration of horizontal illuminances measured for each options: a comparable DF_m is found, with a mean absolute deviation within the five options of 0.048.

If the analysis is limited to the quantitative aspect the five options give the same performance, while differences emerge as far as the parameters dealing with quality of luminous environment are concerned.

In particular daylight penetration and distribution and daylight glare index for a frontal point of view have been compared for the five options.

Results from data elaboration has led to a preliminary evaluation of the window options.

OPTION 1 is the solution with the best daylight penetration, having lower illuminance values near the window and relatively high values in the rear of the room. The interreflected component is increased by the contiguity of the window to the high reflective ceiling.

It has the lowest DGI, but dealing with other qualitative aspects, such as view, this option seems to have the worst performance: it allows the perception of changing daytime hours, but it excludes the view of the horizon and the foreground (building, trees, etc.).

OPTION 2,3,5 give similar performances. In particular it emerges a greater discrepancy between the illumination near the window and in the rear of the interior. The difference is less evident for option 5 which has vertical components combined with a continuous horizontal aperture adjacent to the ceiling.

DGI reaches higher values for these options, even if the difference among the five options is not so great.

Option 2 and 3 are probably the best solutions in terms of external view, because they enable the contemporary view of sky, horizon and foreground.

OPTION 4 is an intermediate solution. It gives an illuminance distribution similar to option 1, an intermediate DGI, and an external view of both sky and foreground.

The analysis of qualitative parameters and indexes could give additional information for designing daylighting systems, not only in their dimensions but even in relation to their shape and position.

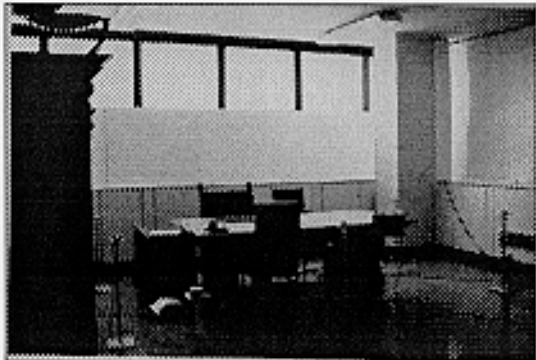
An overall analysis of the luminous environmental quality and its effects on psychological and emotional aspects needs for a subjective survey.

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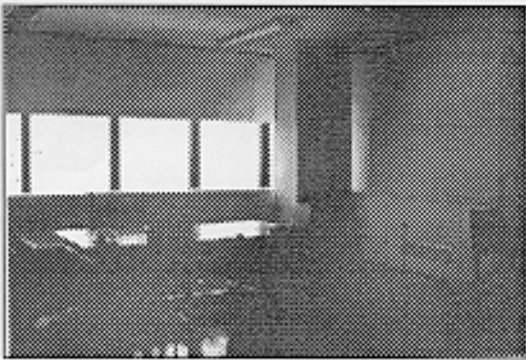
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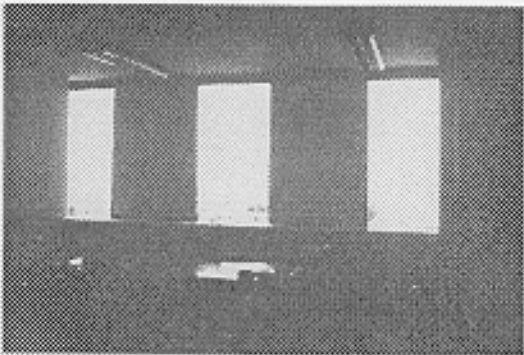
Fig. 6 - Proposed window options (a: option 1; b: option 2; c: option 3; d: option 4; e: option 5)



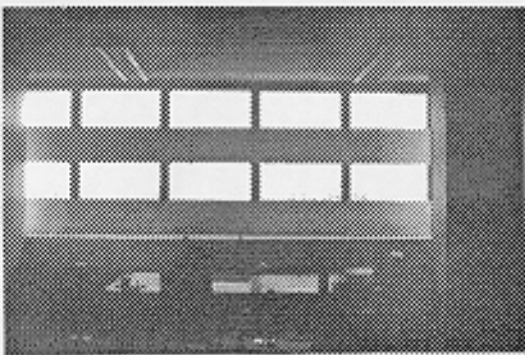
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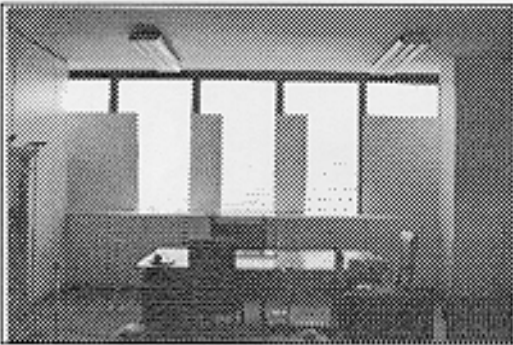
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d



e

Fig. 8 - Illuminance distribution for original condition and different options

