International Journal of Low-Carbon Technologies Advance Access published February 4, 2011

Use of low-cost daylighting system: custom design and application consequences in an office environment

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Abstract

Nowadays, many working environments are located within facilities that are not visually connected with the exterior. This is due to the new architectural paradigms as regards the design, based on the possibility to substitute natural light for artificial lighting even in daytime. Accordingly, the need of reducing energy costs and the user's wish to optimize lighting and visual comfort levels raises the option of innovative natural lighting systems implementation. For a luminous retrofitting case, located in Mendoza, Argentina, a specific methodology used determined that the more adequate natural lighting strategy would be redirecting direct sunlight, working on the reflected light design. The methodology proposed is formed by an analysis of the initial situation, conditions modelization and design resolving proposals, through luminous evaluation, real and virtual scale model construction, and performance evaluation using heliodon and simulation software. This work points to use natural lighting to reduce energy consumption and get better luminous ambient through the application of a low-cost daylighting system. In the mentioned case, strategies of redirection of the solar component capable of optimizing indoor lighting levels up to a 40% were applied.

Keywords: low cost daylighting system; custom design methodology; energy savings

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Received 19 October 2010; revised 27 November 2010; accepted 29 November 2010

1 INTRODUCTION

At the present time, people spend most of the day hours inside constructions (buildings), staying necessarily indoors during extended periods of time, being expected to carry out efficiently and satisfactorily their assigned tasks.

Within this context, we can identify lighting as an environmental variable that can potentially modify not only the visual system operation state but also the way in which human beings carry out a task. Light quality can act as a positive factor, contributing to enhance people's performance or it can influence negatively on their behaviour, which at the same time, and depending on the context, could affect productivity.

Although it is true that there is not a clear definition of 'lighting quality', there exist many approaches to delimit it. Definitions related to the search of simple photometric indexes calibrated according to subjective answers [1], to the results of holistic design processes based on light patterns [2], to the lighting conditions determination having desirable impact on an efficiently fulfilled task, and on the subject health and behaviour [3], or the systematization of lighting characteristics that enhance our ability to discriminate details, colour, shape, texture and surface finish without diminishing comfort [4, 5].

For indoor working environments, the recommended levels for artificial lighting are generally between 100 and 500 lux depending on the tasks to be developed, normally determined by the standard requirements of norms. In the most favourable cases, sunlight usually has several hours incidence a day on the buildings, raising considerably general lighting levels while contributing differential characteristics such as the levels of intensity, temperature and colour dynamics. These variations of the sunlight are proven to exert a positive influence on the occupants' mood. Notwithstanding, according to a study carried on at the office environment, people manifested a marked preference for a high electric additional light contribution, 800 lux over the prevailing natural lighting [6].

From a complementary perspective, it is necessary to point out that vast investigations indicate that the electric energy consumption associated with artificial lighting sources reaches, depending on the case, between 25 and 50% of the whole

doi:10.1093/ijlct/ctq051

Figure 1. *Panoramic picture—layout of the desks at the office.*

Figure 2. *(Left) Inner view of the light pipes located between the beams. (Right) Outer view of them.*

Figure 3. *LI-COR 189 radiometer and LI-210 SB photometric sensor.*

Figure 4. *Scale model of the analysed building. Inner view: reproduction of the surface reflectances. Outer view: reproduction of the light pipes layout.*

building energy demand. Always considering that the necessary lighting levels on the different work areas for offices location must be ascertained according to regulations (IRAM AADL J 20-06 for Argentina—[7]). The latter, depending on the task, recommend values between 300 and 500 lux.

These values vary depending on the regulation or recommendation origin (country) and their updating within the same country [8].

With respect to the lighting level preferred, Kirschbaum and Tonello [9] demonstrated in their results that the lighting of a facility used for office location with light walls and lighted with fluorescent lamps (day light) was evaluated as moderately attractive and stimulating for lighting levels between 500 and 600 lux over the work plane. Increasing the lighting levels ~1200 lux, the facility was evaluated as light, moderately attractive, stimulating and warm.

Reflecting upon natural lighting behaviour and whether they should be evaluated by objective procedures or not, Fontoynont [10] concludes that the users of a lighted indoor space perceive natural lighting quality through a mixed sensation. On the one hand, it is expected that natural lighting accomplishes with the illuminance level requirements over the work area, without causing glare. On the other hand, it is expected that the results are visually agreeable.

The following work is a lighting retrofitting case at an office environment, emerged from its occupants' spontaneous demand, which includes a diagnosis on the natural lighting condition in a space without lateral windows offering as a result a methodological proposal, taking into account the specific problematic of artificial and natural lighting complementariness at an office working during daytime in sunny weather.

2 METHODOLOGY AND MATERIALS

The methodology proposed is divided into three stages:

(1) diagnostic analysis of the initial lighting situation in a study case;
(2) modelization of lighting conditions;
(3) development of design resolving proposals.

The luminous evaluations will be carried out on the real space, based on a scale model and simulations on a virtual scale model.

2.1 Study case

The present work is based on the retrofitting of the natural lighting of an office without lateral windows, but with the presence of light pipes on the ceiling, mainly for natural ventilation (Figure 1). The office is located in a single-storey building. The corresponding latitude for its location is 32°52′S, its longitude is 68°51′O and presents a semi-arid climate.

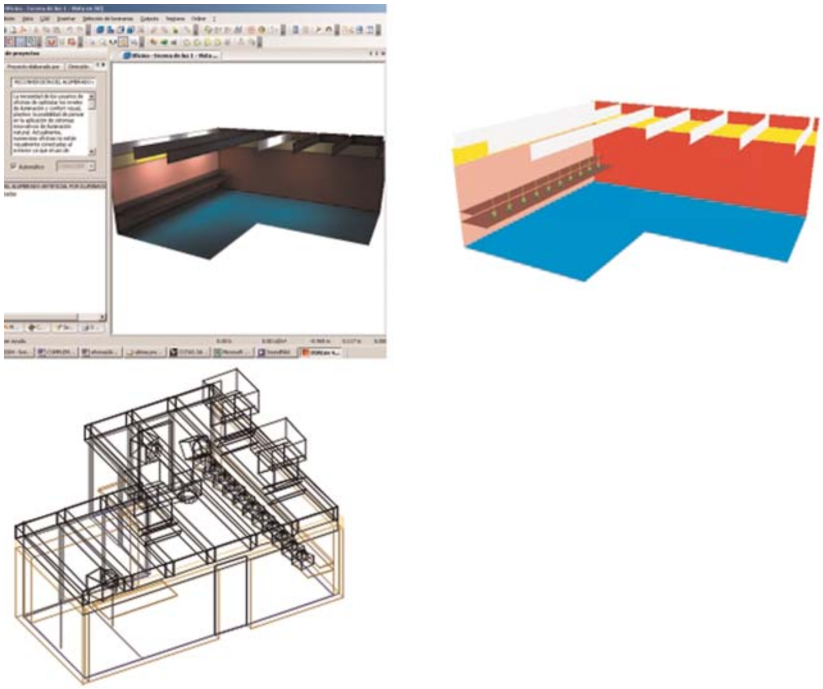

Figure 5. *Image of the interphase obtained with DIALux, rendering, schema of measuring points location and virtual structure view, respectively.*

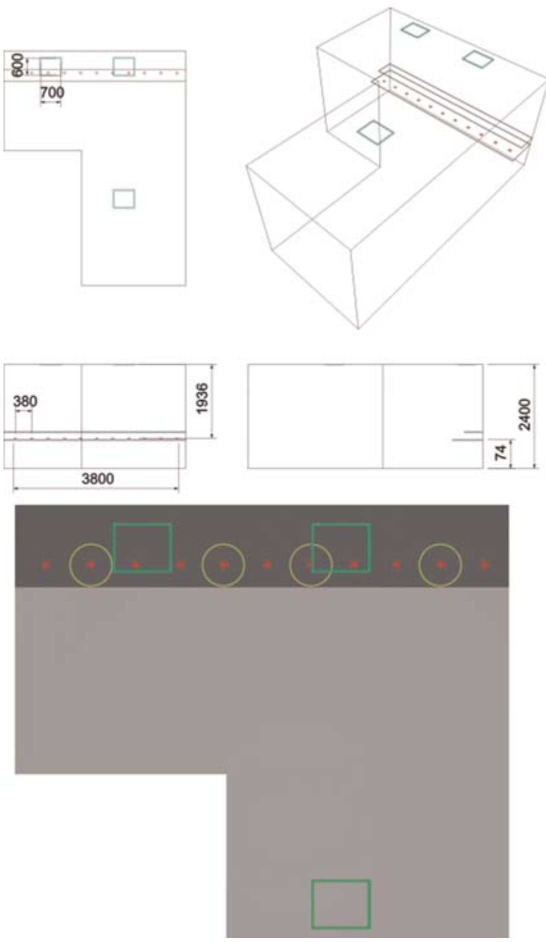

Figure 6. *Schema of the location of the sensors. Red: sensor. Yellow: working places. Green: light pipe location.*

Figure 7. *Visual presentation of the three rooms analysed. Real situation, scale model picture and image captured by DiaLux.*

Table 1. *Values registered on the working area in the real situation (reference values).*

Photometric sensor	Values registered
21 September	
1	98
2	133
3	188
4	273
5	424
6	681
7	14 497
8	263
9	263
10	304
Um (min/med)	0.057229619

The work place has a 33 m^2 surface, and five work positions arranged for the computer and read-write tasks. The installation of the artificial lighting is formed by three fluorescent lamps 40 W each, without diffusers, nor louvers.

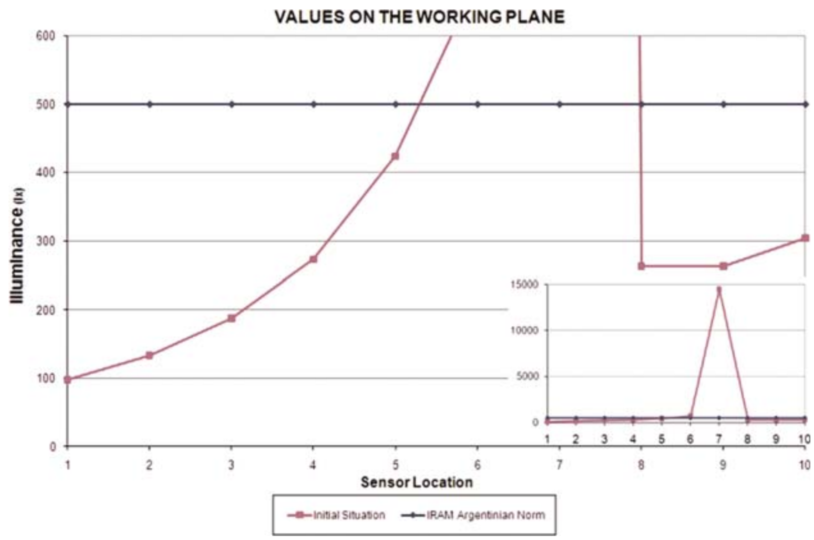

Figure 8. *In blue, the recommended value for IRAM standards can be seen, 500 lux.*

The initial evaluation showed that the lamps are on during the complete workday: from 8:00 a.m. up to 4:00 p.m. There are two light pipes that supply natural lighting and ventilation placed over the desks line with its transparent glass surface oriented to the Equator with a size of 700 mm × 700 mm each, separated by 1700 mm, inserted between two beams 400 mm (height) as part of the building structure (Figure 2).

2.2 Characteristics of the problem

As it was already mentioned, this study at the office location started as a consequence of an informal requirement on behalf of their occupants.

As regards the possible strategies to apply while solving the mentioned inconveniences, a change over the inner walls reflectance was discarded (brick-red façade 42% reflectance) since the occupants preferred warm colours to thwart the light 'coolness' effect and to keep the architectural style.

On the other hand, the proposal about generating a better access and use of the natural light available aroused a great enthusiasm related to the possibility of obtaining a climatic reference of the office external conditions (which is devoided of windows to allow this function) apart from a natural record of time.

Finally, it is worth mentioning that the implementation costs would be run by the workers. This reason motivated special care about the resolving proposals design being low cost as regards production and installation.

2.3 Initial measuring

Over the work area surface, 10 measuring points were uniformly distributed in order to measure horizontal illuminances, at a height of 700 mm above the ground (height of real horizontal work area). In all the cases, the device used was a LI-COR 189 radiometer, with a photometric sensor LI-210 SB (Figure 3). This sensor has a sensitive area of 8 mm which is located at the centre of a cylinder of 24 mm diameter and 20 mm height. The decision of making the model to scale at a 1:20 ratio was based mainly on the idea of conserving the dimension order of the sensor body [11, 12].

2.3.1 Setting

The illuminance measuring carried out on each of the working positions for 21 September at noon under clear sky conditions was taken as the reference value. The experimental study shows discrepancies caused by slight differences in surface reflectances and photometer cosine responses. These discrepancies were reduced to a +5 % to −5 % relative divergence, by putting in the effort to carefully mock up the geometrical and photometrical features of the test module. This included a calibration of the photometric sensor, whose cosine response appeared to be at the end responsible for the remaining relative divergence observed between the daylighting performance figures.

2.3.2 Design conditions

(1) Sky conditions: clear Sky
(2) Latitude, longitude and time zone: 32°52′S; 68°51′O; −4 (Mendoza, Argentina)
(3) Light pipes direction: Equator
(4) Real day month, hour: 21 September, 13:00; 21 March, 13:00
(5) Global horizontal illuminance (Eg): Spring 98Klx, Autumn 93Klx
(6) Wall reflectance (%): 42
(7) Floor reflectance (%): 38
(8) Ceiling reflectance (%): 80
(9) Light pipe glass: transmission 80%; reflectance 20% (commercial catalogue)

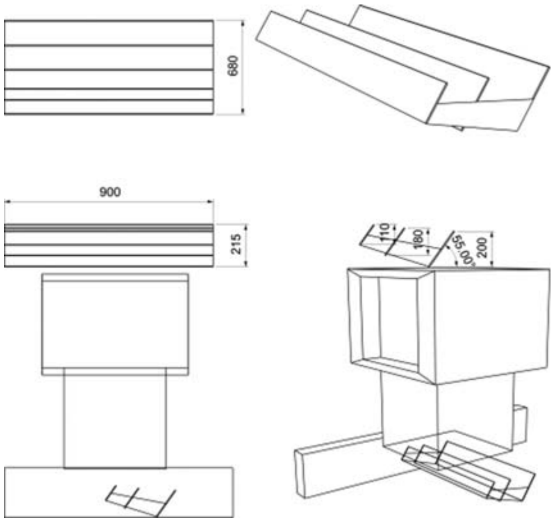

Figure 9. *Proposal 1, sunlight spot redirection to the ceiling and diffusion from that point.*

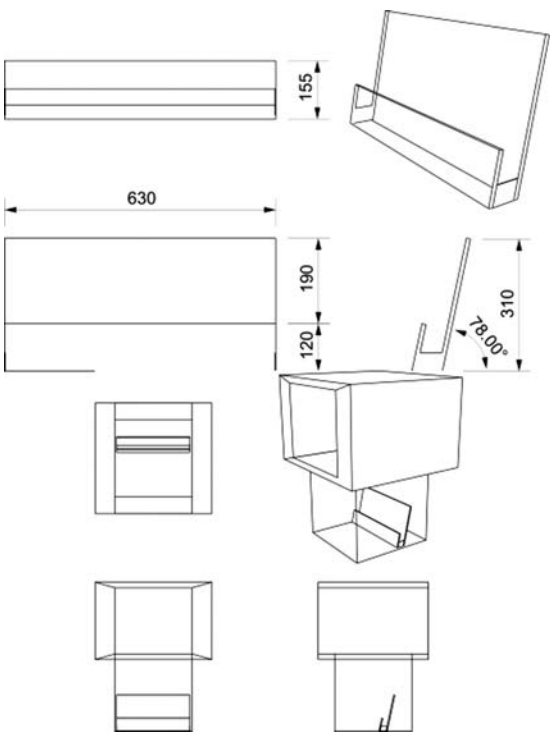

Figure 10. *Proposal 2, redirection and diffusion of the sunlight spot from the light pipe cavity.*

2.3.3 Scale model

To evaluate the natural lighting conditions supplied by the skylights at the representative seasons (solstices and equinoxes), a scale model 1:20 was built (Figure 4). It was made of 2 mm thick cardboard in order for it to be lightproof in all of its edges and had a detachable roof for manipulating internal elements. The reflectance of the internal surfaces of the real office was measured with the help of a luminance meter

Table 2. *Cost analysis for the proposal developed.*

Proposal 1		Proposal 2	
Item	Cost	Item	Cost
Galvanized sheet; 1 m^2	20 USD	Galvanized sheet; 1 m^2	20 USD
Opaque synthetic enamel paint; 1 l	6 USD	Opaque synthetic enamel paint; 0.7 l	4.2USD
Labour	45 USD	Labour	20 USD
Total	71 USD	Total	44.2 USD

(Minolta LS-110) and a Kodak luminance pattern and this was also carried out on the scale model. It also had a small groove for entering a guide that would place the sensor on each different planned measuring point. With the help of a heliodon, measures were taken with the intention of observing the behaviour of the daylight supplied by the light pipes inside the setting. In June and December, only the presence of the diffuse and reflected components could be observed. In March and September, due to the sunlight incident angle, a direct light beam entering through each light pipe could be noticed.

2.3.4 Virtual scale model

In order to evaluate and compare the real situation and the resolving proposals, a software simulation of the luminous conditions was carried out through DIALux 4.8. This CAD software was developed by the Deutches Institut für angewandte Lichttechnik and makes it possible to calculate both daylight and artificial one (*.ies files) together or individually. It uses ray tracing to perform all lighting calculations and includes a renderer as well as other tools for measuring the simulated light levels (Figure 5).

For the real model as well as for the virtual one, the measuring of the illuminances was planned for the horizontal working level of the occupants, i.e. the space on the east wall of the place, at 0.74 m height where people do reading and writing tasks at the same time that they carry out IT workers duties. All the lighting tests were programmed under clear sky conditions, including the option of calculating direct daylight. A 10-point grid comprising a 3.8 m longitudinal area was defined, replicating the positions of both the mock up and the real situation, making sure that in every working place, there is at least one illuminance sensor (Figure 6).

2.4 Data analysis

From the first evaluation of the natural lighting of the place intended for the job positions onwards, it was detected that specifically during the months of March and September, there exists an important lack of uniformity among them. This situation could be visualized in the three

Figure 11. *Site appearance with natural lighting system on 21 September. (Left) Scale model with diffuser; (right) Virtual scale model with diffuser.*

Table 3. *Lighting levels showed by each model with respect to the values registered in the real situation.*

Sensor	Original situation	Retrofitting
21 September		
1	98	155
2	133	232
3	188	282
4	273	288
5	424	354
6	681	362
7	14 497	360
8	263	367
9	263	290
10	304	208
Um	0.06	0.53

analysed models (Figures 7). The values obtained are indicated in Table 1 and Figure 8. For the remaining months of the year, the values are within the established ranges recommended by the norms.

2.5 Proposal of natural lighting system for retrofitting

It was stated as a design objective to elevate the general level of lighting and to seek for a uniformity of natural light over the principal working areas.

The proposal was based on the redirection of the luminous flux that produces the sunlight spot observed over the working areas during the months of March/September, reflecting it through interposing an opaque white finish surface in the inner hole of each light pipe. The expected result is to eliminate the excessive contrast caused by the sunlight spot on the workers' visual field and redirect it so as to balance the secondary natural lighting that should enhance the final flux over the working area line (Figures 9 and 10) (Table 2).

3 RESULTS

3.1 Predictive calculation

In the measuring process carried out on the real and virtual scale model after applying the devices, it could be observed an important improvement on the lighting levels and uniformity quotients over the work areas surface.

As similar luminous intensity over the working areas were obtained in both proposals, taking as a parameter economy and simplicity as regards installation processes, a proposal number 2 was chosen for its application in the real setting. Figure 11 shows the luminous appearance inside the office after applying the systems.

The results exposed correspond with 21 September, date chosen as a reference parameter for being the most critical luminous situation to solve.

It is worth clarifying that during the remaining months of the year, the proposed device manages to keep the usual

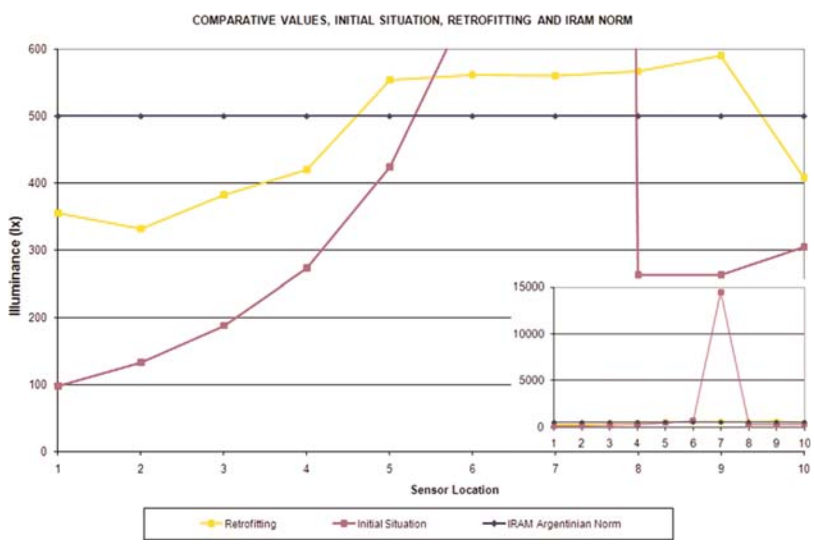

Figure 12. *Graphical representation of the initial values, the achieved values and those recommended by IRAM standards, 500 lux.*

lighting and uniformity levels of the predominant, diffuse and reflected light captured by the light pipes at the site.

3.2 Registered values

After finishing the natural lighting improving systems in the real location, a photometric survey was carried out following the measuring protocol created at the original setting luminous situation diagnosis.

It can be observed from the values obtained that there was a significant improvement of the general lighting levels in lux over the working area. Even though the enhancement of the luminous intensity reaches, depending on the measuring location, up to a 37% (Sensor 1), the most significant improvement is obtaining a uniformity quotient 90% more balanced, within the IRAM norms recommendations for Argentina (Table 3 and Figure 12).

4 CONCLUSIONS

The present study was carried out in response to a demand of lighting improvement at a public office on its users' behalf. After the initial luminous evaluation, a retrofitting of the lighting system proposal was chosen, introducing through innovative systems a natural lighting component adequately controlled in accordance with the tasks being developed at the site.

The design of the developed systems, and their application results pre-visualization were possible thanks to the use of material as well as virtual simulation tools. This process allowed a better adjustment in the stages previous to systems installation.

As a result, the retrofitting not only optimized lighting levels up to a 37%, but also improved other aspects of the setting lighting, such as uniformity (0.53 over 0.4 recommended by IRAM norm) and the possibility to obtain a space–time reference from the exterior thanks to the dynamism added by natural light.

Finally, it is important to highlight that the possibility of intervening in the development of innovative natural lighting systems based on strategies of redirection of the solar component, for instance, allows us to reach highly efficient solutions even when having low complexity technologies available or dealing with serious financial restrictions.

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