682: A Study on Daylighting Internally Reflected Component – Correlation Between Theoretical and Real ArchItectural Models

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Abstract

Good designs are featured by the use of efficient technology and by the passive uses of renewable energy, as daylighting. In situations where the direct light values are low or in points where it is not possible to visualize the sky, the internally reflected light (IRC) might be the answer. The present work aims at tackling the IRC contribution inside the buildings through theoretical models with geometric variations and surfaces reflectances. The results obtained in these models are compared with measurements in the scale model of a real building performed under a mirror- box artificial sky. This comparison enabled to stress daylighting design through geometric drawings and reflectance's manipulation. Two methods were adopted: a graphic and an analytical method. The research made it possible to correlate the IRC with the environment physical features.

Keywords: daylighting; internally reflected component; design.

1. Introduction

As far as daylighing is concerned, it is the designer's role to meet the building programming, plastic and energetic needs; besides providing the necessary confort to its user [6,9,11].

It is the architect's responsibility to interfere in the indirect illumination. According to Lynes (1968), the internally reflected light will depend not only on the walls reflected component but also on the environment configuration.

The most critical decisions for a well daylit building come during the early phase of architectural design, when the building's configuration and fenestration are formulated [7].

The daylit building design rely on the relationship among the environment, the space to be lit and on the many apertures size, shape and location through which the light will pass through. An understanding of this proportional relationship between the space and the aperture allows the designer to manipulate daylighting so as to change its incidence, distribution, quantity and quality within a space [12].

The architect is inclined to consider daylighting as another impeding element within a complex process such as building design. Instead, it should be not only regarded as a factor that increases the design quality but as something that should be commercially defended. Accepting daylighting and the environmental principles as organizational principles must be the only way to reach satisfactory results, ensuring the design final quality [10].

2. Objective

The current work aims at tackling the internal reflections impact on a daylit built environment, considering the inner space geometry and surface properties.

3. Metodology

3.1 Choosing the internally daylighting estimation method

Methods that use computer softwares are more suitable for this study because they enable measurements at several points simultaneously. In addition, it is easier to obtain parametric ratings and data for a variety of models, with rapidity and reliability.

3.2 Selecting the simulation software

Nowadays there are many efficient softwares for daylighting simulation; one of them is the software APOLUX, developed in the Laboratory of Environmental Comfort at Federal University of Santa Catarina [4] where this research was held. This program, which works with mathematical formulation based on radiosity algorithm, was chosen because it relies on constant technical support and enables adjusting the programme according to the work needs. The daylight factor, DF, lighting relative concept was adopted with the purpose of data reading (**DFr** - **D**aylight **F**actor **r**eflected, concerning the **I**nternal **R**eflected **C**omponet - **IRC**).

3.3 .Simulations input data

It was settled that an only condition for the environment would be set, in which the models were displayed with the purpose of exploiting a wider variety of the models relevant to the research.

The city of Florianópolis was adopted as the venue for the research to take place. It is geographically positioned to 27˚30' South Latitude and 48˚00' West. Longitude. The March 21st equinox at 12 am was chosen as the experiment date under a standard CIE overcast sky [3], used in the research due to its directional uniformity.

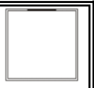
A work plan at 0,75m from the floor was taken on with the purpose of doing daylight calculations.

3.4 Study Models

With the intention of observing daylight behaviour concerning the environment configuration, four standard models were developed from which all the other models are derived. They have the same area, but the length, width and the ceiling height present variations.

The first model consists of a square base with three metres ceiling height ,being the other models originated from the former. The second and third are parallelograms, one long in length and the other in size, both keeping the same ceiling height. The fourth keeps the first's same base, however, its ceiling height is increased by 25%, see Table 1. Through these geometries, it is possible to highlight the reflected light correlation in four possible environmental conditions: intermediary (A), deep (B), wide (C) and high (D).

Table 1: Models characteristics.

MODEL	 A	 B	 C	 D
ÁREA	36m²	36m²	36m²	36m²
WIDTH	6 m	4 m	9 m	6 m
DEPTH	6 m	9 m	4 m	6 m
HEIGHT	3 m	3 m	3 m	3,75 m

3.4.1 Internally reflected index variation on the surfaces.

A low reflectance (ρ=20%), a medium one (ρ=40%) and an high reflectance (ρ=80%) were selected for this study, all applied to the environment internal surfaces. The ground reflectance was the same for all the models, 20%. Walls and ceiling altern high, medium, low and null, see Table 2. Through these combinations it was possible to study these surfaces influence as light diffusing to the four geometries respectively. The models present a centralized, lateral aperture as light source. The apertures geometry and dimension were kept the same to all models and the dimension is equivalent to 16% of the floor area.

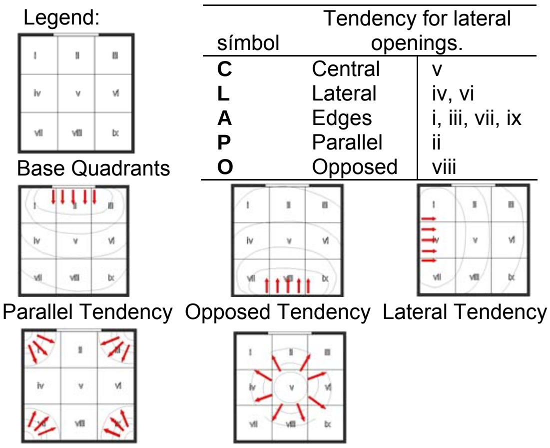
Table 2: Reflectances combination.

Combinations	MODEL	 V_A1	 V_A2	 V_A3	 V_A4	 V_A5	 V_A6	 V_A7	 V_A8
Reflectance	ceiling	80% higt	40% medium	20% low	0% null	80% high	80% high	80% medium	40% medium
	wall	80% high	80% high	80% high	80% high	40% medium	20% low	0% null	40% medium
	floor	20% low	20% low	20% low	20% low	20% low	20% low	20% low	20% low

3.5 Graphic method

The use of graphic methods, to assess the performance of arquitectural solutions concerning natural light, is increasing. In literature, authors such as Lam (1986), Robbins (1986), Moore(1991), Baker et al. (1993), Baker and Steemers (2002) can be found among those who proposed the use of images, to highlight daylit performance related to architectural forms. Their studies describe the use of a set of concepts, taking into account the different types of daylit environments as general party design tool.

It is assumed that the reflected light can be directioned to a determined environment area according to the spacial geometry, apertures and surfaces features. As far as daylighting is concerned, the apertures are regarded as the main sources. Therefore, they are a crucial element to classify the internal reflected light direction. With the purpose of enabling the reading of such direction, a classification was developed, indicated in Figure 1, presenting a lighting tendency to lateral apertures as: central, edges, opposed, lateral and parallel to the apertures. In certain circumstances, more than one situation might be found as a solution. Since this classification takes into account every aperture. The space is divided into 9 quadrants of the same area. The ones which reveal the highest percentage of **d**aylight **f**actor, concerning internally **r**eflected light (**DFr**), will be responsible for the light directioning in the environment.



símbol	Tendency for lateral openings.	
C	Central	v
L	Lateral	iv, vi
A	Edges	i, iii, vii, ix
P	Parallel	ii
O	Opposed	viii

Fig 1. Light distribution tendencies classification.

The reflected lighting maping in the models is accomplished through two graphics: one 2D, regarding the study general scale and another one 3D, displaying individual scale. A zoning consisted of 5 intervals was exploited, situated between the maximum and the minimum DFr value spotted among the models, allowinte comparisons in all the study group. These zones reflect the amount of internally reflected light contribution to the spaces.

3.6 Analytic method

The environment performance is analysed according to the increase attributed to the IRC, so that light is equally distributed in it. The assessment of such contribution in the models is carried out through the correlation among the coefficient of variation (cv), the total light parcel (DFm- total illumination), and the direct light parcel (DFm-direct light).

$$cv = \frac{\sigma}{DFm}\cdot 100 \qquad \text{(eq.1)}$$

where : σ= standard deviation
DFm= Daylight **F**actor **m**edium

The final result of such relation was called reduction percentage, associated to the respective reflected light parcel contribution. The systems that allow a higher reduction percentage, consequently, point to a solution where the IRC shows greater representativity in the environment luminous uniformity. The reduction percentage is worked out through the equation number 2.

$$\Delta rp = \left[1-\left(\frac{cv_{total}}{cv_{direct}}\right)\right]\times 100 \qquad \text{(eq.2)}$$

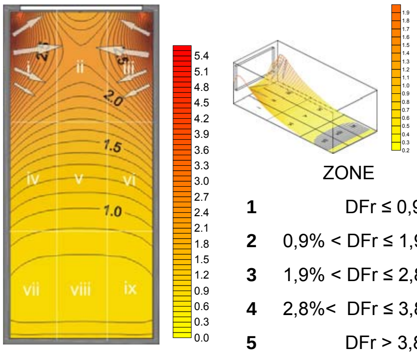
where : Δrp = reduction percentual

It is important to emphasise that the more homogeneous an environment is, the smaller the variation coefficient becomes. However, for this study, the tackled issue is the IRC contribution, therefore, models with uniform lighting are not necessarily those that present stronger IRC contribution.

4. Results analysis

4.1 Graphic method

In this article, only the maps related to deep models will be presented graphically (Fig. 2), since it was the geometry selected in the comparison with the architectural example. However, the results obtained concerning the reflectances variations to the four respective geometries have their results presented in this text.

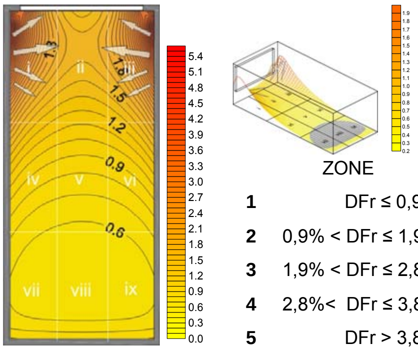


Ceiling:
ρ =80%

Wall
ρ=80%

	ZONE	AREA
1	DFr ≤ 0,9%	35,4%
2	0,9% < DFr ≤ 1,9%	34.9%
3	1,9% < DFr ≤ 2,8%	23,3%
4	2,8%< DFr ≤ 3,8%	5,2%
5	DFr > 3,8%	1,2%

Tendency: “A” - Deep geometry
(a)

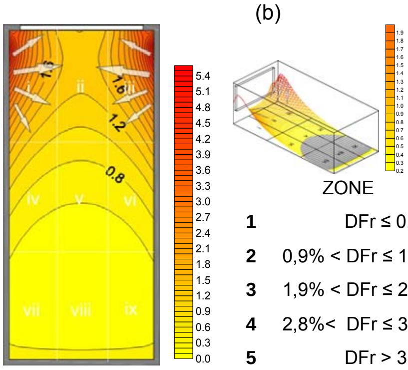


Ceiling:
ρ =40%

Wall
ρ=80%

	ZONE	AREA
1	DFr ≤ 0,9%	53,6%
2	0,9% < DFr ≤ 1,9%	35%
3	1,9% < DFr ≤ 2,8%	8%
4	2,8%< DFr ≤ 3,8%	3%
5	DFr > 3,8%	0,4%

Tendency: “A” - Deep geometry
(b)

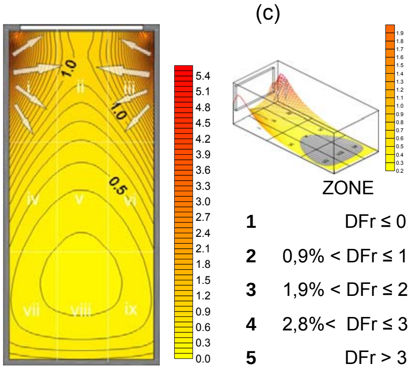


Ceiling:
ρ =20%

Wall
ρ=80%

	ZONE	AREA
1	DFr ≤ 0,9%	61,4%
2	0,9% < DFr ≤ 1,9%	29,5%
3	1,9% < DFr ≤ 2,8%	6,58%
4	2,8%< DFr ≤ 3,8%	2,2%
5	DFr > 3,8%	0,4%

Tendency: “A” - Deep geometry
(c)

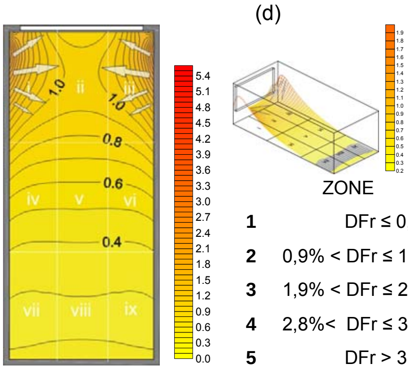


Ceiling:
ρ =0%

Wall
ρ=80%

	ZONE	AREA
1	DFr ≤ 0,9%	73,8%
2	0,9% < DFr ≤ 1,9%	20,1%
3	1,9% < DFr ≤ 2,8%	4,7%
4	2,8%< DFr ≤ 3,8%	1,1%
5	DFr > 3,8%	0,2%

Tendency: “A” - Deep geometry
(d)

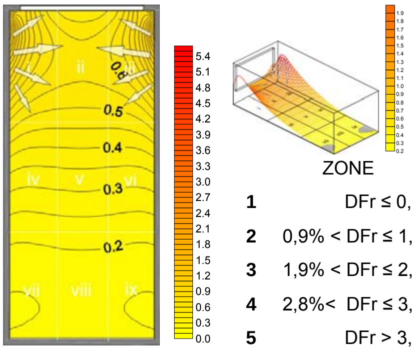


Ceiling:
ρ =80%

Wall
ρ=40%

	ZONE	AREA
1	DFr ≤ 0,9%	76,9%
2	0,9% < DFr ≤ 1,9%	22,5%
3	1,9% < DFr ≤ 2,8%	0,6%
4	2,8%< DFr ≤ 3,8%	0%
5	DFr > 3,8%	0%

Tendency: “A” - Deep geometry
(e)

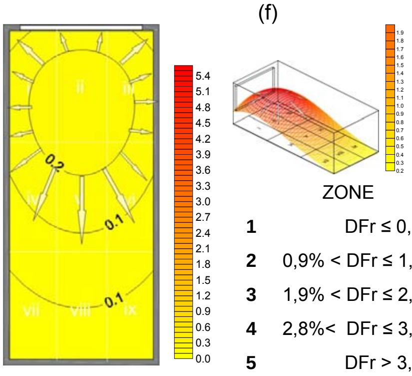


Ceiling:
ρ =80%

Wall
ρ=20%

	ZONE	AREA
1	DFr ≤ 0,9%	99%
2	0,9% < DFr ≤ 1,9%	1%
3	1,9% < DFr ≤ 2,8%	0%
4	2,8%< DFr ≤ 3,8%	0%
5	DFr > 3,8%	0%

Tendency: “A” - Deep geometry
(f)

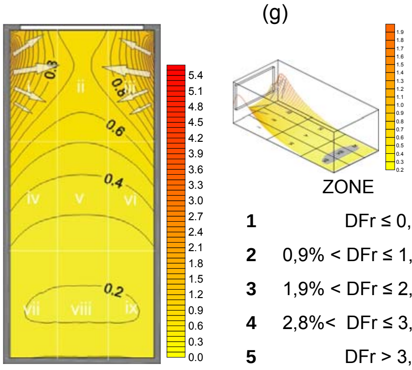


Ceiling:
ρ =80%

Wall
ρ=0%

	ZONE	AREA
1	DFr ≤ 0,9%	100%
2	0,9% < DFr ≤ 1,9%	0%
3	1,9% < DFr ≤ 2,8%	0%
4	2,8%< DFr ≤ 3,8%	0%
5	DFr > 3,8%	0%

Tendency: “C” - Deep geometry
(g)



Ceiling:
ρ =40%

Wall
ρ=40%

	ZONE	AREA
1	DFr ≤ 0,9%	91%
2	0,9% < DFr ≤ 1,9%	8,8%
3	1,9% < DFr ≤ 2,8%	0,2%
4	2,8%< DFr ≤ 3,8%	0%
5	DFr > 3,8%	0%

Tendency: “A” - Deep geometry
(h)

Fig 2. Isolux graphs for different reflectances in deep geometry.

Through the isolux graphics analysis, it can be concluded that the reflectances variations between wall and ceiling affect not only the direction tendency but also the reflected luminous flux intensity. The reflectances alterations results are described in the following lines.

With the ceiling reflectance reduction, the main light loss occurs in the central region. The reflections take place on the walls mainly in the quadrants i, iii and viii to high and intermediary geometries. In deep geometries, light is reflected from the edges (i e iii), whereas in wider models it reflects from the aperture opposite plan (viii), (see figure 2a,b,c,d).

Nevertheless, the reflections intensity is also reduced, due to the fact that the light exchanges do not take place between ceiling and walll.

On the other hand, when the wall reflectance is reduced, the reflected light distribution starts from the centre. As the wall reflections are minimised, the reflected light by the ceiling, more precisely by a region closer to the window creates this radial distribution, fig. 2a,e,f,g.

By reducing the walls and ceiling reflectances simultaneously by half, from 80% (fig. 2a) to 40% (fig. 2h), the lighting intensity in the analysis plan suffered reduction in the same proportion. The models with 80% reflectance presented about 90% of their area in the lighting zone 2 (0,9% < DFr ≤ 1,9%) transfering this same amount to zone 1 (DFr ≤ 0,9%).

The deep geometry was the exception, since its reflection was 80%, the greatest portion of the analysis plan area (70%) was spread to the lighting zone 1 and 2, and the remaining 30% throughout the other zones. With a 40% reduction of reflectance, zone 1 was predominant, as well as the other three geometries. For such environments, the higher the reflections are, the most heterogeneous the light space is, unless the reflectance are deeply manipulated to promote balance.

The reflections direction remained the same by reducing the ceiling and wall reflectances to half (ρ=80% to ρ=40%). As far as the **DFrm** (**D**aylight **F**actor **M**edium **R**eflected) is concerned, it was reduced to one third to all geometries. However, this reduction was lower to the highest model.

Disregarding the geometric variations, the **DFrm** value found was very close to the models with identical reflectances and different geometries.

It was also observed that apart from the space geometry, the reflections originated from the ceiling promoted levels of illumination lower than the wall. This is justified by the fact that parts of the wall face the sky, whereas the ceiling depends on the reflections that come from the floor (reminding that this study does not take into account the building external surfaces).

The correlation between the ceiling reflectance and the **DFrm**, can be explained by the same equation to intermediary and wide environments. What means that these geometries react in the same way towards the amount of light alterations. But this does not necessarily apply to light direction behaviour.

The deep and wide models present the same equation concerning the determination coefficient to the correlation between wall reflectance and the **DFrm**. Such result is consequence of the same wall area as well as from identical environmental floor plan in study, where only the aperture insertion plan differs.

4.2 Analytic method

When evaluating the IRC contribution it is clear that the higher the surfaces reflectances are, the stronger its contribution is. However, there is a relationship between the reflectances and the environment configuration. By simultaneously reducing the wall and ceiling reflectances by half, from 80% to 40%, all the geometries present similar results. The IRC contribution in order to increase the environment uniformity becomes almost 3 times lower, apart from the high models when the contribution is reduced to half only.

The IRC contribution is more strongly influenced by the walls reflectances rather than by the ceiling ones, this is possibly for the reason that the wall area represents almost twice as the ceiling area. This is equally applied to the four geometries respectively.

The bigger amplitude of IRC contribution values, generated by reflectances between 80% and 0%, took place in the intermediary and wider geometries, for ceiling and wall. The smallest one occurred in high environments for reduction on the ceiling and in deep models for reductions on the walls. What means that high geometries do not favour ceiling reflections and deep ones are not suitable to the walls reflections enhancement.

The correlation between the IRC contribution resulted from the reflectances is relevant to the ceiling as well as to the wall, to the four geometries respectively. In all cases practically 100% of the variations can be explained by the respective straight lines and equations.

The IRC contribution responds through the same equations to the walls reflectances variations to intermediary and wide environments. Both present a high coefficient of determination off 0,99.

A wider amplitude was noticed between the curves related to the ceiling and wall in high environments, possibly due to the fact that this is the geometry that presentes a bigger ratio between the wall and ceiling area.

5. Architectural example related to the theoretical model

The adopted building, was a residence situated in Paris. An illumination study was accomplished in the environment through physical scale model under an artificial mirror-box sky, with the participation of undergraduate students. The study gave more emphasis to the kitchen area, where one of the walls was painted red (ρ= 20%). The colour alteration to white was suggested (ρ= 80% a 100%). The **DFm** (**D**aylight **F**actor **m**edium) was considered, referred to the environment total illumination, however, as the only altered variable was the wall reflectance, the illumination values variables can be attributed to the light reflected parcel.

Figure 3 shows a study comparison,considering the reflectances alterations in buildings, with the results obtained in theoretical models simulations. Models reltives to figures 2f and 2a were highlighted in which the ceiling reflectance was kept constant (ρ= 80%) and the four walls reflectance corresponds to 20% and 80% respectively.

Apart from the fact that the reflectances variation takes place in the four walls in theoretical models and in just one in the architectural example, the reflectance increase result from 20% to 80% in both cases, is attributed to the environment lighting increase. On the other hand, there was no significant alteration in the light direction.

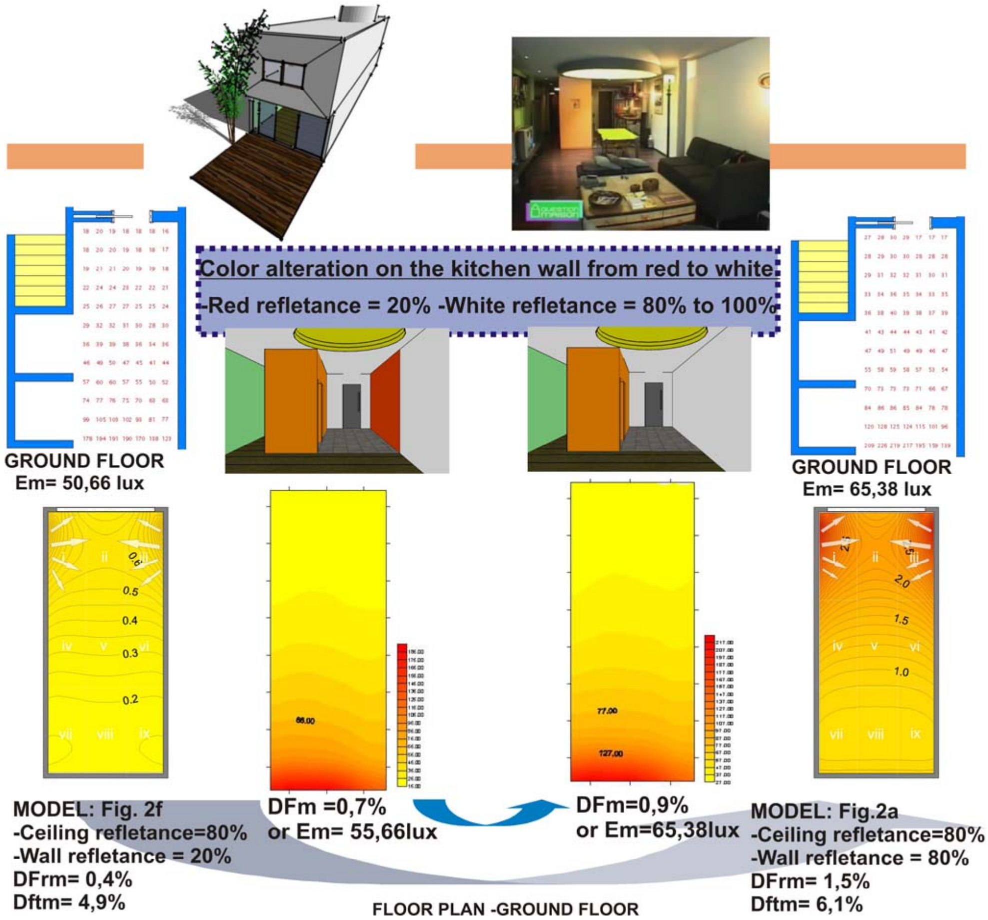


Fig.3. Relationship between theoretical models and architectural example. Residence in Paris.

6. Conclusion

The results obtained led to the conclusion that the surfaces reflectance alteration implies in changes in the light direction intensity only. Just in the extreme case, where a null reflectance to the walls was adopted, an alteration in light direction took place. The reflections that in other models derived from the envelope edges or the opposed surface, came to be distributed radially.

The reflections on the walls are more significant in relation to the ones on the ceiling. Not only because they are almost twice the area, but also for the reason that some portions of these surfaces receive light which comes straight from the sky.

The simultaneous reduction in the wall and ceiling reflectances cause greater impact in the reflected light contribution, to make the lighting environment uniform in spaces whose geometry is intermediary and wide, followed by deep geometry and with less intensity in high spaces.

With regard to the IRC contribution, it can be affirmed that its values increase is assured by a rise in **DFrm** (**D**aylight **F**actor **r**eflected **m**edium), when the variant is the surfaces reflectance that keeps correlation independent from the space geometry. On the other hand, the **DFrm** is highly influenced by surfaces reflectance alterations.

In design applications, it is advisable to choose colours with high reflectances in areas which are more distant from the apertures, with the purpose of reaching a more uniform light distribution. Aiming at a better use of the reflected light in the environment interior areas, the furniture can be used in order to reach these reflectances kinds of combination.

Hence, the internal surfaces most favoured by the sky vision angle will be more expressive in the reflected light direction, followed by surfaces that receive light directly from these ones. The proper use of such surfaces, through their reflectances increase, for example, might improve the environment lighting performance.

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