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Solar control design by matching criteria between its shading mask and the shadow desirability schedule to improve natural daylighting in an office building in the tropic

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Abstract: Natural daylighting issues now are included in the design goals of shading devices, but the meteorological data needed to simulate its daylighting performance are hardly included during the early stages of the architectural design process. When a shadow device is perfectly sized and placed, it does not mask more sky than needed, nor does it allow unwanted solar entrance. To keep undesirable masks at their minimum while keeping desirable masks at their maximum, a perfect coupling is needed, something rarely achieved intuitively. An optimization method starting from minimum input was developed, useful when many of the project's energy efficiency decisions are still to be made. The Solar Coupling index here defined and applied, assess the deviation of an architectural alternative from the "perfect match": the best possible correspondence between the masked region and the shade desirability schedule. The methodology was applied in a 65.000 m2 office tower in Medellín Colombia, applying for LEED GOLD Core & Shell v3. The paper shows the evolution of the facade design process, illustrating the counterbalance between shading, natural daylighting exploitation and required aluminium expenses, illustrating the possibilities of the Solar Coupling method as an early design tool.

Keywords: Shadow efficiency, Shading device, Solar control, Daylighting, Sky visibility

Introduction

To avoid direct solar radiation income during the periods when solar gain will be unwanted is a basic premise of energy efficient buildings. If solar control is handled with high shading coefficient glass, the thermal load reduction will be a transmission-conduction issue. Optionally, when the envelope design includes shading devices, the search for energy efficiency becomes essentially a geometric issue. In this second case, the aim will be to prevent visibility towards the sectors of the sky dome where solar trajectories happen during time periods the shadow will be desirable. If visibility restriction towards those "unsuitable" sectors of the sky dome is not complete, the solar control device will mask a smaller portion of the sky dome than needed, providing insufficient solar control. Shade shortcoming will evolve in higher cooling power needs, higher initial investment in equipment, higher energy consumption of the mechanical cooling system and unwanted solar intrusion. In this situation, it is almost sure that users will try to block annoying solar intrusion by closing curtains or blinds, preventing daylighting and visual contact with the surroundings (William et al, 2012). The opposite situation could also happen: if the shading device masks a broader part of the sky dome than needed, it will include regions where there will not happen unwanted solar trajectories, precisely where the possibilities of taking advantage of diffuse light are the highest (Lan, 1986) (Bodart et al., 2002). Unnecessary sky masking will reduce the possibilities for natural light exploitation and greater use of daytime artificial lighting will be necessary (Reinhart et al, 2006).

Because excess or insufficiency in sky masking has a negative impact on energy efficiency and environmental quality of a building, the ideal situation is to design openings that maximize diffuse lighting while guaranteeing the absence of solar intrusion into the building. Interdependence relationship between diffuse lighting exploitation and shading depends on the geometrical configuration of solar control devices but it is strongly modified by changes in the facade’s orientation, opening’s shape, latitude and site skyline, making the task little intuitive during the preliminary drawings stage. High level of realism is needed for modelling natural lighting from climatic information (Mardaljevic et al, 2009) and that is also the case for thermal modelling (Monteoliva et al, 2012) (Rogers, 2006). Once the design team is finally prepared to provide the architectural information needed for carrying out the dynamic simulations of energy performance and conjugated lighting, the design flexibility is not as high as it was during the early design stages because the project has already gathered enough decisions that limit design choices.

Close correspondence between needed and provided shadow, only depends on the similarity between the masking originated by a shading device and the shade desirability schedule. This compromise relationship reaches an optimal point when a solar control device prevents any solar intrusion without limiting visibility towards any other sector of the sky dome (Figure 1). Reached the maximum level of coupling, mobile shading devices, selective glazing or automated systems would be the ways to continue increasing energy efficiency of an optimized shade (Nielsen et al, 2011). Because such perfect match is rarely perfect, it is important to calculate the bias from this ideal situation and define a metric of the situation since in any of the two scenarios: deficiency or excess, the result will be an increase in the energy needs. Once the design process reaches enough detail such condition is detected easily, but now the adjustment needs will be expensive in time and team effort.

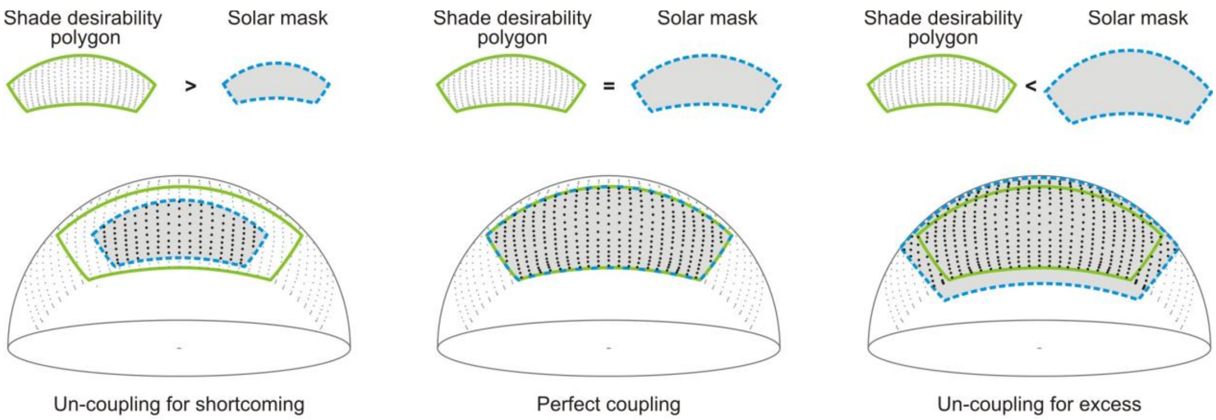

Figure 1 – Relationships between lighting exploitation possibilities and shade. Left: Un-coupling by shortcoming, when the shade desirability polygon is greater than shadow device´s solar mask. The room will be luminous but overheated. Centre: Perfect match. Right: Un-coupling by excess: the shading mask exceeds the desirability schedule. The room will be over-shadowed. Source: Author (2017).

Objective

Early decisions have the strongest impact on design. If the initial drawings provided to start energy detailed studies guarantee the Solar Coupling of every opening is close to its optimal, the starting point of HVAC designers would be better tuned and a solution could be reached in a less expensive way. Taking advantage of the fact that Solar Coupling is just a geometric property and that its calculation requires little input information, an analysis method allowing an early diagnosis of the relationship between natural lighting and shading was developed. The aim was to create and test a tool useful during the facade conception, promoting decisions that favour daylighting and solar protection. The results obtained help the architecture design team to identify the most advisable alternative and find equivalent solutions from the perspective of the natural lighting-shading relationship, quantifying the shade improvement margin of any opening, no matter the geometrical complexity involved.

Methodology

Shading masks are a classic tool of solar design. Basic shapes collections are included in a great deal of Bioclimatic literature (Olgyay, 1963) (Lippsmeier, 1969) (Baruch, 1976) (Szokolay, 1977) (Yáñez, 1988). Superposing a shading mask over a solar chart and count masked solar positions is a simple way to estimate the efficiency a solar control device will have. Additionally, the counting of non-blocked positions is the simplest method to know its optimization margin. Solar Coupling calculations and the computer code that allows its practical application are based on the relationships between spherical polygons obtained from the shadow desirability schedule and the opaque elements surrounding every studied opening. In order to make the calculations, initial 3D polygons must be transformed in 2D shading masks. Transform three-dimensional opaque elements representing a shading device into their corresponding spherical polygons, required to divide every one of their sides into short segments. Once those segments were drawn, every vertex was transferred towards a spherical surface representing the sky dome using size relations between similar triangles from a point operating as the polar coordinate system origin (Figure 2). Using geometric transformations applied on individual points instead of deriving trigonometric functions for specific shapes, is what allowed calculating the shading mask for any opening, regardless of its geometric complexity.

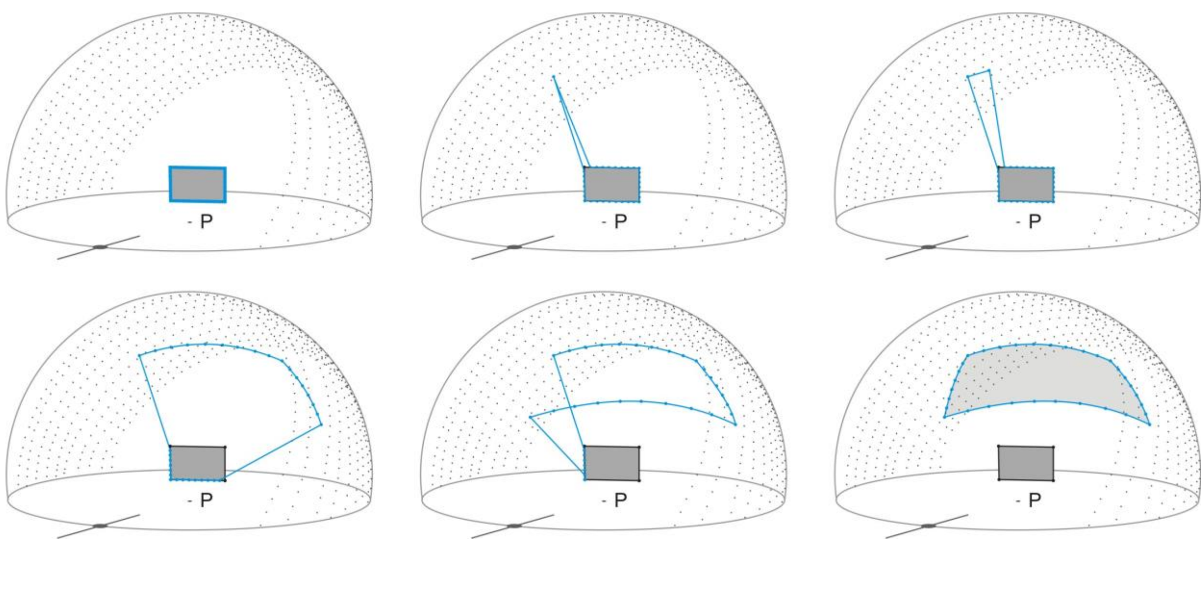

Figure 2. Drawing of a spherical shading mask. Transformation of any opaque element into its corresponding masking polygon from point P. Source: Author (2017).

To calculate masked sky regions, thousands of randomly distributed points on a spherical surface representing the sky dome were counted. Applying an algorithm previously developed that allows to determine whether or not a point is included in a closed polygon (Salazar, 2009), the belonging condition of every point to every group of spherical polygons was verified to classify them into four sets: Shaded (points included in the masked region and belonging to a shadow desirability polygon). Not Shaded (not included in the masked region and belonging to a shadow desirability polygon). Visible (not included in any masked region) and Not Visible (included in the masked region but not belonging to any shadow desirability polygon). This last set of points corresponds to the part of the sky unnecessarily masked. The counting of points belonging to those four sets allowed to calculate the proportions among the different regions in which the sky dome is divided by an opening, its shading elements and the neighbour objects. The addition of those four percentages is always equal to the unit (Figure 3, left).

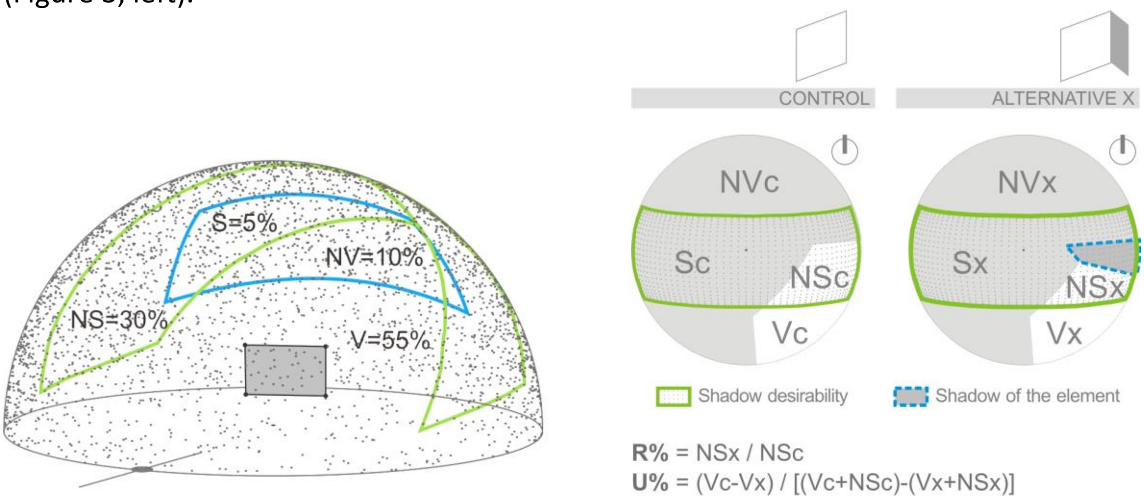

Figure 3: Left: Points classification depending on whether or not are included in the shading desirability polygon (green) and/or the shading mask (blue). Four groups were defined: Shaded (S), Not-Shaded (NS) corresponding to the shade shortcoming, Visible (V) and Not-Visible (NV) corresponding to the unnecessarily masked sky. Right: Remanence (R%) and Un-coupling (U%) of a shading element by means of the comparison between the studied alternative and a control opening used as a reference. Source: Author (2017).

Solar Coupling depends on masking polygons size and position. When shade sizing is done, the masked region at least should be as wide as the shading desirability polygon. This first condition is verified when the Not Shaded value (NS) is equal to zero. Besides, the masked region should not include portions of the visible sky dome, situation reached when the Not-Visible value (NV) is equal to zero. As can be noticed, the best possible condition happens when the masking polygons and the shading desirability polygons meet point by point. To define the Solar Coupling as a property of comparative nature, a reference case is necessary. The obtained values (Vc and NSc) from a control opening used as a reference and the subsequent values (Vx and NSx) from any opening, allowed calculating the Un-coupling U% and Remanence R% using equations 1 and 2. The former is defined as the percentage of the sky dome that has been masked even though it is not part of the shading desirability polygon. The last defined as the percentage of solar positions that should be blocked but have not been masked yet (Figure 3, right). Both values expressed as a percentage of the control opening.

$$U\% = (Vc-Vx) / [(Vc+NSc)-(Vx+NSx)] \quad \text{Eq. 1}$$

$$R\% = NSx / NSc \quad \text{Eq. 2}$$

Minimizing the un-coupling (U% close or equal to zero) while guaranteeing the shading conditions previously established (R%=0) is the path to design shading devices causing a minimal restriction to natural light exploitation. A maximal un-coupling (U%=100) means that the shading device does not block any additional part of the shading desirability polygon compared to the reference opening. A maximal remanence (R%=100) means that the alternative being evaluated does not offer any additional masking compared to the reference opening.

Results and discussion

To test the method three shade alternatives on a prototype square opening located in latitude 6.25°N were evaluated. The calculations considered three shade sizes in a progressive width of 0.50m, 1.0m and 1.50m and the Solar Coupling diagrams (Figure 4) show the obtained results. The reference opening: same size and orientation without any shadow element in front of it, is always located at the upper right side of every diagram, while the best possible value corresponds to the origin. The Un-coupling (U%) lies on the abscissas: as a point moves away from the origin, it will unnecessarily mask a greater part of the sky dome. The remanence (R%) is on the ordinates: as a point moves away from the origin, it will leave unmasked a greater part of the shading desirability zone.

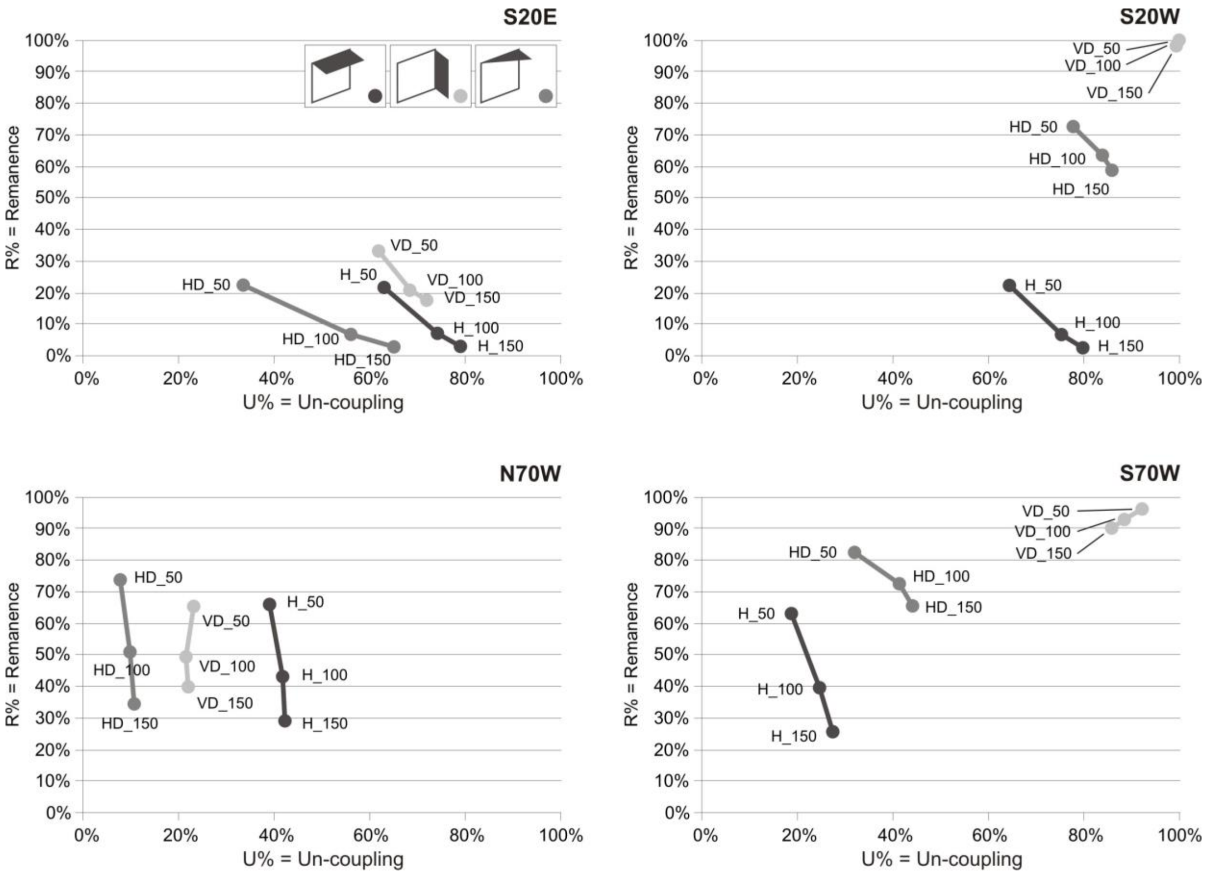

Figure 4. Solar Coupling Diagrams of a square opening facing different orientations in latitude 6.25°N. Three shading alternatives of increased width in cm were used: Horizontal overhang (H), Vertical fin (VD), and Triangular shade (HD). The control opening used as reference maintains size and orientation but lacks of any shadow element and its obtained value is always located at the upper right side of every diagram. The best possible Solar Coupling attainable corresponds to the origin. Source: Author (2017).

Points vertically lined up will generate equivalent unnecessary sky dome obstructions, but the one placed the lowest will have a better solar performance since it leaves fewer solar trajectories unprotected and, therefore, will generate less solar direct gains. Points horizontally lined up leave equivalent portions of the shading desirability polygon unmasked, but the one located farthest to the left will be preferable, since it will allow visibility towards a greater part of the sky dome and, therefore, will favour a higher level of daylight exploitation.

The prototype window test revealed significant differences between the shade alternatives evaluated. As can be noticed in figure 4, for a S20W square opening changing from 0.50m vertical elements to horizontal ones would reduce up to a fifth the solar income without important changes in its level of light exploitation. The situation is totally different in S20E openings, because same change would halve the natural lighting possibilities without any significant reduction in the solar gains. It is possible to make other comparisons, e.g. shape changes are more favourable than shading device enlargement in some orientations.

Figure 5. Left: Business Centre “Milla de Oro” designed by AIA in 2012 and located in Medellín, Colombia. Right: Built façade, corresponding to the alternative number 15 in figure 6. Photo: Valentina Zuluaga (2017).

Finished the test, the method was applied in the facade design of a 65.000 m^2 Business Centre located in Medellín Colombia (6.25°N, 75.6°W and 1550m above sea level). The “Milla de Oro” project, designed by AIA Architects and actually applying for LEED GOLD Core & Shell v3, proposed since the first sketches a high level of shadowing instead of the high reflectance glazing, the standard look of an office building in the city. A single 0.70m overhang at 2.70m height is the starting point of the analysis. The office towers have two west facing facades maintaining a single shade design in both orientations in order to have rounded corners. The South West façade has the highest solar exposure and the shading devices were designed under SW considerations. It explains why the obtained results are better than the North West results, where the façade is slightly overprotected and gets less natural lighting than the maximum for its orientation would allow (Figure 6).

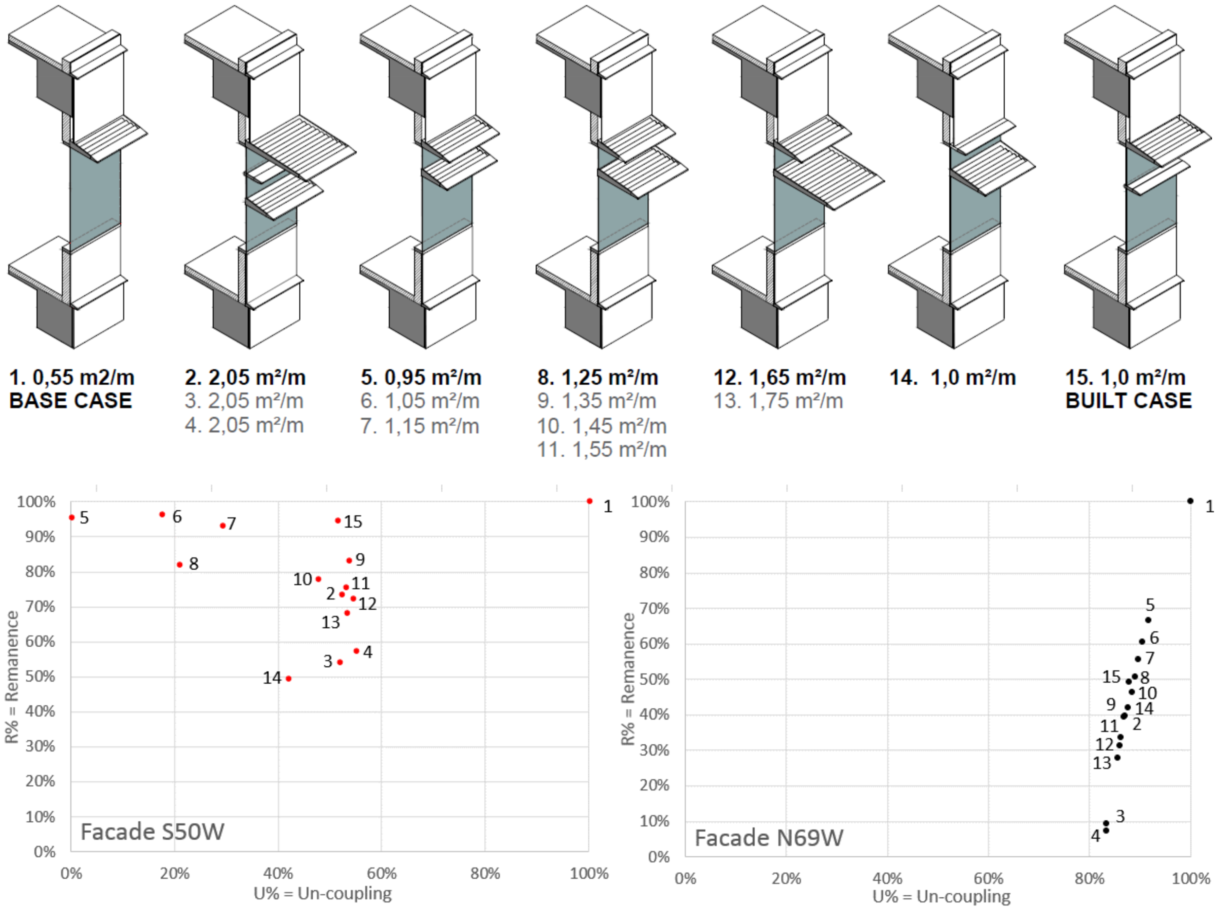

Figure 6. Sketches evaluated during the first design stages and its aluminium needs. Below, the corresponding Solar Coupling Diagrams in South West and North West facades. Source: Author (2017).

The 15 evaluated alternatives and the aluminium needs expressed in m^2 of aluminium per typical floor facade metre, reveal the explorations made during the early stages of the architectural design. In the beginning (alternatives 2, 3, 4) the aluminium needs were high, testing the possibilities of use clear glazing. The corresponding results (points 2, 3 and 4 in both diagrams) reveal the performance of design choices equally expensive. Once the aluminium investment needed to counterbalance the wind loads was included as a design variable, sketch number 5 show an aluminium cut off. Several choices considering two shelves and glazing as clear as possible (alternatives 6 to 11) were evaluated. Sketches number 14 and 15 show the final choices under consideration. From this point detailed thermal load calculation started, orientated to HVAC design and to define the final glazing specifications.

Conclusions

Show the Solar Coupling in an intuitive diagram, easy to understand even for people with basic knowledge on energy efficiency, allows that Architectural design teams interested in energy conservation promote lower energy demands from the early design stages. Starting from basic geometric information make possible to compare between similar façade sketches, identify the optimization margin and visualize the effectiveness of decisions oriented to minimize solar intrusion, maximizing the natural light exploitation possibilities and improving indoor environment conditions.

The method used to calculate the Solar Coupling in the Business Centre allowed to define numerically a minimal coupling threshold and to work to reach it from the early design stages. The typical un-coupling values in built facades frequently will surpass the ideal value, but the distancing from this theoretical situation constitutes an unbiased method to quantify the mismatch between the solar performance of any shading device and the best attainable condition.

To give opportune information according to design team agenda, a homogenous sky model was used to reduce computing time. Further improvements can be included (e.g. solar data, cloud coverage and ground reflections), but including climate data and materials optical properties would take out the method from the domain of the standard team that produce architectural sketches, leading the research to the natural lightning prediction area.

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