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MC 12-29: Design and validation of a daylight responsive façade system

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Abstract
Despite the increased awareness on the energy potential of performance oriented design, there are few examples in building practice. This study, which was developed during a TU Delft Master thesis in collaboration with the firm "Broekbakema", aims at providing an integrated design process for the daylight assessment of a typical office space in the high-rise project, currently designed by the firm in the Netherlands. For this reason, the geometry of a north-south oriented modular unit was tested via the Dialux lighting simulation software, while the Ecotect databases on solar altitudes provided input for parametric scripts of rotating reflectors for daylight enhancement. Their finalized positions and design were validated through simulations in DAYSIM Radiance tool. Luminance output was used to evaluate comfort. The study achieved to provide performance evaluations during the early design, to validate a daylight responsive façade system and formulate a method for daylight comfort regarding inadequately lit spaces.

Keywords: daylight responsive façade, Radiance, office spaces' daylight assessment

Introduction
The biggest opportunities for the improvement of a building's CO_2 footprint lie within decisions made during the conceptual phase of the design, when orientation, massing, materials and systems are proposed (Gane, Haymaker, 2010). Such a realization led the design team of the "Broekbakema" architectural office to set an inter-disciplinary approach to lay the basic principles for the elaboration of the design of a sustainable high-rise, regarding engineering input, both in relation to the bear-loading structure and to the climate concept of the building. The daylight assessment of a typical unit of the building was the scope of this study, which evolved as part of this broader frame.

In principle, climate-based daylight modeling (CBDM) can be achieved either by using computer simulation techniques or physical scale models in a sky simulator. However, most of the studies carried out today use computer simulation techniques. For the needs of the present study three different software packages were used; DIALUX for the tests on the overall geometry, since it can provide fast output of the illuminance values and indicate the daylight factor on a set calculation plane. The results from DIALUX were used to specify optimal configurations of the given geometry. ECOTECT provided a complete database in order to obtain the solar altitude and azimuth especially for the solstices and equinoxes. RADIANCE as a calculation tool of Diva for Rhino was utilized, in order to test the performance of sun-control systems and their effect on the luminance levels of the interior. Radiance was also used for comfort validation so as to estimate the levels of luminance within the field of view at different positions in the room and the overall glare probability (DGP) of the scene.

Case Study

The site refers to a 185m x25m lot, location: 51.923732^{o}, -4.467625^{o}, Conradstraat Rotterdam, north-south oriented, which can be built up to a height of 150m. The anticipated annual hours of sunshine are 1601.5h, with maximum sunshine duration in summer and minimum sunshine duration in winter (June: 192hours, July: 205hours, Aug.: 197 hours/ Nov.:59hours, Dec.:43hours-Jan.: 54hours, source: annual report for 2010, The Royal Netherland Meteorological Institute).

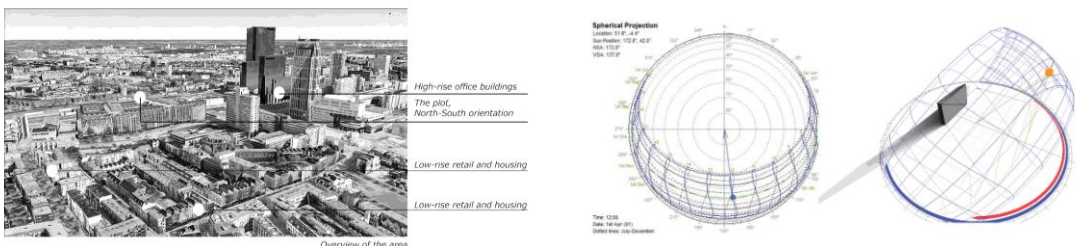


Figure 1. Left and right; Overview of the plot and the building volume in its context, right; sun path and shading (Ecotect).

The building was conceived as a sequence of spaces that occupy a central core, parallel to its length. Around the core a corridor has been designed, in the form of two overhangs, towards the north and the south side of the building. The extreme dimensions of each modular unit, 13x13x22m and the sizing of its elements (1.5m for slabs and 0.75m for interior elements) as well as the sizing of the overhangs (ranging between 7-9m) were the first parameters to be tested, in order to specify the most problematic zones and define the maximum number of floors that could possibly occupy the interior.

Methodology

The modular unit as described above (Fig.2) is assumed as a north-south lit volume. (Reflectance values; walls=50%, floors=20%, ceiling=70%, glass=6%/glass transparency=70%). The study evolved as follows: Tests on the primary geometry were performed, including the specification of the possible number and position of floors. The simulation output provided a correlation between light-levels and length of overhang/ floor -position. Further-on, a number of gaps were opened in the overhang in order to test possible improvement in illuminance values. For this set of tests the model was simulated as single- glazed towards the interior and without glazing towards the ends of the overhangs due to the calculation restrictions of the DIALUX software regarding double glazed cavities.

Literature study led to a classification and analysis of daylight-control systems, including light shelves, mirror reflectors, anidolic collectors, light ducts and light tubes. The most commonly applied system is based on the light shelves, for reasons related to their functionality, their integration in the architectural design, the low maintenance and installation costs and the effectiveness of performance. Consequently, a system of light shelves that work as specular reflectors at various positions on the façade, was chosen. A number of tests were undertaken for the validation of an optimal design for the reflectors.

Five types of reflecting panels (light shelves) were compared; typical flat surfaces (aluminum semi-spectral), typical curved surfaces (50mm lamellas, aluminum semi-spectral) and the Köster lamellas' cross- sections RETROflex, RETROluxU, RETROluxO (aluminum semi-spectral) as an alternative to the current curved reflectors (www.koester-lichtplanung.com). The tests were performed for March21st and June 21st. The evaluation of the results was based on the luminance values and their distribution as measured by DAYSIM. Following the validation of the reflector typology, tests were performed in order to specify the necessary number of reflectors and their rotation angles and positions on the façade. Finally, comfort was assessed for a typical office space behind the proposed façade system; Radiance was used to estimate the levels of luminance within the field of view from workstations in different zones of the room.

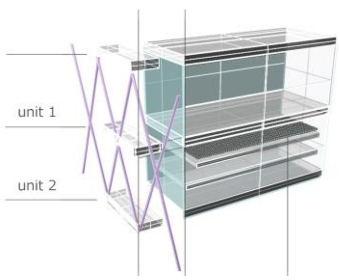


Figure 2. Simulation model; the unit

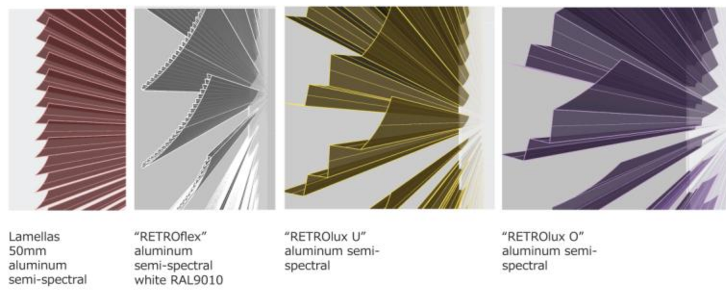


Figure 3. Typical lamellas 50mm and the 3 Köster systems.

DGP

The most critical luminance relationships to be reviewed are those between the daylit opening, its immediately adjacent surfaces and the surfaces surrounding the work stations (Osterhaus, 2005). The DGP (Daylight Glare Probability) values provided an indication of the glare effect anticipated in the interior. The DGP percentage is a function of the vertical eye illuminance, the glare source luminance, its solid angle and position index as expressed in the equation:

$$DGP = 5.87 \cdot 10^{-5} \cdot E_v + 9.18 \cdot 10^{-2} \cdot \log\left[1 + \sum_i \frac{L_{s,i}^2 \omega_{si}}{E_v^{1.87} \cdot pi^2}\right] + 0.16$$

(Wienold, J., Christoffersen, J., 2006). Where E_v is the vertical eye illuminance, $L_{s,i}$ the luminance of the source, ω_{si} the solid angle of source, p the position index. The position index expresses the change in discomfort glare when the position of the source changes in relation to the eye of the observer as seen in the equation:

$$\ln P = \left[35.2 - 0.31889\tau - 1.22e^{\frac{-2x}{9}}\right] 10^{-3} \cdot \sigma + \left[21 + 0.26667\tau - 0.0029\tau^2\right] \cdot 10^{-5} \cdot \sigma^2$$

Where τ the angle from vertical of plane containing source and line of sight and σ the angle between line of sight and line from observer to source . The above equations prove the importance of the following parameters for the evaluation of glare: the position of the observer in the scene (camera in the software environment), the angle of visual field and the relative position of the sun.

Results

More than 70% of the interior is adequately lit by daylight if no floors are added. No more than 2 floors should be placed inside the unit. In such a case the optimal solution is

to position the first floor at a height of 4.50m and the second at a height of 9m. Three illuminance zones were specified: Highly daylit area: zone1 = 2EWH = 2abτ/c, Intermediately daylit area: zone2 = 1.5EWH + 2EWH (Osterhaus, 2005).
Where *a* is the width of the window above 0.9m, *b* is the height of the window above 0.9m, *c* the width of the window and τ the transmission of the window plane (for low-e coating τ= 75%). The illuminance values change as seen in Fig.4. From zone1 to zone2 (4.58 m) illuminance drops by 4.3%. Further in zone 2 (7.328m to 12.869m) illuminance drops by 0.5% (Calculation plane: height=0.75m from each floor slab, precision of calculation: 225 nodes).

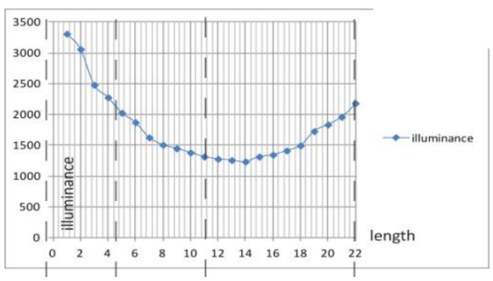


Figure 2. Drop of illuminance across the Floorplan

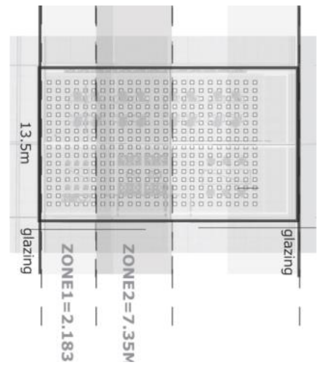


Figure 3. Floor plan; Three zones

Further-on, the overhang is altered so that light can penetrate it. The minimum gap for a slab thickness=1.5m is 2.5m so that the illuminance values are improved for the 3rd floor, zone 1 and 2, for a clear sky. The impact on floor 2 and 1 is not significant.

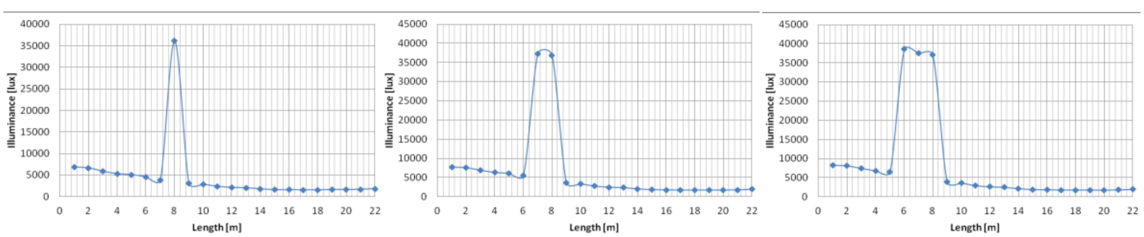
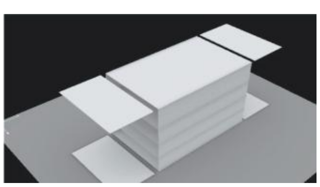
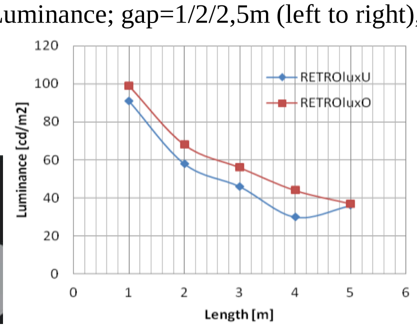


Figure 4. Luminance; gap=1/2/2,5m (left to right), 3rd floor, March 21st





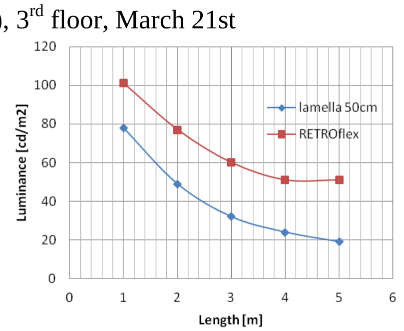


Figure 5. Model with gaps

Figure 6. RETROlux-U vs RETROluxO

Figure 7. Lamella50mm vs RETRO-flex system

According to the luminance values acquired from DAYSIM, the cross-section of the RETROflex system is the most efficient in reflecting the incident light deeper into the unit. The tests measured the levels of apparent brightness and its distribution for a clear sky for June21st (Fig.8, 9). For the validation of the positions of the reflectors, the systems were tested for March 21st and June 21st for a clear sky. The DAYSIM results proved that a system of small-scale lamellas does not contribute to the enhancement of the light levels inside the building (Fig.10; radial=0.66m, in-between distance =0.28m, rotation angles: 24^{o}, 156^{o}). For this reason, the lamellas were resized (x3). As proven by the tests, the bigger the radial length of the blade, the more effective it is in terms of light reflectance (Fig.11, luminance distribution). Yet, the relationship size/light performance is not linear. When the size and vertical distance of the reflectors change with a factor of 3, the light levels change with a factor of 1.7. The most favourable luminance values/distribution were reached for a system of 3 reflectors with radial length L=2m. In this case two of them should be placed towards the exterior end of the façade with a vertical distance of 1.25m and rotation angles of 11^{o}, and one towards the interior of the corridor with 176^{o} rotation (Fig.11).

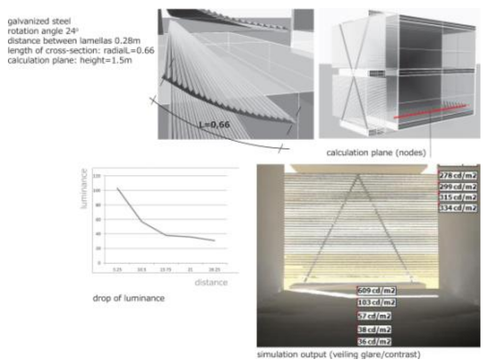


Figure 8. Test for reflectors, radialL = 0.66m

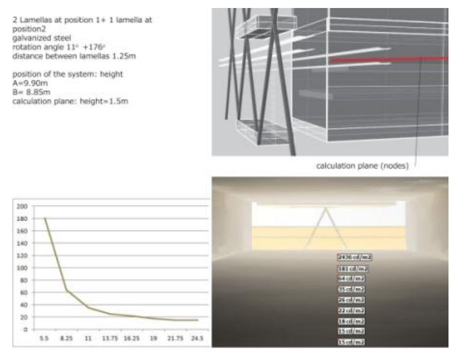


Figure 9. Test for reflectors, radialL = 2m

For comfort evaluation the tests were performed for zone2 and 3, and the camera was placed at the height of the individual sitting at the workstation (h=1.3m; height slightly above the averages 1135-1325 for men, 1055-1230 for women). The average luminance ratios for zone 2 were; ceiling/desk=1/5, window/desk=1/19 (within acceptable limits; Osterhaus, 2005). Only a zone of a width of 2.9m in the centre of the third floor is expected to be underlit during the year. This zone is expected to give high contrast values, due the extreme difference in apparent brightness between this area and the window plane. The DGP ranges between 26% and 28% for the summer (9:00 to 18:00) and between 24% and 30% for winter (9:00 to 16:00). Glare is observed only for the evening hours due to the low position of the sun. For those hours shading is necessary.

Figure 10. GP28% zone2, camera h=1.3m, June21st, clear sky, 11:00

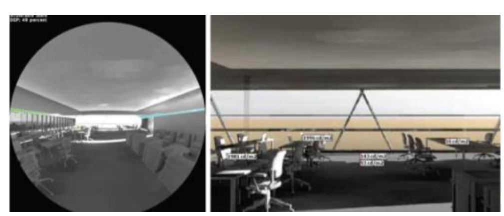


Figure 11. GP49% zone2,camera h=1.3m, June21st, clear sky, 18:00

Conclusions

Daylight validation led to alterations during the concept phase of the design of the specific case-study as presented in this paper, and to the design of a system of reflectors that can be applied on the façade in order to improve the levels and the distribution of daylight in the interior and consequently enhance the use of daylight for the illumination of a building during working hours. At the same time a new method is proposed in this study, aiming to the daylight assessment and improvement of under lit spaces is composed in the following steps:

1. A general evaluation of the daylight condition due to the geometrical characteristics of a space. This can be obtained via simulation software (illuminance output). If needed, an elaboration of the results can be obtained by adding the reflectivity and the color of the materials to the parameters used.

2. Enhance the daylight by using a system of reflectors. The basic characteristics of the reflectors have to be specified and include; the cross-section, the minimum vertical distance between the reflectors (half of the axial length), their size. The improvement of performance to the increase of the reflector size follows a ratio close to 2/3.

3. Comfort assessment; This can be performed using DAYSIM simulations via the following measurements: a. Distribution of luminance inside the room, b. Contrast between adjacent spaces, c. Contrast between ceiling and working plane, d. Contrast between window and working plane, e. The DGP values.

Summary: position and rotation angle of the panels for the redirection of light.

March 21st		10:00 am			11:00 am			12:00 am			13:00 am			14:00 am		
		θ=29.6°			θ= 34.9°			θ= 37.6°			θ= 37.3°			θ= 34.1°		
		pos1	position2		pos1	position2		pos1	position2		pos1	position2		pos1	position2	
		pl1	pl2	pl3	pl1	pl2	pl3	pl1	pl2	pl3	pl1	pl2	pl3	pl1	pl2	pl3
	height of reflector (m)	4.5	7.2	2.53	2.5	5.65	0.73	2.5	5.65	0.73	2.57	5.65	0.76	2.17	5.67	0.73
	rotation angle of reflector	0°	7°	7°	0°	7°	7°	0°	7°	7°	0°	7°	7°	0°	7°	7°
June 21st		09:00 am			10:00 am			11:00 am			12:00 am			14:00 am		
		θ= 42.7°			θ= 51.1o			θ= 57.7°			θ= 61.3°			θ= 55.6°		
		position1		position2	position1		position2	position1		pos2	position1		pos2	position1		pos2
		pl1	pl2	pl3	pl1	pl2	pl3	pl1	pl2	pl3	pl1	pl2	pl3	pl1	pl2	pl3
	height of reflector (m)	2.85	7.7	0.96	2.85	7.7	0.96	5.76	10.86	1.90	5.9	10.45	0.45	7.48	11.00	0.42
	rotation angle of reflector	16°	16°	16°	16°	16°	16°	24°	24°	24°	25°	25°	23°	23°	23°	19°

Figure 12. Rotation angles and height of the 3 reflectors

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