Modern Environmental Science and Engineering (ISSN 2333-2581)
May 2016, Volume 2, No. 5, pp. 358-364
Doi: 10.15341/mese(2333-2581)/05.02.2016/009
Academic Star Publishing Company, 2016
www.academicstar.us

A New Dynamic Climate-Based Daylight Metric for Sustainable Building Design in Hot Climates

Muhammad Adel A. Mahmoud[1], Islam Ayman Mashaly[2], Yussra Mohamed Rashed[2], and Khaled Nassar[2]

1. Housing and Building National Research Center (HBNRC), Egypt

2. Department of Construction and Architectural Engineering, American University in Cairo, Egypt

Abstract: Daylight performance metrics are moving away from the traditional daylight factor and average illuminance to more climatic-based metrics such as Daylight Autonomy (DA) and Useful Daylight Index (UDI). These metrics offer a better measure of the daylight performance throughout the year and incorporate the varying weather conditions and as such are dubbed climatic-based metrics. However, in hot climates where the ratio of direct to diffuse is highest, achieving these metrics may result in over-heating the spaces. Achieving acceptable climatic-based metrics for the space may result in unacceptable heat gains. The Day light Autonomy and the Useful Daylight Index do not account for the total amount of lux-hours achieved throughout the year. The solution thus far has been to run coupled-energy and daylight simulations and in order to assess the effect of achieving certain climatic-based metrics on the heat gain and thermal performance of the space. In this paper a new metric is proposed that takes into account the total amount of lux-hours achieved throughout the year and the irradiation for different time step into a single measure. Details about the measure and sample test cases are presented.

Key words: climate-based, simulation, daylight, sustainability

1. Introduction

In order to assess the daylighting performance of a particular design climatic (often called dynamic) daylighting measures are used. These measures relate the degree to which a particular level of required illumination is achieved throughout the year. Since there is a direct relationship between the total amount of lux-hours and thermal heat gains, it may be of importance to develop a metric that rewards achieving the required illuminance levels throughout the year while minimizing the total amount of lux-hours that are achieved in times of the year where cooling may be required for example. This means that the weather conditions at the times in which the designer daylight metrics were computed needs to be taken into consideration. An accurate indication of the weather conditions at different times is cooling and heating degree days. It is therefore desirable to increase the amount of lux-hours when the heating degree days are highest and minimize the lux-hours values during hot times when the cooling degree days are highest, simultaneously while increasing metrics such as the DA and the UDI

Our aim here is to develop a new measure that takes into account the thermal aspects associated with daylighting. Daylighting and solar thermal gains are often positively correlated. In particular, if a specific design achieves acceptable scores for the climatic-based daylighting measures, then it may be often the case that this can be on the account of exceedingly high thermal gains. A number of previous studies have considered the interrelation between day light performance and thermal performance such as R. Sullivan et al. (1992) [1] and C. A. Johnson et al. (1999) [2] and more recently Ochoa et al. (2012) [3],

Corresponding author: Muhammad Adel A. Mahmoud, Ph.D. Candidate, Assistant Researcher, research areas/interests: daylight simulations. E-mail: Muhammad.adel@hotmail.ca.

Tsikaloudak et al. (2012) [4], Aldawoud (2013) [5], Lee and Tavil (2007) [6], Inoue et al. (2008) [7], Athienitis and Tzempelikos (2002) [8].

Without any particular design treatments, then as more daylight is achieved the thermal loads would increase. To examine this, a chart was created to assume the relation between daylight and thermal load, as shown in Fig. 1. In Fig. 1, the theoretical values for the irradiation and the amount of lux-hours achieved throughout a year for a standard room is plotted. By increasing the window size the lux-hour increase as well as the amount of direct and diffuse solar gains of the space.

The amount of lux-hour increase is one measure of daylighting performance but as several researchers have noted before is not a very valid or accurate one. Hence the need for the climatic-based or dynamic based measures. It is expected that there is a direct relationship between the thermal gain and the daylighting performance for a particular design. The thermal gains could be measured in many terms, one of the most direct measures is, for instance, the cumulative hourly direct irradiation, but on the other hand we may make use of the several climatic-based measures.

The relationship may assume a linear or depending on the actual design parameters, i.e., there may be some designs that allow for the same daylight performance but with a varied degree of thermal gains. This happens in cases where complex fenestrations systems for example can be used or when specific shading devices or glazing treatments are utilized. In absence of complex window designs or treatments it is expected that this range is minimal. This trend continues until the maximum value for the daylight measure can be achieved after which no possible improvements in the daylight performance can be achieved. The remaining design cases after this point all increase the amount of thermal gains with no or even worsening values for the daylight performance measures.

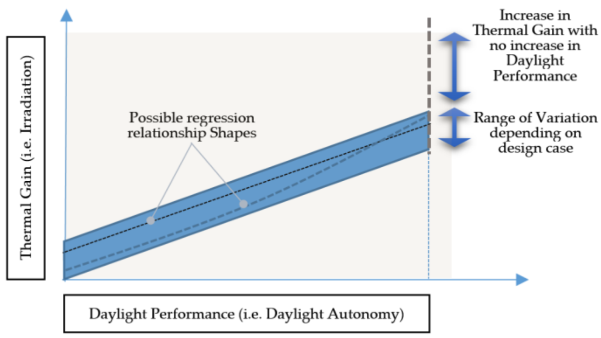


Fig. 1 An assumed relationship between daylight performance and thermal performance.

Some climatic-based or dynamic based measures may result in worse values after a certain point and others may reach their maximum value and hold. Those measures that penalize for over lighting for example would start to drop while others that do not will hold at maximum values. This specific trend is explored in this paper as will be described in the next sections.

The remainder of this paper is organized as follows; we first start with a description of the experimental set up and then go to discuss the simulation parameters and methodology. This is followed by a presentation of our proposed measure and a review of the simulation results. Finally conclusions and recommendations for future research are presented.

2. Layout and Considered Configurations

In order to be able to study the interrelation between daylighting performance and thermal performance and explore the theoretical relationship proposed above, a parametric model using Grasshopper for Rhino was developed. The model is shown in Fig. 2 and is divided into five main parts. The first portion of the definition is used to control the various parameters used in the simulation. The second part of the model is used to modify the window to wall ratio of the typical room used. The standard room used is based on the one developed in Wagdy (2013) [9].

In this part of the model the window to wall ratio is varied in a systematic method as described in Wagdy (2013) [9], so that the various design parameters are varied systematically to increase the increments of the window to wall ratio. Firstly, the height is changed to the maximum value, then the width and finally the sill height are increase at certain increments to maintain unit step increases in the WWR.

This is shown in more detail in Fig. 3. The developed grasshopper model then makes use of the Diva interface to send the simulation to RADIANCE for a full analysis and results generation, which makes up the third part of the grasshopper definition. In the fourth part the grid and sensor values are calculated and finally in the last par the results are exported to excel.

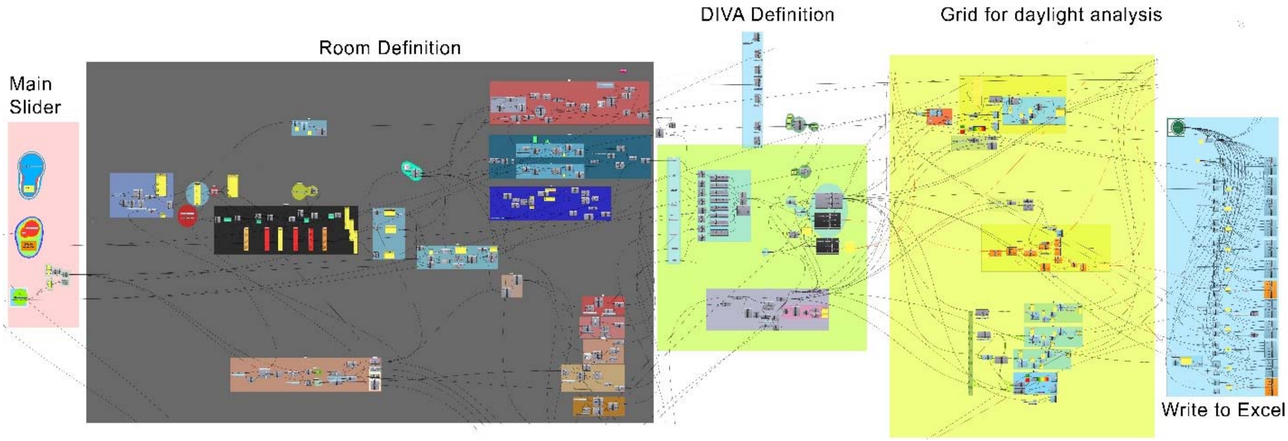


Fig. 2 Model development window to wall ratio (WWR) variations.

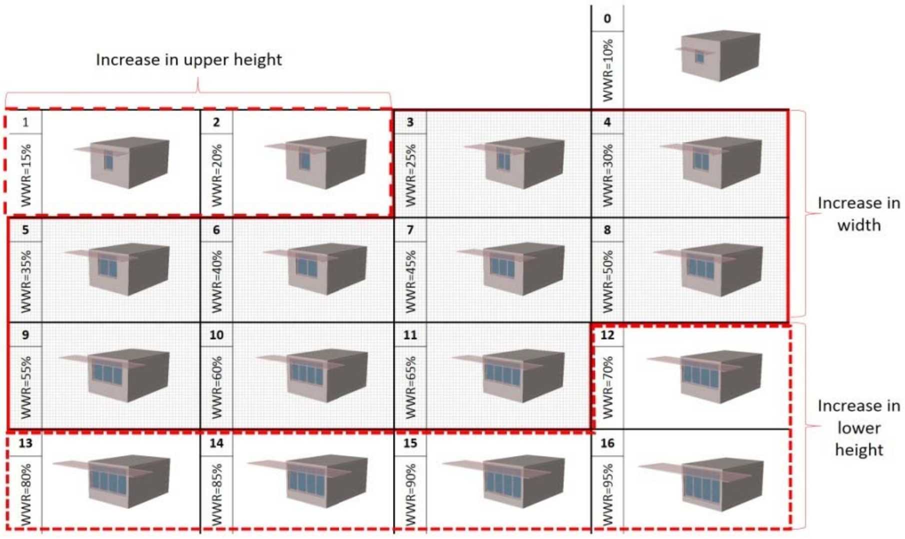


Fig. 3 Model development window to wall ratio (WWR) variations.

It is important to note that a shading device is used that a constant shading angle is kept constant throughout our simulations as shown in Fig. 4. The two extreme cases of south and east facades are considered here, since they would tend to more clearly demonstrate the relationship between daylight and thermal performance.

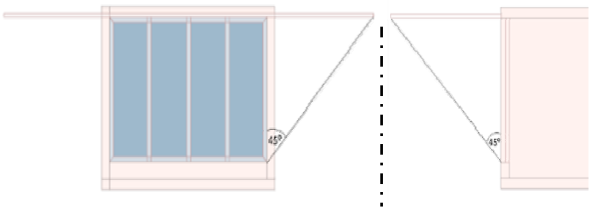


Fig. 4 Shading geometry, this shading angle is constant for all cases.

Simulations are carried out and in total 17 cases are considered as can be seen in Fig. 3. For each case the solar irradiation is calculated at each of the room's sensor points. In addition, for each case considered the Daylight Autonomy (DA) was calculated. Daylight Autonomy (DA) is one of a number of daylight metrics that consider the annual performance of a particular design. DA basically represented as a percentage of annual daytime hours that a given point in a space is above a specified illumination level [10].

The measure was originally proposed by the Association Suisse des Electriciens in 1989 and was later developed by Christoph Reinhart between 2001 and 2004 [11]. Daylight Autonomy considers the specific geographic location for a particular space and hence uses the actual weather information on an annual basis.

In addition, since it represents the times that artificial lighting may not be needed it is strongly related to electric lighting energy savings if the user defined a specific threshold that would bet based upon electric lighting criteria.

The designer is usually free to set a specific limit above which Daylight Autonomy is calculated. In our simulations we used a typical value for Daylight Autonomy threshold of 300 lux (DA300). The Daylight Autonomy percentage calculation represents how much of the floor area achieved 50% or more daylight autonomy in DIVA analysis.

$$\text{Rooms DA\%} = \frac{(No.of\ nodes)_{sDA\geq 50\%}}{Total\ No.of\ Nodes} \quad (1)$$

Table 1 shows the different parameters used in running the simulation. The RADIANCE parameters are shown in terms of the number of ambient bounces and ambient divisions as well as other parameters. In addition, the different parameters used for the typical space are shown.

3. Results and Discussion

Coupled thermal and daylight simulations were first carried out for the 17 cases of different WWR to

Table 1 The room and simulation parameters used for all simulation cases.

Room Dim.	L = 6 m, W = 4 m, H = 3 m	
Simulation Parameters	ab(ambient bounces)	06
	ad(ambient divisions)	1000
	as (ambient super samples)	20
	ar (ambient resolution)	300
	aa(ambient accuracy)	0.1
Assigned Materials	Walls; Generic Interior Wall	Reflectance = 50%
	Floor; Generic Floor	Reflectance = 20%
	Ceiling; Generic Ceiling	Reflectance = 80%
	Window Frame	Metal Diffuse
	Window Glazing; Double Pane	Transmittance = 80%
	Shading; Outside Facade	Reflectance = 35%
	Ground; Outside Ground	Reflectance = 20%

increase the solar irradiation and the lux-hours coming into the room. Figs. 5 and 6 shows the annual cumulative irradiation at each sensor point for all the 17 cases versus the average Daylight Autonomy values at those same sensor points. This is shown for the south and east facades separately.

The graphical percent values represent the percentage of the floor area that exceeds 300 lux for at least 50% of the time. The results follow the assumed shape discussed in Fig. 1. Note that there may be different sensor points, where higher irradiation values are realized, while achieving the same DA performance. This is due to the fact that points on the inside of the space in one of the cases for example may have the same daylight performance as another sensor point further out in another case.

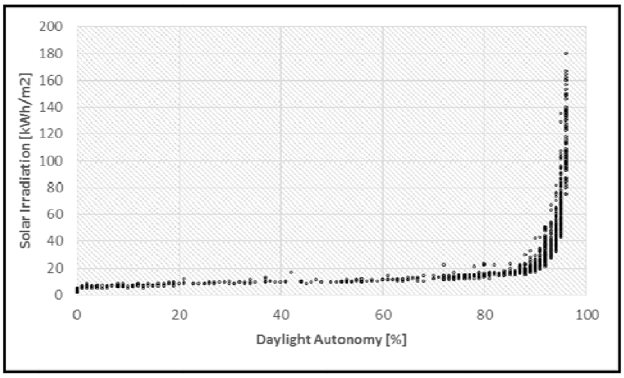


Fig. 5 Solar irradiation versus DA for South facing orientation at different sensor points for all 17 cases.

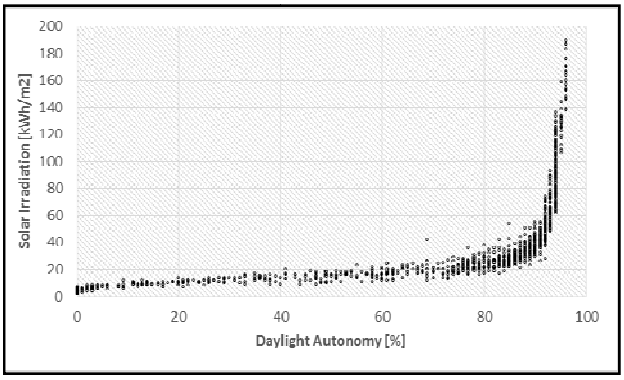


Fig. 6 Solar irradiation versus DA for East facing orientation at different sensor points for all 17 cases.

It is also interesting to note that the variation in the east is more profound, i.e., that for the east façade points such as the ones we noted in different cases will result in wider variations in thermal irradiation with the same values for DA performance. This means that the gap in the assumed Fig. 1 is wider for the east façade compared to the south one. This is expected since in the east façade will have varying amount of direct radiation due to the movement of the sun compared to the southern façade which may have more uniform solar radiation falling on it.

In order to study the results further, Figs. 7 and 8 show the solar irradiation versus the DA for the south and east facing orientation for the 17 test cases. The results shown in these figures is basically the aggregated values of each of the sensor points for each case.

The average cumulative annual irradiation for all the sensor points for each cases is presented with the average DA performance for the sensor points in each case. As such there are 17 data points in each graph, one for the south facing façade and another for the east facing facades. Again the same trend expected as in figure 1 above, holds for the aggregated values of the test cases. In fact, one may be able to add a clear regression line between the solar irradiation as the dependant variable and the DA as the independent variable for both the south and each facades. For the east façade the linear regression equation is:

$$y = 0.3247x + 5.1363 \quad (2)$$

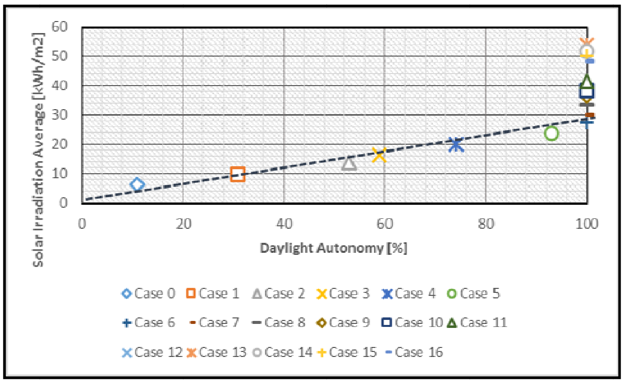


Fig. 7 Solar irradiation versus DA for South facing orientation for the 17 test cases.

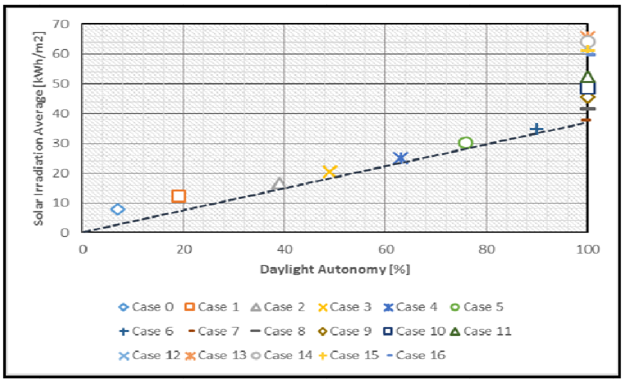
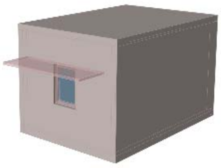
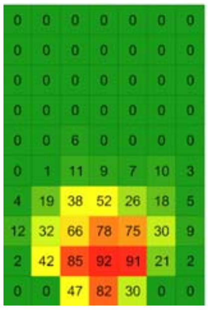


Fig. 8 Solar irradiation versus DA for East facing orientation for the 17 test cases.

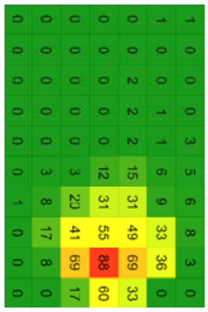
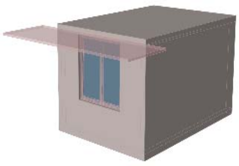
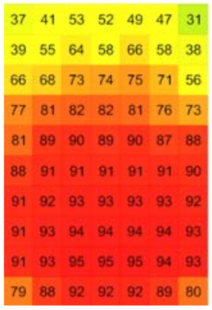
Where x is the DA and y is the expected average cumulative annual irradiation for all the sensor points. We are therefore able to predict what would be the maximum value for the average cumulative annual irradiation from this equation. In this case for example, if we plug in a value of one for x to try to find the maximum value for the average cumulative annual irradiation, we would get about 38 kWh for every meter squared. Although this is evident from the chart in our case, it may not be for other cases where is more expensive to conduct a full simulation analysis for every possible design case.

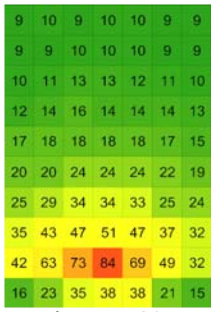
In our simple example, we were able to do so because our only varying parameter was the window to wall ratio. However, in more complex examples that may not be the case and therefore one will be able to simulate only a small subset of the design parameter values and then plot these values to come up with a similar regression equation. It is important to note

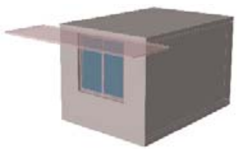
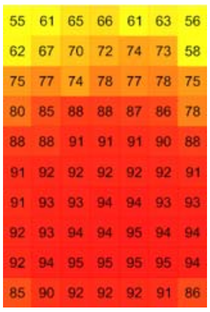
Table 2 The sensor points data for some extreme cases.

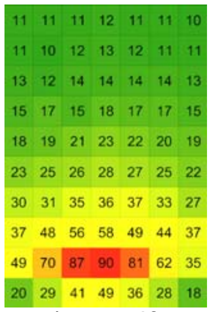
<table>
<tr><th rowspan="2">Case Description</th><th colspan="2">South</th><th colspan="2">East</th></tr>
<tr><th>Daylight Autonomy</th><th>Solar Irradiation</th><th>Daylight Autonomy</th><th>Solar Irradiation</th></tr>
<tr><td>Case Number: 0

WWR = 10%
Sill Height = 1.0 m</td>
<td>

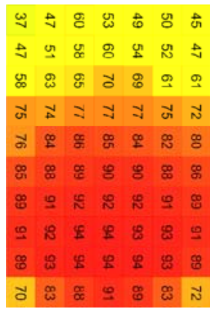
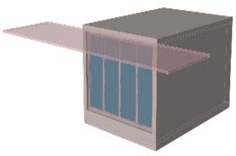
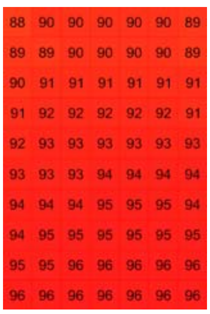
DA = 11%</td>
<td>

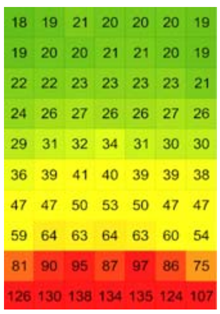
Average = 6</td>
<td>
DA = 7%</td>
<td>
Average = 8</td></tr>
<tr><td>Case Number: 5

WWR = 35%
Sill Height = 1.0 m</td>
<td>

DA = 93%</td>
<td>

Average = 24</td>
<td>
DA = 76%</td>
<td>
Average = 30</td></tr>
<tr><td>Case Number: 6

WWR = 40%
Sill Height = 1.0 m</td>
<td>

DA = 100%</td>
<td>

Average = 28</td>
<td>
DA = 90%</td>
<td>
Average = 35</td></tr>
<tr><td>
Case Number: 16
WWR = 90%
Sill Height= 0.3 m</td>
<td>

DA = 100%</td>
<td>

Average = 48</td>
<td>
DA = 100%</td>
<td>
Average = 59</td></tr>
</table>

however that the degree of confidence limits of these regression equation will vary. For example for the east facing façade the R^2 value was 0.996. While the equation for the south facing façade was

$$y = 0.2348x + 2.7396 \quad (3)$$

The R^2 value for the south facing façade was 0.9841, which is slightly lower than that of the east façade. Therefore as noted the regression equations will vary with firstly the degree of sophistication of the design parameters considered and secondly with the orientation of the façade. In any case a new proposed measure for the combined performance may be expressed as

$$\text{Proposed Measure} = \frac{Max\{1, DA\}}{Irradiation} \quad (4)$$

This measure would reward higher daylight performance in terms of Daylight availability up to a maximum value of 100% while penalize higher irradiation values gained. As such cases on the inflection point of the curves in Figs. 7 and 8 would be considered superior and would achieve higher scores in our proposed measure as compared to cases which increase the irradiation without increasing the DA values. Table 2 shows details of some of the extreme cases.

4. Conclusion

Daylighting and solar thermal gains are often positively correlated. In particular, if a specific design achieves acceptable scores for the climatic-based daylighting measures, then it may be often the case that this can be on the account of exceedingly high thermal gains. In this paper a new metric is proposed that takes into account the total amount of lux-hours achieved throughout the year and the distribution of these lux-hours with the cooling and heating degree days for different time steps. There remains more work to be done.

The proposed metric is limited to convention fenestration and would not apply to complex fenestration systems where no correlation is expected between energy gains and lighting performance such spectrum selective fenestration systems. Large solar irradiation values mean extensive thermal gain loads which is an undesirable effect in hot zones most of the year. However, higher values are beneficial whenever the temperature drops below comfort levels. Therefore, it may still be wise to develop a performance index that can be calculated on seasonal basis, with the solar irradiation increase being favourable during winter only.

References

[1] R. Sullivan, E. S. Lee and S. Selkowitz, A method of optimizing solar control and daylighting performance in commercial office building, in: *Proc. ASHRAE Conf. Therm Perform Exterior Envelops Build*, 1992, pp. 313-319.

[2] C. A. Johnson, R. W. Besant and G. J. Schoenau, Economic preferred window orientation and optimum fenestration design of a non-daylit and daylit large office building for different climate conditions and different billing structures, *ASHRAE Trans.* 96 (1990) 23-33.

[3] Carlos E. Ochoa, Myriam B. C. Aries, Evert J. van Loenen and Jan L. M. Hensen, Considerations on design optimization criteria for window providing low energy consumption and high visual comfort, *Appl. Energy* 95 (2012) 238-245.

[4] K. Tsikaloudaki, K. Laskos, Th. Theodosiou and D. Bikas, Assessing cooling energy performance of windows for office building in the Mediterranean zone, *Energy Build* 49 (2012) 192-199.

[5] Abdelsalam Aldawoud, Conventional fixed shading devices in comparison to an electrochromic glazing system in hot, dry climate, *Energy Build* 59 (2013) 104-110.

[6] E. S. Lee and A. Tavil, Energy and visual comfort performance of electrochromic windows with overhangs, *Build Environ* 42 (2007) 2439-2449.

[7] Takashi Inoue, Masayuki Ichinose and Naoyoshi Ichikawa, Thermotropic glass with active dimming control for solar shading and daylighting, *Energy Build* 40 (2008) 385-393.

[8] A. K. Athienitis and A. Tzempelikos, A methodology for simulation of daylight room illuminance distribution and light dimming for a room with a controlled shading device, *Sol Energy* 72 (2002) 271-281.

[9] A. Wagdy, New parametric workflow based on validated daylighting simulation, in: *Proceedings of the Building Simulation Conference*, Cairo, Egypt, 2013.

[10] C. F. Reinhart and O. Walkenhorst, Validation of dynamic RADIANCE-based daylight simulations for a test office with external blinds, *Energy and Buildings* 33 (7) (2001) 683-697.

[11] C. F. Reinhart, J. Mardaljevic and Z. Rogers, Dynamic daylight performance metrics for sustainable building design, *Leukos* 3 (1) (2006) 7-31.