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Proposal of a façade design approach for daylight performance determination in buildings

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Abstract

Daylighting is a key component for incorporating visual comfort conditions and reducing energy consumption in buildings. In order to assess daylight potential in the building design phase, diverse performance metrics are developed and are being used in building design phase. These metrics are also integrated into several dynamic lighting simulation algorithms so architects, lighting designers or façade consultants can practically determine the daylight performance of designated façade alternatives in terms of daylight availability, compare design variants and perform necessary revisions during the building design phase. This study deals with proposal of a façade design process in terms of daylight performance determination and aims to describe current daylight metrics that can be used for façade design and applications. Proposed process consists of determination stages based on daylight illuminance, control of glare and view out conditions. With the implementation of this process to façade design, it is possible to provide visual comfort conditions and minimise lighting energy efficiency in buildings.

Keywords
Façade design, Visual comfort, Daylight performance, Daylight metrics.

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1. Introduction

Daylighting in architecture provides several advantages in terms of its contribution to interior design, transparency and view out requirements in buildings, dynamic effects on physiological and psychological comfort conditions as well as its impact on reducing lighting energy requirements (Yılmaz, Yener, 2016). Efficient use of daylighting in buildings is only possible by means of daylight performance analysis in terms of visual comfort conditions starting from the building design stage and the integration of obtained results with the building façade design process. Thus, with the help of performed daylight performance analysis, it is possible to avoid problems that can be encountered in the future and optimization of façade design alternatives can be done considering effective use of daylight.

"Building façade design stage" is an important phase in the architectural design considering the facts that direction, dimensions, positioning of daylight apertures and decisions regarding the use of solar control elements are often determined. These decisions play a significant role on the daylight availability in spaces as well as provision of visual comfort conditions. "Daylighting" can be interpreted as an important design parameter in façade design and by the use of traditional and modern daylighting systems, spaces can benefit from daylight at a great percentage.

Providing maintained illuminance levels inside a building by the use of daylighting, the prevention of daylight-glare, obtaining sufficient exterior contact and view out with the outside environment are the main features expected from a façade design in terms of daylight performance. Today, diverse daylighting analysis methodologies and tools have been developed and are being used to ensure desired amount of natural light in buildings. In this study, current daylight performance metrics that can be used for façade design and applications are presented and proposal of a façade design process in terms of daylight performance determination is performed. The background of the proposed approach and its objectives are described in this study.

2. Daylight performance determination process in façade design

In order to design sustainable, visually comfortable and low energy buildings; it is necessary to consider optimization of visual, thermal and acoustic comfort conditions in the building façade design phase. Daylighting is an important design parameter in the façade design and evaluation of daylight performance for the building façade alternatives in the early design phase should be provided.

In order to provide visual comfort conditions and sufficient use of daylighting in spaces (when the use of daylight is essential in terms of physiological or psychological aspects and/or energy related issues), the daylight performance of the evaluated façade alternatives should be calculated in the following steps:

- Determination of daylight distribution in the space (modelling the daylighting potential of the space on an annual basis)
- Assessment of glare caused by daylight on an annual basis,
- Determination of view out conditions

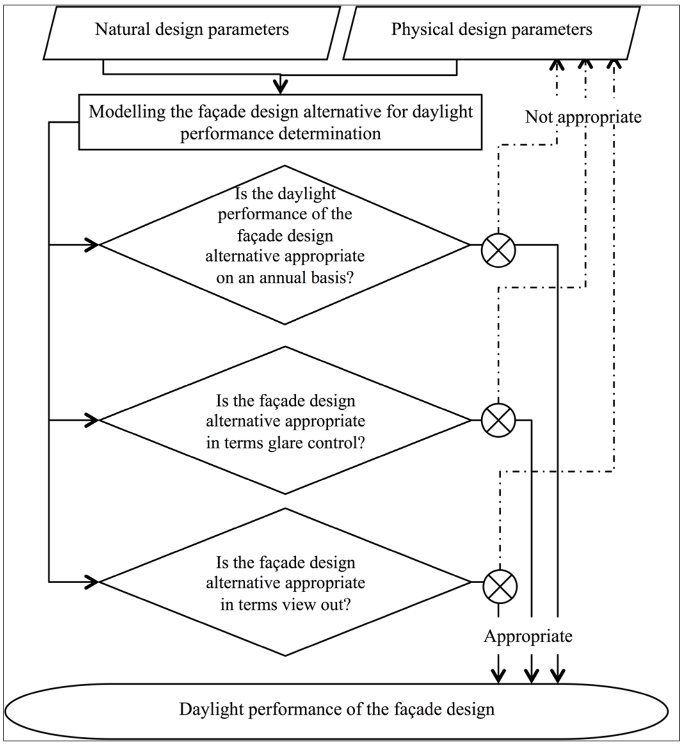


Figure 1. *Daylight performance determination process of the façade design.*

Taking into account the steps required for the evaluation of daylighting performance, it is possible to obtain daylight performance results for evaluated façade alternatives and decide on the most effective façade design variant in terms of daylighting. The aim of this study is to introduce a method for façade design process that can be used for daylight performance determination and guide the architectural lighting design process so that optimal façade decisions are obtained in terms of daylighting. Figure 1 represents the daylight performance determination process for façade design as a flowchart.

In the proposed performance based façade design approach in terms of daylighting, considering the natural design parameters and physical design parameters, the façade alternative is modelled using a state of the art daylighting simulation program and necessary steps for assessment of daylight performance is followed. In this holistic approach, various assessment methodologies based on relevant standards and cutting edge scientific studies are used together. This approach aims to give direction for the pre-design phase of building façades and obtain visually pleasing daylit environments.

In this façade design process, determination of natural design parameters (such as external illuminance, solar position, turbidity of the atmosphere, qualifications of sun and sky as sources of natural light, light reflectance properties of the ground, natural obstructions, geographical location, etc.) is crucial in order to obtain the most realistic results in daylight performance calculations. In order to use this process effectively, data regarding these parameters should be obtained in terms of the validity of the daylight performance evaluation.

Physical design parameters affecting daylight conditions in buildings consist of artificial obstructions, building orientation, physical and geometrical characteristics of the space, light reflectances of room surfaces, properties related with daylight apertures (their dimension, direction and optical features, transparency ratio, etc.) and shading devices. Most of these parameters are dependent on the architect or façade designer and are determined at the initial design phase. Therefore determination of these parameters should be performed considering daylighting and preliminary design decisions must be optimized by the use of proposed approach.

According to this approach, determination of daylight distribution in the space is performed by modelling the daylighting potential of the space on an annual basis. The daylight availability of the space is obtained and in cases where the evaluated pre-design decision lacks the required conditions in terms of daylight availability, modifications of the physical design parameters should be performed and façade alternative must be revised. Assessment of glare caused by daylight is also performed in this approach and if the evaluated design variant is found to have insufficient conditions in terms of glare, façade alternative should be optimized in order to reduce glare caused by daylighting. View out is another parameter that this design approach considers since all occupants of a building should have an opportunity for a dynamic view and visual contact with the outside environment.

Daylight- responsive façade designs are aimed to be obtained by the use of proposed design approach and obtained daylight performance results. This part of the study focuses on available methods to be used in daylight performance determination process of the façade design.

2.1. Assessment of façade designs in terms of daylight illuminance

With the use of a correct daylighting strategy in buildings, it is possible to provide the maintained illuminance levels given in the international standards and perform necessary visual comfort conditions in buildings. In order to determine the façade design's performance in terms of daylight illuminance, several daylight performance metrics had been developed and used since 1900. These metrics are used in order to determine the daylight potential in buildings based on developed sky models for certain times. These metrics refer to the quantity of daylight on specific surfaces, mostly horizontal workplane.

The traditional daylight illuminance metrics are often stated as single point in time or static daylight metrics since they define a relative daylight illuminance for a single point or reference plane for a standard time and sky condition. Daylight Factor-DF, the ratio of internal illuminances to exterior illuminances, under a CIE overcast sky, is an example to these metrics. The major limitations of using single point in time- STM metrics are that they address a single condition under a standard sky model and they do not give information on the annual dynamic conditions (IES, 2013). Additionally when Daylight Factor method is used as a performance indicator, direct effect of sunlighting is ignored and orientation-based differences are not considered (Moon, Spencer, 1946; IES, 2013). Therefore, daylighting metrics indicating dynamic daylighting conditions are developed in recent years using actual climate based weather data and giving annual results (Cantin, Dubois, 2011).

With the use of dynamic daylight metrics during the proposed performance based façade design approach in terms of daylighting, it is possible to obtain daylight illuminance based comparisons amongst façade alternatives. Dynamic daylight metrics that can be used as part of the proposed approach are introduced in this part of the study.

2.1.1. Daylight autonomy

Daylight Autonomy (DA) method is the oldest dynamic daylight metric (proposed by the Association Suisse des Electriciens in 1989 and improved by Christoph Reinhart between 2001-2004) developed to assess the daylight performance of a given space on an annual basis (Reinhart et al., 2006).

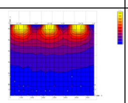
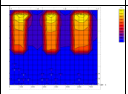
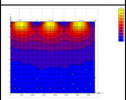
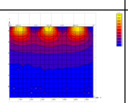
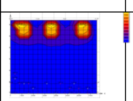
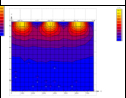
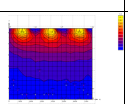
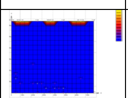
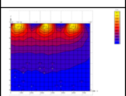
This metric is represented as a percentage of annual hours that a given point in a space is above the required illumination level with the use of daylighting only. This approach considers the use of geographic location specific weather information on an annual basis. This indicator is also used for daylight linked electric lighting design and estimation of lighting energy savings on an annual basis.

2.1.2. Continuous daylight autonomy

Continuous Daylight Autonomy (cDA) is developed by Rogers Z. in 2006 as a modification of Daylight Autonomy (Reinhart et al., 2006). The main difference of this method is that it uses the effect of dynamic conditions in spaces and attributes partial credit to time steps when daylight illuminance is less than required illuminance in the investigated space (Cantin, Dubois, 2011; IESNA, 2011). This indicator is also used for daylight linked electric lighting control system and correlate well to define the lighting energy saving potential of a building by the help of daylighting (IESNA, 2011).

An example to calculation of Continuous Daylight Authonomy is given for a sample classroom space in Istanbul under representative dates and sky type conditions in Table 1. In this example, the probability to perform the maintained illuminance (E_m) by daylight illuminance only is calculated within the space for each representative calculation date and time. According to EN 12464 Standard, the required illuminance level is specified as 300 lx (EN 12464-1, 2011). In this respect, the probability to perform the maintained illuminance (E_m) by daylight is multiplied by the representative total hour of each calculation time and obtained result is divided by the total annual occupancy hour of the investigated space

Table 1. *Calculation of Continuous Daylight Autonomy (CDA) for a south-oriented classroom located in Istanbul using daylight distribution results.*

	08:00	12:00	16:00	Date	Probability to perform E_m (300 lx) (a)	Representative total hour- h (b)	a x b	CDA Result
15 December	 Overcast Sky	 Intermediate Sky	 Overcast Sky	15 December 08:00	0,16	198	32,05	%59
				15 December 12:00	0,93	198	184,6	
				15 December 16:00	0,15	198	30,0	
15 March	 Overcast Sky	 Intermediate Sky	 Overcast Sky	15 March 08:00	0,42	258	107,7	
				15 March 12:00	0,93	258	238,7	
				15 March 16:00	0,48	258	124,8	
15 June	 Intermediate Sky	 Clear Sky	 Intermediate Sky	15 June 08:00	0,72	132	94,8	
				15 June 12:00	0,96	132	127,0	
				15 June 16:00	0,73	132	95,9	

(1764 h). Consequently, the annual Continuous Daylight Autonomy result is obtained as a percentage for the investigated classroom (Yılmaz, 2014).

2.1.3. Zonal/spatial daylight autonomy

Zonal/ Spatial Contunious Daylight Autonomy (zDA, sDA) methods are obtained by the modification of Daylight Autonomy method representing a measure of the percent of a zone or a space that provides a spesific Daylight Autonomy value for a given period. This metric is related with the percentage of area that meets the required illuminance by daylight only throughout the occupation times of the building (IES, 2013).

2.1.4. Maximum daylight autonomy

Maximum Daylight Autonomy (mDA) method is used to assess the time periods when the daylight illuminance is at least ten times higher that the required illuminance levels within the space. This metric is generally applicable in order to control occurrence of glare caused by daylight and excessive amount of heat gains in buildings. According to this method, the percentage of occupancy hours when the daylight illuminance is in the upper bound is used to express the conditions having potential risk of glare (IES, 2013). This metric can be calculated for a specific point on the working plane or for a grid of points representing a critical area of the working plane (Url-1).

2.1.5. Useful daylight illuminance

Useful Daylight Illuminance (UDI) is modified from Daylight Autonomy method by Mardaljevic and Nabil in 2005. According to this metric, the illuminance levels caused by daylight is classified into three illumination ranges as follows:

- Inadequate daylight illuminance (<100 lux),
- usefull daylight illuminance (100-2000 lux),
- daylight illuminance exceeding required levels (>2000 lux) (Nabil, Mardaljevic, 2006).

This metric provides full credit only to values between 100 lux and 2,000 lux suggesting that horizontal illumination values outside of this range are not useful and the upper threshold value-2000 lux is found to cause glare in this method. The graphical percent values represent the percentage of the floor area that that meets the UDI criteria at least 50% of the time.

2.1.6 Annual daylight exposure

Annual Daylight Exposure (ADE) metric indicates the total amount of visible light incident on a specific point measured as lux-hours per year. This metric is specifically suitable to be used for museum and exhibition building's façade designs in order to minimize the deterioration of artifacts caused by daylighting. Use of this metric is necessary to be able to revise the improper daylighting design alternatives during the design phase.

2.1.7 Annual sunlight exposure

Similar to annual daylight exposure metric, Annual Sunlight Exposure (ASE) is the metric referring to the total number of hours where a specific point receieves direct sunlight in a year. This metric is suitable to be used when a space is unobstructed and control of glare is necessitated by means of shading devices. With the help of this metric, the time periods when shading is required in the interior spaces can be determined and appropriate design of shading systems can be performed.

2.2. Assessment of façade designs in terms of control of glare

In façade design, control of glare from daylight apertures is a necessity in order to perform the required visual comfort conditions. Glare is the sensation produced by a sufficiently greater luminance within the visual field causing annoyance, discomfort or loss in visual performance and visibility (IESNA, 2011). Disability glare is the aspect of glare causing a direct reduction in person's ability to see whereas Discomfort glare is the discomfort sensation causing distraction, annoyance and dazzle. (IESNA, 2011; Osterhaus, 2005; Borisuit et al., 2010; Waers et al, 1995).

Currently, there are several available methods for the prediction of discom-

Table 2. Corresponding degrees of DGI.

Degree of perceived glare	DGI
Just perceptible	16-18
Just acceptable	20
Borderline between Comfort and Discomfort	22
Just uncomfortable	24-26
Just intolerable	>28

fort glare caused by daylighting to express the discomfort through an index. Daylight Glare Index (DGI) is a former index formed basing on the 'Cornell Formula' but recent studies show that its application in different viewing positions can yield to unreliable results and unacceptable glare conditions (IESNA, 2011; Werner, Osterhaus, 2005; Wienold, Christoffersen, 2006). Daylight Glare Index (DGI) can be calculated using Equation 1 and 2. In Table 2, corresponding degrees of DGI are given.

$$DGI=10 \log \sum_{i=1}^{n} G_i \quad (1)$$

$$G_i = 0{,}478\ [L_s^{1.6}\Omega_i^{0.8} / L_b + (0.07\ \omega^{0.5}\ L_w] \quad (2)$$

L_s: luminance of source (cd/m^2)
L_b: background luminance (cd/m^2)
L_w: luminance of the window in function of the relative areas of sky, obstruction and ground (cd/m^2)
Ω: solid angle of the window (sr)
ω: solid angle of the source, modified in function of the line of sight (sr).

Recently developed Daylight Glare Probability (DGP) metric is formed basing on the experimental results of a research and is calculated with Equation 3 (Jakubiec, Reinhart, 2012). In several studies using DGP method, better correlation with human subject's response is found compared to DGI (Jakubiec, Reinhart, 2012; Suk, Schiler, 2013). In this metric, glare probabilities higher than 30% are found to cause perceptible glare for the occupants. DGP can also be calculated practically and accurately by using a simulation program 'Evalglare' that uses fish-eye images generated by RADIANCE program (Jakubiec, Reinhart, 2012).

Table 3. Corresponding degrees of DGP.

Degree of perceived glare	DGP
Not perceptible	<35
Just perceptible	35-40
Just uncomfortable	40-45
Just intolerable	>45

$$DGP = 5.87\ x\ 10^{-5} E_V + 9{,}18\ x\ 10^{-2}\ log\left(1 + \sum_j \frac{L_{s,j}^2 \omega_{s,j}}{E_v^{1,87} P_j^2}\right) + 0{,}16 \quad (3)$$

E_V: vertical eye illuminance (lux)
L_s: luminance of source (cd/m^2)
ω_s: solid angle of source (sr)
P: position index

In the developed approach, assessment of discomfort glare caused by daylighting is performed basing on DGP method. In order to evaluate DGP, typical field of view directions in the investigated space should be defined and daylight distribution for the investigated view directions should be calculated on an annual basis. By using obtained HDR visualisations that contain luminance distribution data for the investigated view directions, DGP can be calculated for each HDR image and evaluation result of the annual daylight glare potential can be ontained as a percentage. In Table 3, corresponding degrees of DGP are given.

2.3. Assessment of façade designs in terms of view out

View is a dynamic experience about how the changes in outside world is perceived, satisfying the physiological need of the eye for a change of focus as well as providing an awareness of the environment beyond the building (CIBSE, 1994). As a result of this, it is extremely important to design façade alternatives that are fulfilling the required conditions in terms of view out.

In a study related with view out and visual requirements, providing a minimum transparency ratio of 20% in the daylit space is suggested in order to supply optimum view out and occupant well-being (Keighley, 1973). This threshold value is also used as a reference in the BS 8206-2:2008, "Lighting for buildings- Part 2: Code of practice for Daylighting" Standard (BS 8206-2, 2008). In this publication, view out is classified into three categories as such:

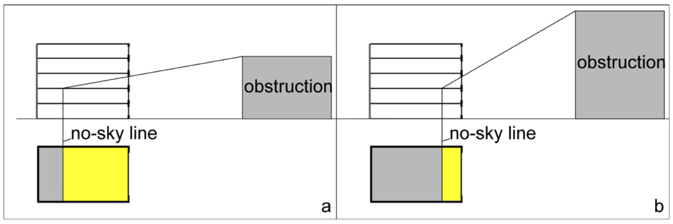


Figure 2. *A representative no-sky line area determination drawing for two obstruction types (a: obstruction angle of 10° and b: obstruction angle of 30°).*

- upper/distant view (sky and its boundary with natural or physical scene),
- middle view (natural or physical scene)
- lower/close view (nearby ground).

For the most completely satisfying conditions in terms of view out, building façades should be designed to incorporate these three layers of views.

In order to analyse the view out conditions for a façade design alternative, the exterior obstructions should be considered studiously. There are diverse methods available for analysis of view out in the design phase of buildings. In order to benefit from daylighting and visible sky, the visible sky angle (θ) measured from the centre of the window, in a vertical plane (section) perpendicular to that of the window is suggested to be between 65°-90°. In this approach, determination of the spaces with limited view-out conditions can be performed using no-sky line method, which represents the workplane area from which no sky can be seen (Littlefair, 2011). The no-sky line can be determined by the use of building plan and section showing the relationship between the façade daylight aperture and external obstructions. In Figure 2, a representative no-sky line area determination drawing for two obstruction types (a: obstruction angle of 10° and b: obstruction angle of 30°) are given. This comparative illustrations clearly show that the no-sky line subdivides the space into two parts and the area with access to sky view is highlighted with yellow color.

3. Conclusion

The use of daylighting is of significant importance in terms of providing visual comfort conditions and reducing energy consumption in buildings. In this study, proposal of a façade design process in terms of daylight performance determination is performed with the aim of optimizing the daylight conditions starting from the building design phase on. Proposed design process includes determination stages based on daylight illuminance, control of glare and view out conditions.

With the implementation of this process to façade design, architects, lighting designers or façade consultants can be able to evaluate façade design alternatives and assess daylight potential during the design stage. In order to assess daylight potential in the building design phase, diverse performance metrics are introduced as part of this study. The metrics described are applicable to be used in buildings such as office environments, educational buildings, multi-purpose areas, library buildings where use of daylighting is of great important in terms of visual comfort conditions and lighting energy efficiency. Using one or more of the daylight performance metrics is possible during the façade design phase depending on the building type and climatic conditions. Applying annual daylight performance metrics to the façade design phase is possible with the use of advanced daylight simulation programs, since the dynamic nature of daylighting can be practically. By doing so, determination of designated façade alternatives in terms of daylight availability and comparison of design variants can be performed practically and necessary revisions during the building design phase.

Proposed façade design approach also supports the optimum integration of artificial lighting and daylighting. The daylight determination results obtained in this approach can further be used to evaluate the effect of daylight linked lighting control strategies on lighting energy efficiency. With the implementation of this process in the façade design, it is possible to design energy efficient daylighting systems or perform necessary modifications during the design stage. This approach can also be used for the improvement of existing buildings so that energy conscious design variants can be obtained.

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