Determining Proper Daylighting Design Solution for Visual Comfort and Lighting Energy Efficiency: A Case Study for High-Rise Residential Building

Z A Kılıç¹ and A Köknel Yener²
Istanbul Technical University, Faculty of Architecture, Department of Architecture, Istanbul, Turkey
aybike.klc@gmail.com, yener@itu.edu.tr

Abstract. Promoting the daylight performance that allows to provide visual comfort conditions by minimizing lighting energy consumption is possible with making a balance of window size, glazing type and shading strategy, which are the major design parameters of the daylighting system. Particularly, in high-rise buildings, where large openings enabling higher daylight availability and view out are preferred, the daylighting system becomes a crucial design consideration in terms of ensuring occupants’ visual comfort and improving lighting energy efficiency. This study aims to identify a proper daylighting design solution with regard to window area, glazing type and shading strategy for a high-rise residential building located in Istanbul considering visual comfort and lighting energy efficiency. The dynamic simulations are carried out by DIVA for Rhino version 4.1.0.12. The results are evaluated with the Daylight Autonomy (DA) to detect daylight availability in the space and Daylight Glare Probability (DGP) to describe the visual comfort conditions related to glare. Furthermore, the lighting energy consumption of each alternative is also analysed to determine the proper daylighting solution. The results have revealed that a proper daylighting solution providing visual comfort by improving lighting energy-efficiency can be determined by the evaluation of the daylight performance both qualitatively and quantitatively.

1. Introduction
Daylight has been a powerful tool since the ancient times due to the fact that it has a profound effect on peoples’ health, visual comfort and productivity as well as its impacts on the amount of lighting energy demand and cost. From residential building point of view, creating a visual environment that satisfies occupants is vitally needed to activate biological rhythm particularly for early morning time [1], to protect against mental health issues such as anxiety, stress and depression [2], as well as to improve productivity in the situations when the residential spaces are frequently used as home-office. On the other hand, residential buildings is responsible for 26% of final energy consumption in the EU. Furthermore, the rate of the lighting energy constitutes 14,1% of the final energy consumption, which is the second highest part after space heating in the residential buildings [3]. It is also seen that partial energy demand has been shifting from the commercial to the residential buildings during the Covid-19 pandemic [4]. When the occupation time (weekdays and weekends) and the changing space requirements are also considered, daylighting becomes a fundamental strategy in residential buildings to enable a more sustainable living environment in such a way that will fulfill visual comfort requirements by
making use of the least lighting energy. Additionally, the high-rise residential buildings, consisting of a significant part of the residential building stock, should be considered in terms of daylighting system due to having generally deeper room plans [1], and highly glazed areas.

Daylighting design depends on the natural and architectural design parameters, which should be taken into consideration at all design stages starting from the scale of settlement to the material selection. Among them, the window-wall ratio (WWR), glazing type and shading strategy have been identified as the most important daylighting design parameters affecting overall energy consumption and daylight availability in the buildings [5, 6]. Window wall ratio (WWR), which is the ratio of the window area to the window-wall area is a key factor that influences the amount of daylight entering into the spaces, and therefore visual comfort conditions and lighting energy load. It is generally suggested to create WWR around 30% for providing good daylight and high energy performance [7, 8, 9]. Glazing type is also one of the significant variable in controlling daylight availability because of the light transmittance. It is suggested that the glass with a transmittance higher than 0.7 should be used in residential design [10]. Moreover, the glazing material of the side lighting should ensure a view that is perceived to be clear, undistorted and neutrally coloured [11]. Window glazing may also have a very crucial role to prevent discomfort because of glare and excessive heat gain caused by solar radiation [12]. Shading is another critical daylighting design consideration due to the harmful drawbacks of direct sunlight on the comfort conditions as well as total energy loads for especially highly-glazed buildings. The researches show that fixed shading devices are the most convenient option for preventing discomfort due to the glare [6], and perform more effective on decreasing total energy consumption regarding cooling loads rather than solar control glazing for hot climates [8]. On the other hand, the movable shading strategies can lead to desirable solutions in terms of both minimization of energy demand for lighting and cooling, and maximization of daylight utilization besides thermal comfort in especially heating-dominated climate [13].

In view of above, it is well-understood that the window-wall ratio, glazing type and solar shading have played a significant role on the daylight availability both quantitatively and qualitatively, so has lighting energy consumption. Moreover, residential space especially high-rise residential building is a crucial type needed to be analysed in terms of visual comfort conditions due to the aspect ratio, having a highly glazed façade. In this context, this study intends to offer a method in order to determine the proper daylighting design solution for high-rise residential spaces providing the visual comfort condition and lighting energy saving by revealing the comprehensive analysis of the results with Daylight Autonomy (DA) and Daylight Glare Probability (DGP).

2. Method of the study
In order to identify the proper daylighting system for living area placed in the high-rise residential building, the method carried out in the study is depicted in Figure 1. As it is seen in Figure 1, the daylighting design alternatives are firstly analyzed by the Daylight Autonomy (DA), which refers to the ratio of the minimum level of required illumination met by daylight alone to the occupied time during a year [14]. DA has great potential to provide more reliable information about the contribution of the daylight into the lighting energy saving [15]; therefore, it is a very expressive metric to find out energy efficiency in electric lighting according to window design [9]. On the other hand, DA_{50%} is highly correlated with the evaluations of the users’ assessment concerning visual satisfaction [16].

Due to the fact that DA does not define any maximum illuminance level that may cause discomfort because of the glare revealed by daylight, the alternatives that met Daylight Autonomy criteria are also evaluated by daylight glare probability (DGP) metric to ensure a visually comfortable environment. Daylight Glare Probability (DGP) is the first metric developed under real daylight condition in a side-lit space [17]. According to the DGP categories, the glare level occurred at the range of DGP≤45, 45>DGP>40, 40>DGP>35, 35>DGP is accepted as intolerable, disturbing, perceptible and imperceptible glare respectively [18].
Figure 1. The flowchart to determine proper daylighting design solution in scope of the study.

After the simulations are carried out, the results are finally compared in terms of lighting energy efficiency in order to detect the proper daylighting design solution, which provides visual comfort condition by consuming minimum lighting energy.

2.1. Description of the high-rise residential building

The described method is applied for the high-rise residential building located in Istanbul (represents temperate-humid climate), which has 32 story. The sample apartment to investigate is selected as the one which is oriented towards South direction and placed at the mid-level (16th) of the building (Figure 2). It is also assumed that there is no obstacle effect over the building. The reference space for the study is determined as the living area because of the occupation time during the day and requiring the various visual needs considering the different activities. The dimensions of the living area that has only single side aperture are 6.90 m x 5.90 m x 3.00 m. The reflectance of the room surfaces are accepted 70%, 50%, and 20% respectively for the ceiling, wall and floor as the standard values specified in EN 12464-1 [19]. The lighting power density is also assumed as 8 W/m² to express annual lighting energy consumption level for living area [20]. The lighting control system is defined manual on/off switch for two lighting control areas that are defined according to the distance from the window.

Figure 2. The partial floor plan and view of the evaluated residential building in Istanbul.

Daylight calculations are performed on a horizontal reference plane 0.85 m above ground level [11] by creating 79 sensor points, placed 0.60 m apart and 0.50 m from the walls. In accordance with Daylight Autonomy criteria, the threshold illuminance level for living area is accepted 300 lux that is generally accepted as required illuminance level for moderately easy task in continuously occupied interiors [11, 21]. It is also assumed that the living space is occupied on weekdays and on weekends between 8 a.m. and 6 p.m. so as to demonstrate the effect of daylight performance on the lighting energy consumption. The view directions to calculate Daylight Glare Probability (DGP) are selected according to the layout.
of living space as shown in Figure 3. The sitting eye level of the occupants for each calculation point is at 1.2m above the floor.

**Figure 3.** The view directions and the eye level of seated person for DGP analysis on the plan/section.

2.2. Determining the daylighting design alternatives regarding window-wall ratio, glazing type and shading strategy

To evaluate the window size, the four different WWR are proposed to range from 0.2 to 0.8 in increments of 0.2 (Table 1). As a threshold value, 20% WWR (W1) is accepted to ensure the recommended window dimensions in order to provide minimum view out for a space with room depth more than 4m [11].

**Table 1.** The window wall ratio alternatives created for sample living space.

| Aperture Design Alternatives | W1 213x150 cm (sill height:75 cm) | W2 425x150 cm (sill height:75 cm) | W3 511x150 cm (sill height:75 cm) | W4 521x225 cm (sill height:37.5 cm) |
|-----------------------------|----------------------------------|----------------------------------|----------------------------------|-----------------------------------|
| WWR                        | 20%                              | 40%                              | 60%                              | 80%                               |

By purpose of finding out the influence of the glazing type on daylight performance and lighting energy consumption, the WWR alternatives are examined for 4 types of glazing mostly used in temperate climate, which differ according to thermal and optical properties preferred for the solar and heat control purpose. The U values of the glazing types selected for the case study are appropriate with the values specified in Turkish Standard TS 825 “Thermal Insulation Requirements in Buildings” [22]. Table 2 lists SHGC, U-factor and VT values for the window glazing types evaluated in the study.

**Table 2.** The window glazing type investigated for daylighting system.

| Glazing Type | Details of Layers | U value [W/K.m²] | SHGCn | VTn | Shading Coefficient (SC) |
|--------------|-------------------|------------------|-------|-----|-------------------------|
| G1           | Low-E / air/ flat 4+16+4 mm | 1.30             | 0.56  | 0.79 | 0.64                   |
| G2           | Green tinted flat/air/Low-E 4+16+4 mm | 1.30             | 0.38  | 0.63 | 0.44                   |
| G3           | Reflective Glazing: Titanium covering/air/Low-E 6+16+6 mm | 1.30             | 0.46  | 0.56 | 0.53                   |
| G4           | Solar Low-E / air/flat/air/Low-E 4+16+4+16+4 mm | 0.7               | 0.48  | 0.69 | 0.53                   |

For the daylighting design alternatives that have not met DGP pre-requisite, an overhang is proposed to prevent glare on account of the direct sunlight. The depth of the overhang is 0.50 m and the light reflectance of it is accepted as 30%. Venetian blind is also recommended as another shading option that
has horizontal pieces with an inclination of 30° and 10 cm spaced apart. The venetian blind is adjusted within 3 cm distance from the outer side of the window. The control type of the venetian blind is defined as manual that is mostly preferred to control solar shading by the residents [23]. Figure 4 shows two shading solutions considered for the daylighting design of the living area and the alternative without shading.

![Image](image_url)

**Figure 4.** The proposed shading solutions in the study.

### 3. Results

- **Assessment of the window-wall ratio and glazing type alternatives in terms of daylight availability**

The daylighting system design alternatives generated for living area are simulated by DIVA for Rhino (version 4.1.0.12). The design alternatives are firstly assessed by the daylight autonomy, which it is expected to meet above 50% of the daytime to provide visual comfort conditions and achieve an energy-efficient lighting solution depending on daylight availability [24, 9].

In aspect of window size, Figure 5 shows that the higher values of window-wall ratio increases daylight autonomy value (a), while it decreases lighting energy consumption (b) in direct proportion as a well-known consequence. The W4 window type alternative (80% WWR) depending on the glazing type (by G1- DA300,58% , by G2- DA300,50% and by G4- DA300,54%) is the only window size that meets daylight autonomy criteria. It is also determined that the increment in window-wall ratio enhances the daylight performance in the living area at the rate of 18-19% among 60% -80%, 5-6% among 40% -60%, 15-16% among 20% - 40%. It means that increasing the window-wall ratio from 60% to 80% and from 20% to 40% have a significant effect on the daylight availability in the living area.

![Image](image_url)

**Figure 5.** The result of daylight availability via Mean Daylight Autonomy (a) and annual lighting energy consumption(b) depending on the WWR and glazing type.

From the viewpoint of glazing type, the results prove that daylight availability depends highly on the properties of the window glazing. Considering the impact of the glazing type on the daylight availability, G1 (Low-E), G4 (triple glazing with Solar Low-E), G2 (tinted glazing) and G3 (reflective glazing) emerged the highest daylight autonomy value for all window-wall ratios in the living area respectively due to their visible transmittance values. Similarly, they also provide the greatest reduction of the
lighting energy consumption as seen in Figure 5. G1 type shows the best performance in terms of both achieving Mean Daylight Autonomy value at the rate of 58%, 40%, 34%, 15%, and decreasing lighting energy consumption at the rate of 5.97%, 28.78%, 22.90%, 28.86% for 80%, 60%, 40%, 20% WWR respectively, when it is compared with G3 glazing type that leads to the worst daylight performance in the living area.

- **Evaluation of the design alternatives with regards of visual discomfort and lighting energy efficiency**

Besides obtaining sufficient daylight illuminance to ensure visual comfort conditions in the spaces, the daylight glare occurred by direct sunlight should be prevented by implementing different shading solutions. On this purpose, the overhang, venetian blind and solar control glazing types are discussed in scope of the study, and evaluated annually with DGP method at two different view directions (VP1 and VP2) for the daylighting design alternatives meeting the daylight autonomy criteria. The simulation outputs showing the effect of the different shading solutions on the visual comfort condition in the living area are depicted in Figure 6. The results are presented for the intolerable glare level (DGP ≥45) that occurred in the occupation hours [21].

As it is concluded from Figure 6, SHD0 alternative (without shading devices) shows the worst performance considering the DGP levels occurred in the living area. It is resulted that the only use of solar control glazing for the daylighting system having large window area are not adequate to eliminate discomfort glare, even though they enable more daylight availability in the living area compared to the other shading solutions. On the other hand, SHD1 (overhang) can slightly decrease annual glare level obtaining at VP1 and VP2 for W4_G1 (80% WWR with Low-E glazing), W4_G2 (80% WWR with tinted glazing) and W4_G4 (80% WWR with Solar Low-E glazing) alternatives at the rate of 1.8% (VP1)- 3.2% (VP2); 0.8% (VP1)- 1.8% (VP2); 1.7% (VP1)- 1.9% (VP2) respectively, compared with SHD0 alternative. It shows that the overhang is not effective in preventing the visual discomfort due to glare in the living area with a high window-wall ratio, while it is the best option in terms of daylight availability (DA) and the view-out.

![Figure 6. The effect of the shading strategy on (a) the annual daylight glare level and (b) the annual lighting energy consumption in the living area.](image)

Depending on the reduction in the annual glare level, the best performance is achieved with the SHD2 solution (venetian blind) for all daylighting design alternatives. SHD2 solution with W4_G1 window alternative performs intolerable glare level (DGP ≥45) 14.5% (VP1) and 6.7% (VP2) with a reduction of 18.6% and 7.3% compared to the none shading alternative. As a result of using SHD2 solution with W4_G2 and W4_G4 alternatives, the rate of intolerable DGP values of the occupation hours are determined as 4.8% (decrement of 15%) and 4.9% (decrement of 18.7%) respectively at VP1 and 6.5% (decrement 2% and 3.1) for both alternatives at VP2. According to the annual glare levels calculated at VP2, W4_G2 and W4_G4 with SHD2 solution are the daylighting design options that achieve the minimum recommendation for glare protection, which is that the DGP for the occupied space does not
exceed a value of 45 in more than 5% of the occupation time of the relevant space [9]. These results show that the Venetian blind is especially more effective for a situation where a direct light source is in the field of view (VP1). It is also observed that overhang performs almost as better as venetian blind to eliminate glare level in the point where the glare source is not in the direct field of view (VP2). It is confirmed that the distance of the viewpoint from the window is very crucial to arrive at the annual glare results.

In accordance with the method of the study, the design alternative providing visual comfort conditions by consuming the least lighting energy is determined as a proper daylighting solution. In this sense, Figure 4 (b) also shows the amount of annual lighting energy consumption realized by W4_G2 and W4_G4 alternatives with SHD2 solution, which provide visual comfort conditions in the living area. The venetian blind is adjusted to the annual lighting energy calculations according to the Daylight Glare Probability Level. Accordingly, it is assumed that users prefer to close Venetian Blind manually for the situation in which DGP level is over 45, which means “occupant cannot adapt” at the viewpoint. As can be deduced from the graph (b), W4_G4 alternative along with SHD2 solution ensures better performance than W4_G2 design solution in terms of annual lighting energy consumption, which are 565.1 kWh and 575.8 kWh respectively.

4. Conclusion
For this study, the proper daylighting design solution for the high-rise residential building located in Istanbul has been determined by taking into consideration three comprehensive parameters that are window size, glazing type and shading strategy via dynamic daylight evaluation metrics (DA, DGP). Considering the window-wall ratio, it is seen that the daylight availability providing the required illuminance level by minimizing lighting energy consumption in the living rooms with deeper spaces can be achieved by only higher WWRs. From the viewpoint of glazing type, Low-E glazing shows the best performance in terms of daylight availability for all WWR options, while tinted glazing mostly eliminate the glare effect caused by daylight. However, the results show that the single use of the glazing alternatives examined in the study is not the effective solution in terms of preventing the glare that leads to visual discomfort contrary to the practical implementation. As to the exterior shading devices, Venetian blind performs effectively to eliminate glare level, while overhang allows more daylight availability and view-out. When the design alternatives are evaluated by both visual comfort and lighting energy efficiency, the W4_G4_SHD2 design alternative representing 80% WWR combined with triple solar Low-E glazing (G4) and using exterior venetian blind has been determined as the best performing daylighting system for the investigated living area in scope of the case study.

The results represent the design alternatives created in the scope of the study. Nevertheless, the outputs can be useful in some aspects for the living spaces having similar architectural and daylighting features. For the future studies, the investigations for shading solutions can be expanded to reveal the effect of both the terrace and balcony as a fixed shading on the visual comfort and lighting energy efficiency especially for the high-rise residential buildings. Moreover, the daylighting system should be assessed in aspect of heating-cooling energy demand for a more holistic assessment of optimal daylighting design solution. The proper daylighting system can be supported with the measurement and the field survey both to validate the proper design solution and to determine the competence of the daylight metrics for the evaluation of the visual comfort conditions in the residential buildings.

References
[1] Abidi S and Rajagopalan P 2020 Investigating daylight in the apartment buildings in Melbourne, Australia Infrastructures 5 10
[2] Aries M B C, Aarts M P J and Van Hoof J 2015 Daylight and health: A review of the evidence and consequences for the built environment Light. Res. Technol. 47 1 6–27
[3] Url 1 [Internet]. [cited 2020 Dec 9]. Available from: https://ec.europa.eu/eurostat/statisticsexplained/index.php?title=Energy_consumption_in_household,
[4] Url 2 [Internet]. [cited 2021 Jan 15]. Available from: https://www.iea.org/reports/energy-efficiency-2020

[5] B. Bhandari N and Sundaram A M 2019 Optimization of Windows for Daylighting and Energy Consumption for South Facade in Office Building in Hot and Dry Climate of India Research into Design for a Connected World. Smart Innovation, Systems and Technologies (Singapore) vol 134

[6] Aste N, Buzzetti M, Del Pero C, and Leonforte F 2018 Glazing’s techno-economic performance: A comparison of window features in office buildings in different climates Energy Build. 159 123–135

[7] Yu F, Wennersen R, and Leng J 2020 A state-of-art review on concepts, criteria, methods and factors for reaching ‘thermal-daylighting balance Build. Environ. 186 107330.

[8] Sepúlveda A, De Luca F, Thalfeldt M and Kurnitski J 2020 Analyzing the fulfillment of daylight and overheating requirements in residential and office buildings in Estonia Build. Environ. 180 1–12

[9] Acosta I, Campano M Á and Molina J F 2016 Window design in architecture: Analysis of energy savings for lighting and visual comfort in residential spaces Appl. Energy 168 493–506.

[10] Zhen M, Du Y, Hong F and Bian G 2019 Simulation analysis of natural lighting of residential buildings in Xi’an, China Sci. Total Environ. 690 197–208.

[11] CEN 2018 EN 17037:2018 Daylight in Buildings (Brussels: Comité Européen de Normalisation)

[12] Skarning G C J, Hviid C A and Svendsen S 2017 The effect of dynamic solar shading on energy, daylighting and thermal comfort in a nearly zero-energy loft room in Rome and Copenhagen Energy Build. 135 302–11

[13] Raji B, Tenpierik M J and Dobbelsteen A V D 2016 An assessment of energy-saving solutions for the envelope design of high-rise buildings in temperate climates: A case study in the Netherlands Energy Build. 124 210–21.

[14] Reinhart C F, Mardaljevic J and Rogers Z 2006 Dynamic daylight performance metrics for sustainable building design LEUKOS - J. Illum. Eng. Soc. North Am. 3 17–31.

[15] Xue P, Mak C M and Huang Y 2016 Quantification of luminous comfort with dynamic daylight metrics in residential buildings Energy Build. 117 99–108

[16] Reinhart C F and Weissman D A 2012 The daylit area - Correlating architectural student assessments with current and emerging daylight availability metrics Build. Environ. 50 155-64.

[17] Wienold J, Kuhn T E, Christoffersen J, Sarey Khanie M and Andersen M 2017 Comparison of luminance based metrics in different lighting conditions CIE Midterm Meeting 2017 (Jeju, Korea, Republic of)

[18] Jakubiec A and Reinhart C 2010 The use of glare metrics in the design of daylit spaces: recommendations for practice 9th international Radiance workshop (Germany)

[19] CEN 2011 EN 12464-1:2011 Light and lighting — Lighting of work places — Part 1: Indoor work places (Brussels: Comité Européen de Normalisation)

[20] CEN 2017 EN 15193-1:2017, Energy performance of buildings - Energy requirements for lighting - Part 1: Specifications (Brussels: Comité Européen de Normalisation)

[21] IESNA 2011 The IESNA Lighting Handbook: Reference & Application 10th Edition (New York: Illuminating Engineering Society of North America)

[22] TSE 2013 TS825: Thermal Insulation Requirements for Buildings (Ankara,Turkey)

[23] Frontczak M, Andersen R V and Wargocki P 2012 Questionnaire survey on factors influencing comfort with indoor environmental quality in Danish housing Build. Environ. 50 56–64

[24] Reinhart C F 2014 Daylighting Handbook I (Boston:Massachusetts Institute of Technology)