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# Subjective and Simulation-Based Analysis of Discomfort Glare Metrics in Office Buildings with Light Shelf Systems

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**Abstract:** Glare is a kind of physiological phenomenon that influences occupants' visual comfort. Discomfort glare scenes in comparison to other levels of glare have been difficult to estimate and need accurate and reliable metrics. In contemporary architecture, the glass façade is so popular since it can remarkably minimize energy consumption in buildings and maximize daylight utilization as a natural energy. However, it is necessary to consider occupants' visual discomfort due to the daylighting glare risks during the initial stage of design. Since the measured glare metrics should have an acceptable correlation with the human subject data study, the agreement on the glare indices is complicated. This paper presents a comparison between subjective and simulation-based analysis of discomfort glare metrics in offices with a light shelf system. The discomfort glare metrics considered in this study include Daylight Glare Index (DGI), CIE Glare Index (CGI), Visual Comfort Probability (VCP), Unified Glare Rating (UGR), and Daylight Glare Probability (DGP). The parallel comparison was conducted by using simulation and questionnaire surveys to determine which criteria are more useful under different conditions. According to the findings, DGP yields the most reliable results in different levels of glare based on the subjective analysis and VCP has the lowest accuracy in each stage. UGR also has the highest accuracy rate for evaluating perceptible glare, DGI is applicable for assessing imperceptible glare, and CGI can be an acceptable index for approximating intolerable glare. The study results significantly reduce the complexity of the problem and can provide useful guidance for designers to select the most reliable glare metric based on climatic conditions.

**Keywords:** discomfort glare; glare metrics; light shelf system; visual comfort; office buildings

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## 1. Introduction

The design of buildings using daylighting-based strategies is very desirable [1]. Daylighting can significantly reduce the energy consumption of buildings and also has a positive impact on occupants' visual comfort [2–5], but an inappropriate daylighting-based design can reduce this advantage [1,3,6,7]. Generally, office environments need careful daylighting design due to their function [6,8–10]. Employees' productivity in offices directly affects the organization's financial efficiency and overall growth [11–13]. At the same time, the minimum possible energy should be used in these environments [14]. Proper design of offices' windows is one of the practical ways to exploit daylighting in office buildings. However, it does not provide satisfactory daylighting of deep spaces due to poor penetration and distribution of the illumination within the space and it can result in visual discomfort and local overheating [15,16]. Direct sunlight and high-brightness contrast also can increase the risk of discomfort glare in office buildings [4,17–19].

Glare is defined as "the sensation produced by luminance within the visual field that is sufficiently greater than the luminance to which the eyes are adapted to cause annoyance, discomfort or loss in visual performance and visibility" [16,20]. To solve this problem, light shelves, as a popular daylighting system, can be used in various shapes [21]. To properly design windows and sun shading devices we should consider glare risk and evaluate it via reliable indicators. Glare is a complex phenomenon and different approaches have been used in its evaluation to calculate the potential of causing discomfort. The following five indices are used for evaluating discomfort glare: Visual Comfort Probability (VCP), CIE Glare Index (CGI), Daylight Glare Index (DGI), Unified Glare Index, and Discomfort Glare Probability (DGP) [16,22–24].

1. Visual Comfort Probability (VCP): This index initially was introduced in order to evaluate discomfort glare probability [16,25] and then it was edited for use in various lighting systems. VCP was only developed to evaluate typical sizes, such as ceiling-mounted lights with uniform illumination. Therefore, it is not suitable for evaluating non-uniform illuminance or for predicting daylight glare [26,27].
2. CIE Glare Index (CGI): To correct the mathematical inconsistencies of the British Glare Index (BGI) for multiple glare sources, a new index was introduced, which was later accepted by the International Commission on Illumination (CIE), and called the CIE glare index [10,26,28].
3. Discomfort Glare Index (DGI): This index is derived from the CGI and its purpose is to predict the glare caused by large glare sources such as a window [29]. The metric is based on subjective ratings from human subjects in a daylit office space. The DGI value is associated with different levels of discomfort glare. A value of 22 is considered a logically acceptable threshold [30–32].
4. Unified Glare Rating (UGR): The value of this index varies between 10 (just imperceptible) and 34 (just intolerable). Similarly to the CGI, a value of 19 is usually considered the borderline between comfortable and discomfort glare [26,33,34].
5. Daylight Glare Probability (DGP): To determine glare, DGP combines vertical eye illuminance with elements of existing glare indices. In comparison with the existing glare indices, DGP shows a very strong correlation with occupants' glare perception [6,18,21,23,35]. A comparison between glare metrics values is tabulated in Table 1.

**Table 1.** Comparison between recommended thresholds of discomfort glare metrics.

| Level of Discomfort Glare | VCP [25,36,37] | CGI [28,38,39] | DGI [30,40] | UGR [33,41] | DGP [35,42] |
|---|---|---|---|---|---|
| just imperceptible | >80 | <13 | <18 | <13 | <0.35 |
| just acceptable | 60–80 | 13–22 | 18–24 | 13–22 | 0.35–0.4 |
| just disturbing | 40–60 | 22–28 | 24–31 | 22–28 | 0.4–0.45 |
| just intolerable | <40 | >28 | >31 | >28 | >0.45 |

While intolerable glare is easier to assess, disturbing glare has been rather difficult to estimate. Discomfort glare is a prevalent problem in office buildings and many research studies have been conducted on this issue [6,16]. A large number of glare metrics have been developed in order to correctly quantify and evaluate the different levels of glare scenes. To enrich the literature review and classify previously published works, some of the important published studies are classified in Table 2. The most important points of these documents are also presented in this table.

**Table 2.** List of important published works in the field (E: educational, O: office, R: residential, T: test room).

| Source | Methodology | Type of LS | LS Variable (s) | Glare | Day-lighting | Considered Metric (s) | Type of Sky | Window Orientation(s) | Case Study Dimensions (Length × Width × Height) | Case Study Space | Climate and Region | Software Platform |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| [43] | Experimental | Internal/External | Width, height, angle, and reflectivity | × | ✓ | Light uniformity | All | South | Dimensions: 6.6 × 4.9 × 2.5 (m) | T | Seoul, Korea; Dwa | - |
| [27] | Experimental, Simulation | Internal/External | N/A | ✓ | × | CIE Glare Index, VCP | Intermediate sky | All orientations | Dimensions: 6.6 × 3 × 3 (m) | O | Johor Bahru, Malaysia; Af | Radiance |
| [7] | Simulation | Internal/External | Position, width, height, and angle | ✓ | ✓ | UDI, ASE, and DGP | Clear sky | South | Dimensions: 10 × 9 × 3.5 (m) | E | Tehran, Iran; BSk | Honeybee |
| [44] | Experimental | External | Angle and reflectivity | ✓ | × | Glare caused by light reflectivity | All | South | Dimensions: 6.6 × 4.9 × 2.5 (m) | T | Seoul, Korea: Dwa | - |
| [6] | Simulation | External | Angle and material | ✓ | ✓ | UDI, DGP | Clear sky | South | Dimensions: 12 × 6 × 5 (m) | O | Wroclaw, Poland; Cfb | DeLuminæ |
| [45] | Simulation | Internal/External | Angle and width | × | ✓ | Daylighting performance | Clear/Overcast | East and west | Dimensions: 18 × 6 × 4.1 (m) | O | Singapore; Af | Radiance |
| [46] | Simulation | Internal/External | Angle | × | ✓ | Daylighting performance | Clear sky | South | Dimensions: 12.6 × 5 × 2.3 (m) | R | Seoul, Korea; Dwa | Radiance |
| [19] | Simulation | Light shelf | Length, angle, and height | × | ✓ | UDI, ASE, and sDA | Different sky cloud cover | WWR, height, length, and angle of light shelves | Dimensions: 8 × 5.8 × 2.9 (m) | E | Sari, Iran: Csa. Tehran, Iran; BSk | Honeybee |
| [47] | Simulation | Internal/External | Width, height, distance from floor and top of the window | × | ✓ | Daylighting performance | Clear sky | East, West | Dimensions: 7.9 × 3.2 × 2.8 (m) | E | Athens, Greece; Cfa | EnergyPlus |
| [1] | Experimental, Simulation | Internal/External | Position, shape, material, and width | × | ✓ | Illuminance values, Daylighting performance | Clear sky | North, West | Dimensions: 9 × 7 × 3.3 (m) | E | Riyadh, Saudi Arabia; BWh | Revit |
| [48] | Experimental, Simulation | Internal/External | Reflectivity, height, and internal light shelf (ILS) curve | ✓ | ✓ | UDI, DA, UI, DGP, Illuminance & luminance values, Daylighting performance | Clear sky | South | Dimensions: 4.6 × 8 × 3 (m) | O | Ha'il, Saudi Arabia; BWh | Diva |

**Table 2.** *Cont.*

| Source | Methodology | Type of LS | LS Variable (s) | Glare | Day-lighting | Considered Metric (s) | Type of Sky | Window Orientation(s) | Case Study Dimensions (Length × Width × Height) | Case Study Space | Climate and Region | Software Platform |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| [49] | Experimental | Internal | Heigh, length, and number | × | ✓ | Daylight ratio or daylight factor and WPI uniformity ratio | various sky conditions | All | Dimensions: 4.2 × 4.2 × 3 (m) | T | Johor, Malaysia; Af | - |
| [50] | Experimental, Simulation | Internal/External | Width, height, distance from floor and top of the window | × | ✓ | Daylighting performance | All type | East, West | Dimensions: 7.9 × 3.2 × 2.8 (m) | E | Athens, Greece; Csa | EnergyPlus |
| [51] | Experimental, Simulation | Internal/External | Width, mounting height, inclination, and reflection index | × | ✓ | Uniformity of daylight distribution, DF | Overcast | South | Dimensions: 7 × 7 × 3.2 (m) | E | Athens, Greece; Csa | Radiance |
| [21] | Experimental, Simulation | Internal/External | Angle, material, and orientation | × | ✓ | Useful Daylight Enhancement. | Clear, cloudy | All | Dimensions: 7 × 7 × 3.2 (m) | E | Chennai, India; Aw | Radiance |
| [52] | Experimental | External | Slope angle | ✓ | ✓ | DF, glare brightness contrast | Clear | North | Dimensions: 14.9 × 8.5 × 2.9 (m) | E | Al-Ain, UAE; BWh | - |
| [53] | Experimental | Internal/External | Distance from the floor | × | ✓ | Illuminance and luminance performance factors | CIE intermediate sky | north-east, south-west, and north-west | Dimensions: 29.7 × 19 × 4.3 (m) | E | Izmir, Turkey; Csa | - |
| [10] | Experimental, Simulation | Internal | Height, length, and number | ✓ | × | CIE Glare Index (CGI), Guth Visual Comfort Probability (GVCP) | Inconsistent cloud formations of intermediate skies | All | Dimensions: 8.4 × 8.4 × 2.7 (m) | O | Johor Bahru, Malaysia; Af | Radiance |
| [54] | Simulation | Internal | N/A | × | ✓ | Daylight illumination | CIE overcast | All | Total area: 937.9 m$^2$ | O | Singapore; Af | Radiance IES-VE |
| [18] | Simulation | Combination of external and internal | Height, angle, and Depth | ✓ | ✓ | UDI and DGP | - | South | Dimensions: 8 × 5 × 2.8 (m) | O | Penang, Malaysia; Af | Honeybee |
| [55] | Simulation | Internal | Position (Vertical and horizontal) | × | ✓ | DR | Clear | North-west, South-east | Dimensions: 6 × 5 × 3.5 (m) | R | Mashhad, Iran; BSk | Honeybee |

Considering the reviewed literature, much research has been conducted on daylighting performance metrics and little research has been conducted on discomfort glare metrics. Moreover, the previous studies did not present a strong correlation between predicted and perceived visual comfort [23,24], and more extensive human-centric research is essential. Especially during the evaluation of discomfort glare metrics, there is obvious evidence confirming that the perceived glare in a controlled experimental environment differs from perceived glare in field situations, since in field studies there are inevitable differences between occupants' emotions or behaviors, their metabolism rates, sky conditions, etc. [23]. As a result, it is currently rather difficult for the designer to decide which glare index to use [22,56].

So, it is necessary to investigate the performance of discomfort glare metrics from different points of view to find out the reliability rate of different glare metrics in the evaluation of occupants' discomfort. This study aims to focus on this important issue and investigates the reliability of the discomfort glare metrics through simulation analysis and subjective surveys to rate the glare indicators. The research is also attempting to identify the most reliable glare metric for evaluating different glare scenes. For this purpose, an existing office building in Tehran was used as a case study and a developed questionnaire was used to collect the subjective data. Then the subjective data are compared with the simulation analysis to find out their correlation and inform the introduction of the most efficient discomfort glare metric in the office environment.

## 2. Methodology

This research aims to compare the reliability of discomfort glare metrics in order to rate existing visual comfort indices in office environments that are located in cold semi-arid climates. To this end, a subjective and simulation-based analysis was conducted for this study in five main steps: (1) an initial data collection through an environmental and climate dataset to identify the key characteristics of the case study location's climate, (2) collecting the human subjective data through evaluating the filled out questionnaires, (3) simulating the case study via building simulation software, (4) normalizing the subjective and simulation-based data in order to compare the outputs directly and, (5) rating the glare metrics in terms of their correlation with human subjective data and their reliability in predicting glare scenes. Accordingly, the different steps of the research process are presented in Figure 1 to better understand the research flowchart.

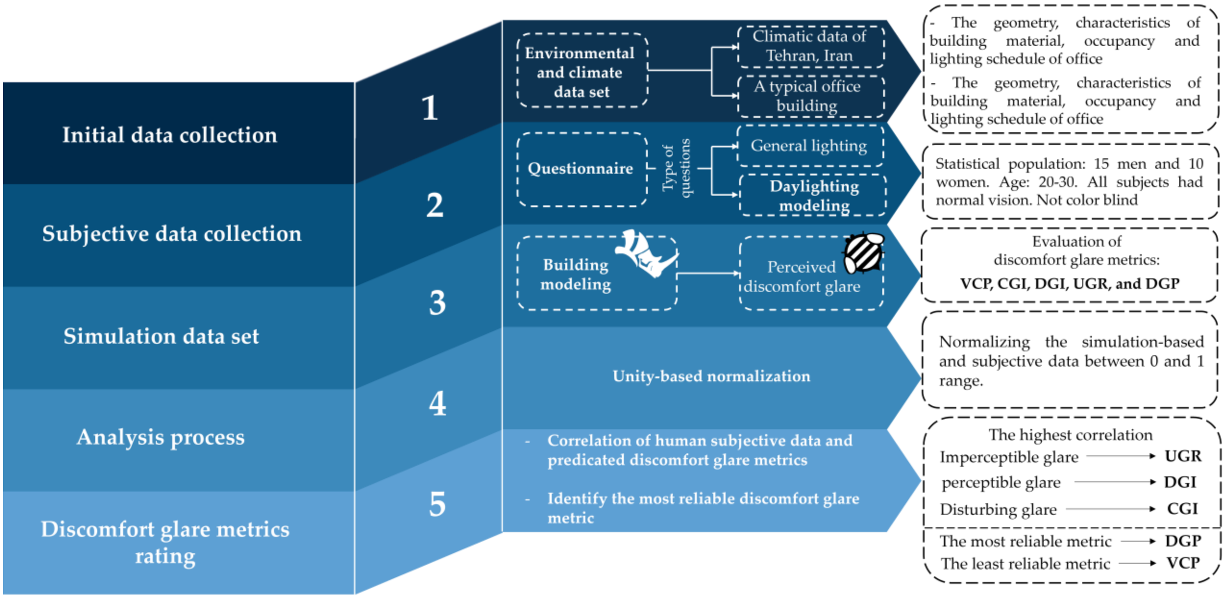



**Figure 1.** Different steps of the research process.

*2.1. Initial Data Collection*

2.1.1. Climatic Data of the Case Study Location

In this research, an office building in Tehran (Iran) was selected as the case study. According to the Köppen–Geiger climate classification [31], the B category (dry) accounts for 82.28% of Iran. In this study, Tehran is considered an example of this climate type. The climate characteristics of Tehran are summarized in Table 3. It is important to consider such information during the early design stage to avoid the occupants' discomfort [57,58].

**Table 3.** Köppen–Geiger climate classification of Tehran [19].

| City | Latitude | Longitude | Elevation (m) | Mean Cloud Cover | Climate | HDD | CDD |
|---|---|---|---|---|---|---|---|
| Tehran | 35.7219° N | 51.3347° E | 1219 | 44.7% | Cold semi-arid (BSk) | 1810 | 865 |

For running the simulation, the Tehran-Mehrabad 407,540 (ITMY) file is imported into the simulation software (Table 4), which is available to download from the EnergyPlus website. It should be noted that Tehran is the capital of Iran.

According to the statistics from meteorological stations collected by the Tehran International Exhibition for 18 years, 10 July to 10 August is the overall warmest period for Tehran, with an average temperature of 35.6 °C, and February is recorded as the coldest month of the year, with an average minimum temperature of −0.7 °C [59]. The window and light shelf are positioned on the south façade, since the south-facing surfaces in Tehran receive more daylight due to the sun's path [60], as it is illustrated in Figure 2.

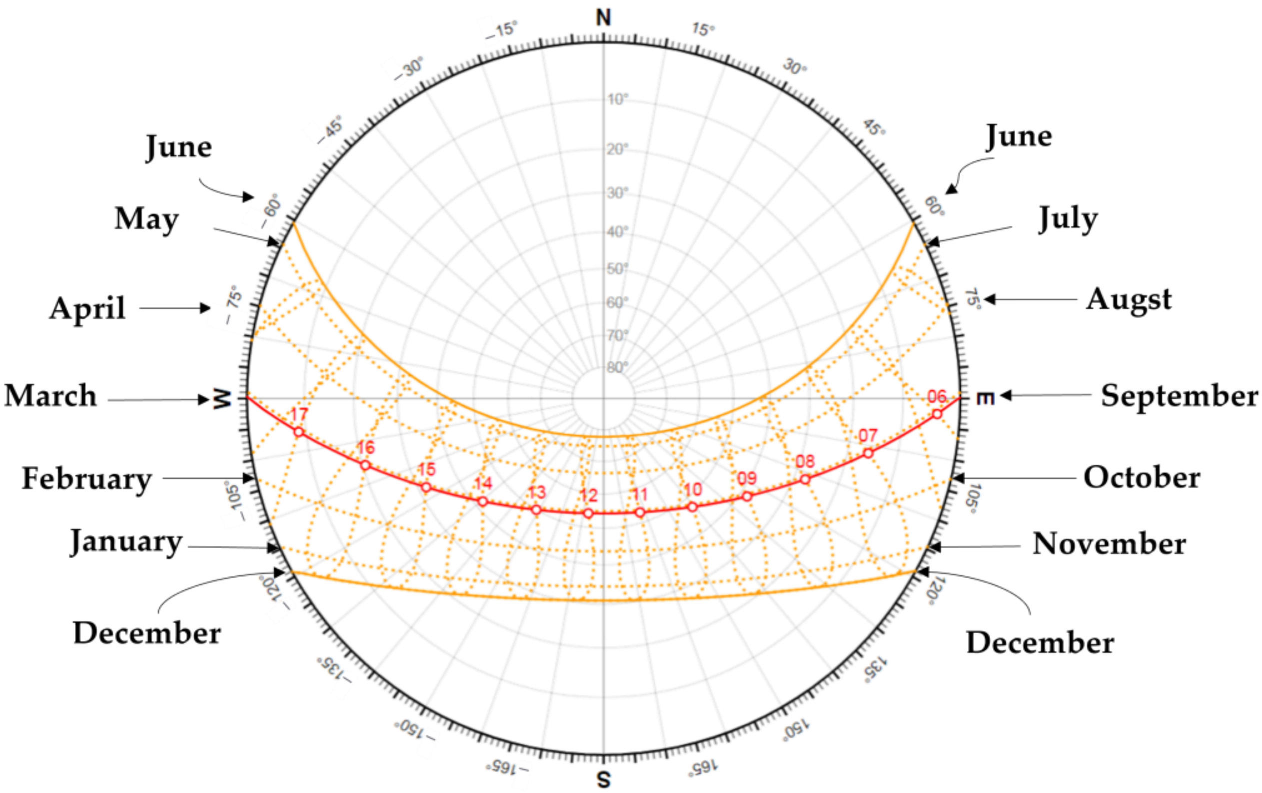



**Figure 2.** Sun path diagram for Tehran during a year.

Iran has three light zones and the city of Tehran belongs to the 3rd zone [61]. The intensity of natural light during the day, throughout Iran, is between 4000 and 40,000 lux. In Table 5, daylight distribution hours are divided into four parts. There are approximately 3800 h of sunlight per year in Tehran.

**Table 4.** The weather file is provided by the EnergyPlus database for Tehran.

| Weather Data | Hourly | | | Monthly | |
|---|---|---|---|---|---|
| | **Avg.** | **Max.** | **Min.** | **Max.** | **Min.** |
| Dry-bulb temperature (°C) | 17.27 | 40 | −5 | 30.07 | 3.88 |
| Relative humidity (%) | 40.57 | 99 | 3 | 62.99 | 21.92 |
| Dew point temperature (°C) | 1.61 | 18.5 | 20 | 6.78 | −3.5 |
| Wind speed (m/s) | 2.71 | 16.3 | 0 | 4.25 | 1.67 |
| Direct normal radiation (Wh/m$^2$) | 206.98 | 775 | 0 | 299.97 | 120.21 |
| Diffuse horizontal radiation (Wh/m$^2$) | 121.15 | 540 | 0 | 177.11 | 64.73 |
| Global horizontal radiation (Wh/m$^2$) | 244.25 | 1069 | 0 | 364.24 | 117.26 |
| Horizontal infrared radiation (Wh/m$^2$) | 340.58 | 489 | 229 | 409.04 | 274.93 |
| Barometric pressure (Pa) | 87,943.21 | 98,300 | 86,900 | 88,416.26 | 87,419.58 |

**Table 5.** Distribution of daylight illuminance in Tehran as a representative of the 3rd zone of Iran [62].

| Zone | <4000 Lux | 4000–8000 Lux | 8000–16,000 Lux | >16,000 Lux |
|---|---|---|---|---|
| 3 | 4923 | 756 | 1094 | 1977 |

According to weather data, the potential of global solar radiation in Tehran is significant. Maximum and minimum direct radiation occurs in July and December, respectively. As can be observed from Table 6, the maximum and the minimum solar radiation occur in August and December, respectively.

**Table 6.** The hours of sunshine in Tehran [19].

| Month | January | February | March | April | May | June | July | August | September | October | November | December | Annual |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Number of hours | 10:20 | 10:50 | 11:55 | 13:04 | 14:02 | 14:31 | 14:18 | 13:28 | 12:22 | 11:12 | 10:15 | 9:47 | 12:00 |
| The sun's altitude at noon on the 21st day of every month (Degree) | 34/4 | 43/7 | 54/5 | 66/2 | 74/5 | 77/7 | 74/7 | 40/66 | 55 | 43/5 | 43/3 | 30/9 | 54/7 |

### 2.1.2. Physical Characteristics of the Case Study

It was assumed that the office unit was located in the mid-level of the building. Thus, only the external wall with a window has heat transfer, and all of the other room enclosures are internal ones without heat transfer. The office room was modeled using the Rhino 7 software, as presented in Figure 3.

The material characteristics of this room are based on the Iranian National Building Regulations [63], which are tabulated in Table 7. The thermal characteristics of the construction, presented in Table 7, are based on the ASHRAE 90.1-2010 [64]. Hoseinzadeh et al. compared ASHRAE and Iran's national standard materials and determined that the ASHRAE proposed material performs better than the other [65].

Setpoint temperatures for heating and cooling were set to 22 °C and 26 °C, respectively, from 8:00 to 17:00 on weekdays only. It is also worth mentioning that Iranian weekdays start from Saturday to Wednesday. On the other hand, the setback temperatures for heating and cooling were 18 °C and 30 °C, respectively, outside of working hours. It was presumed that five occupants with 125 W/person activity levels were in the room. The occupants' CLO value (level of clothing) was adapted from the Dynamic ASHRAE 55 Clothing Model [66,67]. The occupancy, lighting, and electrical equipment schedules were set according to the weekdays in Iran, as shown in Figure 4.

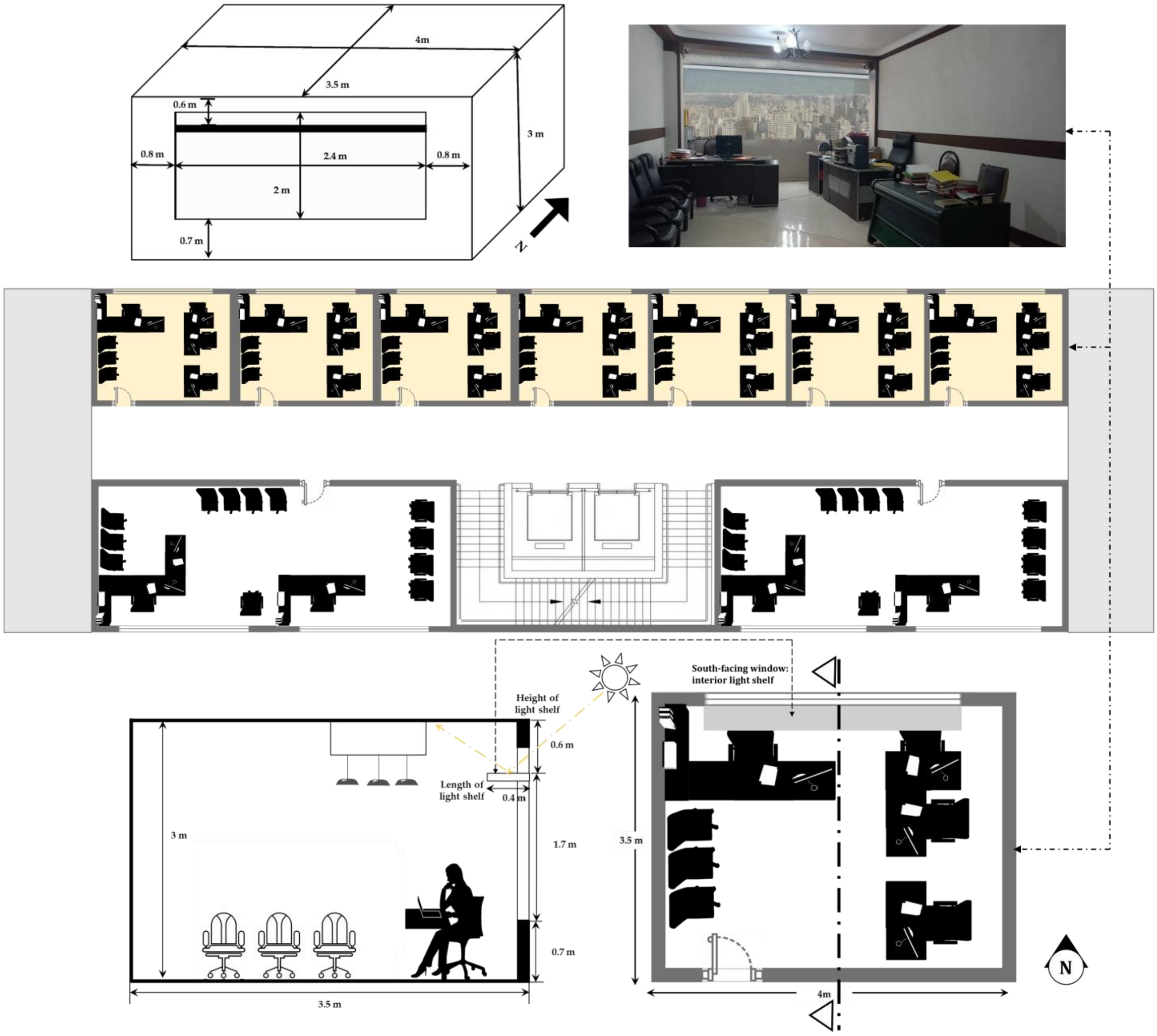



**Figure 3.** The office room 3D elevation (**top-left**), interior photo (**top-right**), site plan (**middle**), floor plan (**bottom-right**), section, and detail of the light shelf (**bottom-left**).

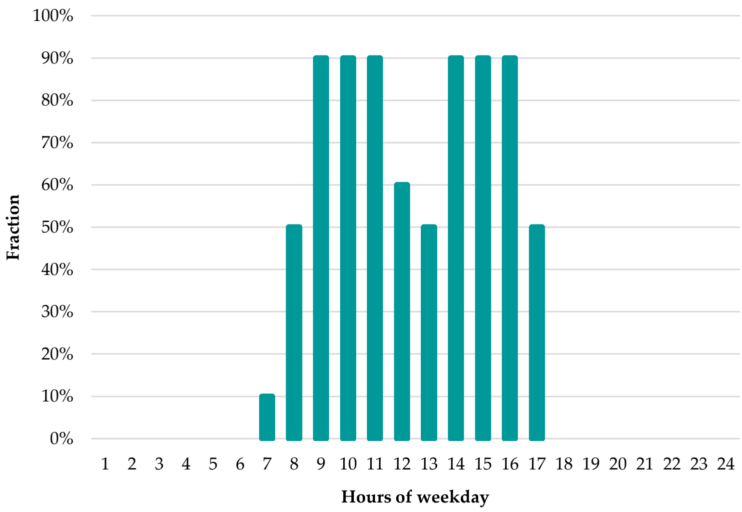



**Figure 4.** The schedule of the office's occupancy, lighting, and electrical equipment.

**Table 7.** Case study material specifications [63].

| Component | Material | U-Value (W/m$^2$ K) |
|---|---|---|
| External Wall | 1-inch stucco<br>8-inch concrete heavyweight<br>Wall insulation<br>0.5-inch gypsum | 0.7813 |
| Roof | Roof membrane<br>Roof insulation<br>Metal decking | 0.2296 |
| Floor | 0.5-inch gypsum<br>Attic floor<br>Floor insulation<br>0.5-inch gypsum | 0.1994 |
| Window | Theoretical glass | 13.88 |
| Window frame | UPVC | 1.6 |
| Light shelf | Aluminum | 1.5 |

The main parameters of the base model are described in Table 8 and the reflectance value for different surfaces of the office room is also shown in Table 9.

**Table 8.** Characteristics of the base model.

| Attributes | Unit | Values |
|---|---|---|
| Case study type | - | Medium office building |
| Working hours | - | 8:00–17:00 |
| Number of people per area | ppl/m$^2$ | 0.0565 |
| Ventilation per area | m$^3$/s·m$^2$ | 0.0003 |
| Equipment loads per area | w/m$^2$ | 7.6424 |
| Lighting density per area | w/m$^2$ | 11.8404 |
| Window orientation | - | South |
| Dimensions of the window (Width × Height) | m | 2.4 × 2 |
| Dimensions of the office room (Length × Width × Height) | m | 4 × 3.5 × 3 (m) |
| Location and climate of case study | - | Tehran (Bsk), Iran |
| Window to Wall Ratio (WWR) | % | 40% |
| Light shelf thickness | m | 0.4 |
| The angle of the light shelf with the window plane | ° | 90 |
| TG (Transmission of Glass) | % | 0.4 |
| LSL (Light shelf Length) | m | 0.4 |
| LSH (Light shelf Height) | m | 0.6 |

The room's electrical equipment was only available during working hours and consumed 450 W constantly. A 500 Watts fluorescent lighting system was used during office hours. Its power was controlled through an automatic dimmer. The sensor was installed in the mid-level of the room and at desk height (0.8 m above the floor) [67].

**Table 9.** Reflectance value for different surfaces of the case study [63].

| Type of Surface | Reflectance Values (%) |
|---|---|
| Interior wall | 45 |
| Exterior wall | 70 |
| Ceiling | 70 |
| Floor | 40 |
| Light shelf | 52 |
| Window | 79 |
| Frame of window | 50 |
| Door | 29 |
| Equipment (monitor, furniture, etc.) | 20–50 |

### 2.2. Subjective Data Collection

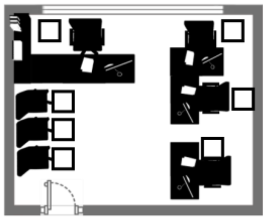
For collecting subjective data, a developed questionnaire was used and 38 respondents (20 men and 18 women) participated. All the participants had worked in the office for at least 6 months. The range of subjects' age was 20–30 years old. The questionnaire was a modified version of the one that was already developed by Pour Ahmadi et al. [15] and includes different aspects that can be categorized into personal information, general lighting, and perception of glare during working hours. The participants also provided their judgment on discomfort glare categories from imperceptible glare to intolerable glare, as shown in Figure 5.

Age: Date:

Gender M ☐ F ☐ Time:

Did you wear glasses or contact lenses while working: Yes: ☐ No: ☐

Specify your desk position during filling questionnaire:



If you perceive the glare, specify the glare source:

Sunlight ☐ Computer monitor ☐ Reflections from the other light surfaces in the room ☐ The other glare sources ☐

How do you perceive the glare in your workplace?

Imperceptible ☐ Acceptable ☐ Disturbing ☐ Intolerable ☐

How do you score the discomfort glare in your workplace? (1–10)

| Imperceptible | Acceptable | Disturbing | Intolerable |
|---|---|---|---|

1 2 3 4 5 6 7 8 9 10

**Figure 5.** Questionnaire blank form.

### 2.3. Simulation Data Set

Rhinoceros is a computer-aided design (CAD) application developed by Robert McNeel & Associates and is based on the NURBS numerical model [68]. Robert McNeel

& Associates [69] have created Grasshopper as a visual programming language plugin for Rhino, which provides parametric evaluation [70]. The Honeybee plugin was first introduced by Mustafa Roudsari in 2013 for energy analysis. To yield the correct answers, selecting suitable simulation software is vital. In this study, the Grasshopper 1.0.0007 version of Rhino 6 (SR16) has been applied for developing the parametric model, and visual analysis has been conducted with the assistance of the Honeybee version of 0.0.66 [2,71]. The simulation was conducted over 15 days, from 1 January to 15 January, under different sky models (overcast, partly cloudy, and clear skies). In the study, the following radiance parameters were used, as they are presented in Table 10.

**Table 10.** The considered radiance parameters for the simulation.

| Type of Radiance Parameters | Value |
|---|---|
| Ambient bounces (-ab) | 2 |
| Ambient divisions (-ad) | 1024 |
| Ambient super samples (-as) | 1024 |
| Ambient resolution (-ar) | 128 |
| Ambient accuracy (-aa) | 0.25 |

### *2.4. Analysis Process*

The metrics considered in this study were DGI, CGI, VCP, UGR, and DGP. The value ranges of these metrics were adjusted based on four levels of glare (i.e., just imperceptible, just acceptable, just uncomfortable, and just intolerable) (Table 1). To compare data results directly, the considered glare indices were normalized and rescaled between the values of 0 and 1. This means that the smallest value (0) indicates just imperceptible glare and the largest value (1) indicates just intolerable glare. The normalization procedure is based on Jakubiec and Reinhart's study (2012) [72], so accordingly, DGI was normalized by multiplying by a factor of 0.01452, and UGR and CGI results were normalized by multiplying by a factor of 0.01607. The VCP results were also normalized by subtracting its value divided by 100 from 1. Since the range value of DGP is always between 0 and 1, it does not require normalization.

### *2.5. Discomfort Glare Metrics Rating Process*

The normalization factors were defined according to the just intolerable level of DGP. The human subjective data derived from questionnaires were coupled with normalized indices to compare glare metrics with questionnaires output. Hence, the just imperceptible answers were coupled with the range below 0.35, the range of 0.35–0.40 was coupled with the just acceptable answers, the just uncomfortable answers were paired with the range of 0.40–0.45, and the just intolerable answers were paired with the range above 0.45.

## **3. Results**

As mentioned in the Section 2, the data were collected from the questionnaires and then compared to the analysis derived from the simulation. The subjective data analysis was coupled with the normalized indicators for comparing the glare metrics with the questionnaire output. The comparison of predicted glare metrics and perceived glare metrics is illustrated in Figure 6, and each of the glare ranges is shown in a different color. It is important to mention that the evaluations were conducted from 8:00 to 17:00 over six different days (clear or sunny, partly cloudy, partly cloudy to at times cloudy, mostly or mainly cloudy, cloudy and overcast sky).

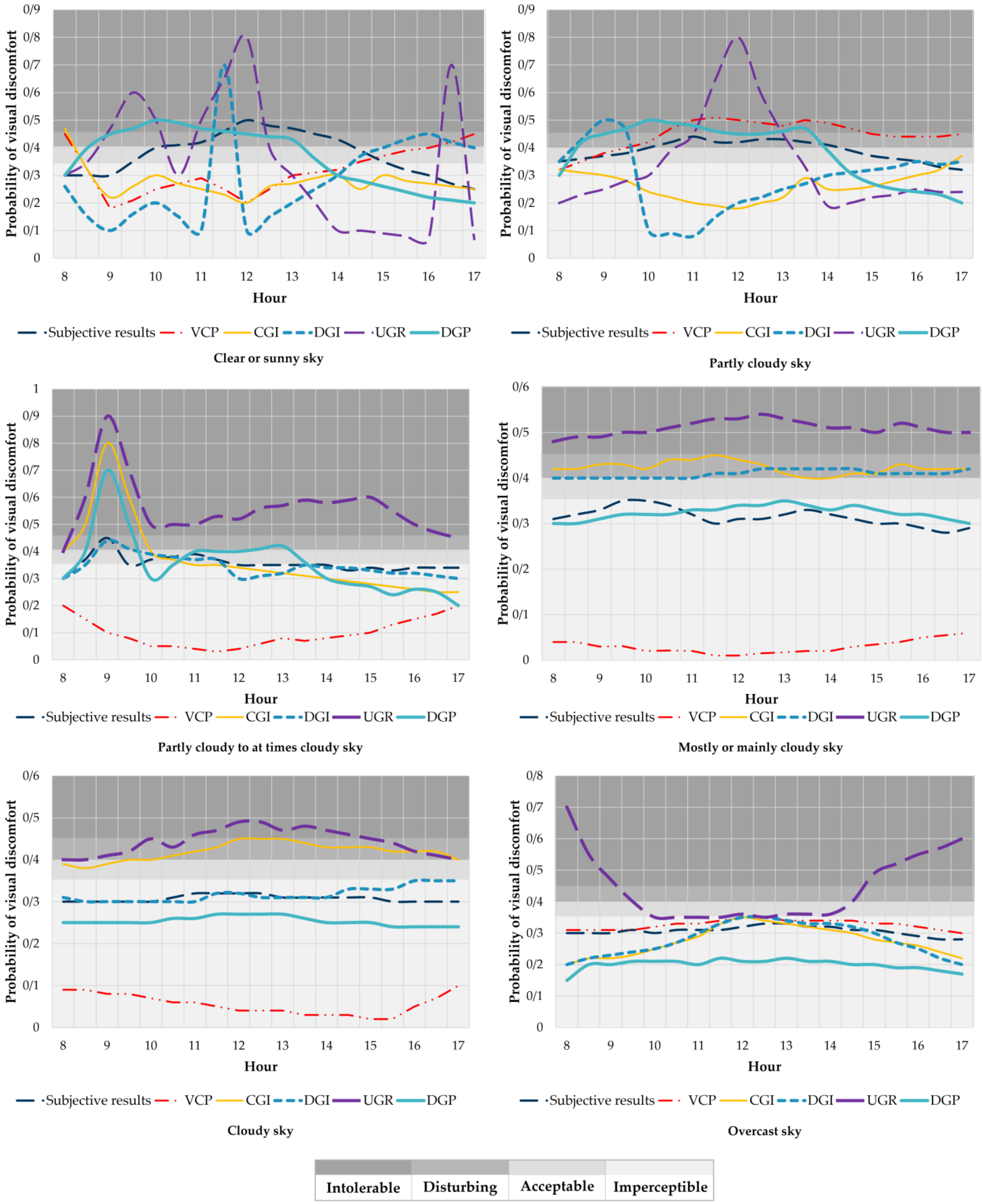



**Figure 6.** Comparison of subjective evaluation and discomfort glare metrics (<0.35: Imperceptible, 0.35–0.4: Acceptable, 0.4–0.45: Disturbing, >0.45: Intolerable).

The subjective glare evaluation data were compared with the existing discomfort glare metrics to determine which glare index had the best correlation with the human subjective evaluations in each glare scene, as presented in Figure 7.

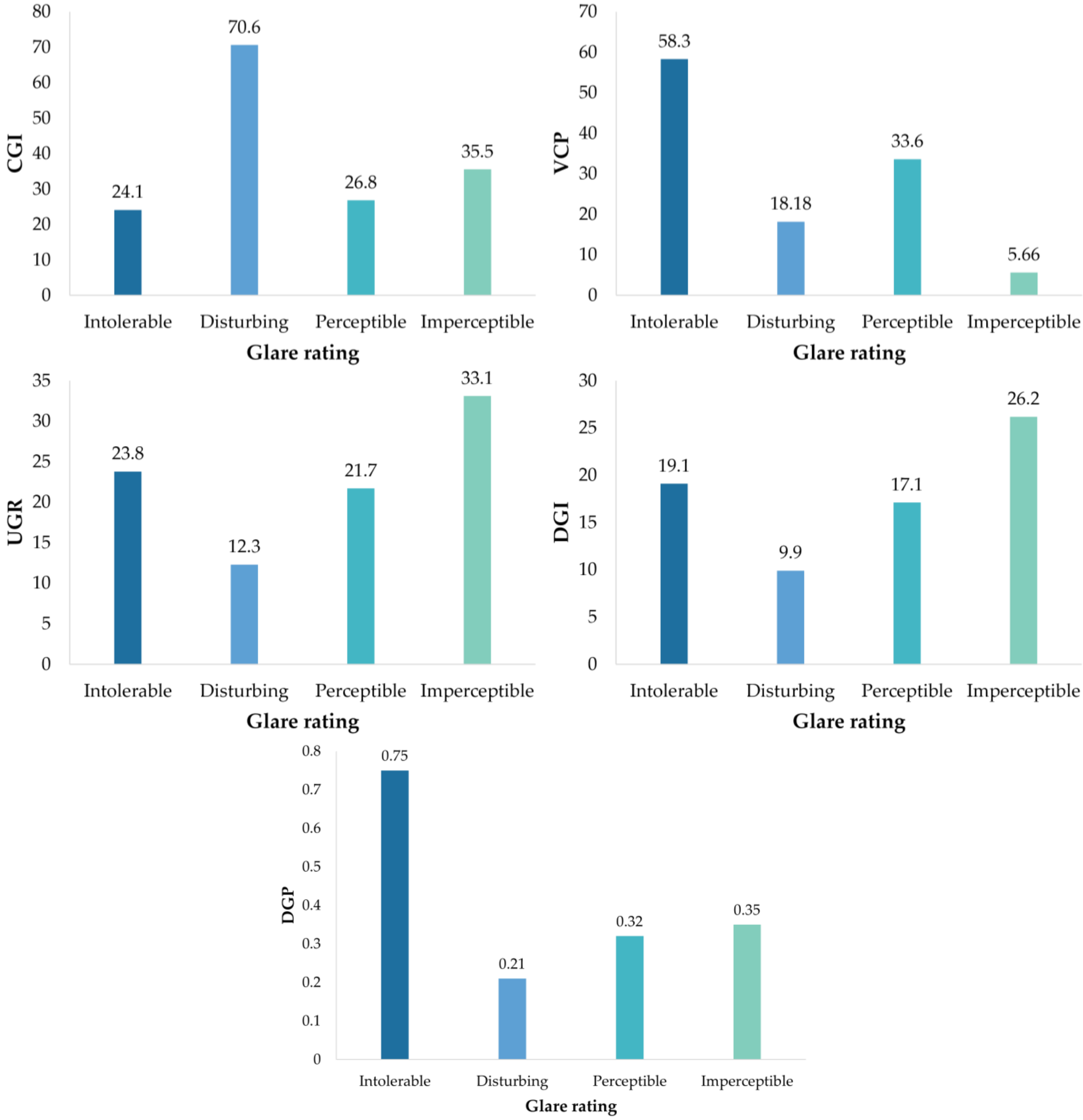



**Figure 7.** Correlation of subjective evaluation and discomfort glare metrics in different glare ratings.

From the results, it is clear that in each glare scene, only one or at most two indicators were correctly aligned with the subjective evaluation, and in some scenes, even none of the indicators followed the subjective evaluation. The results support the previous findings which state that there are wide contradictions between visual metrics in the evaluation of discomfort glare. The rate of accuracy of each discomfort glare index is compared in Figure 8.

Based on the results, DGP shows the highest accuracy rate (about 75.2%) among the other discomfort glare metrics and VCP has the lowest accuracy rate (about 11.3%). On the other hand, the CGI, UGR, and DGI accuracy rates are 24.7%, 27.6%, and 41.8%, respectively.

Amongst the glare metrics, DGP is the only glare index that has an accuracy rate above 50%. For better analysis, the simulated glare scenes were classified into four different ratings (imperceptible, perceptible, disturbing, and intolerable) regarding subjective evaluations.

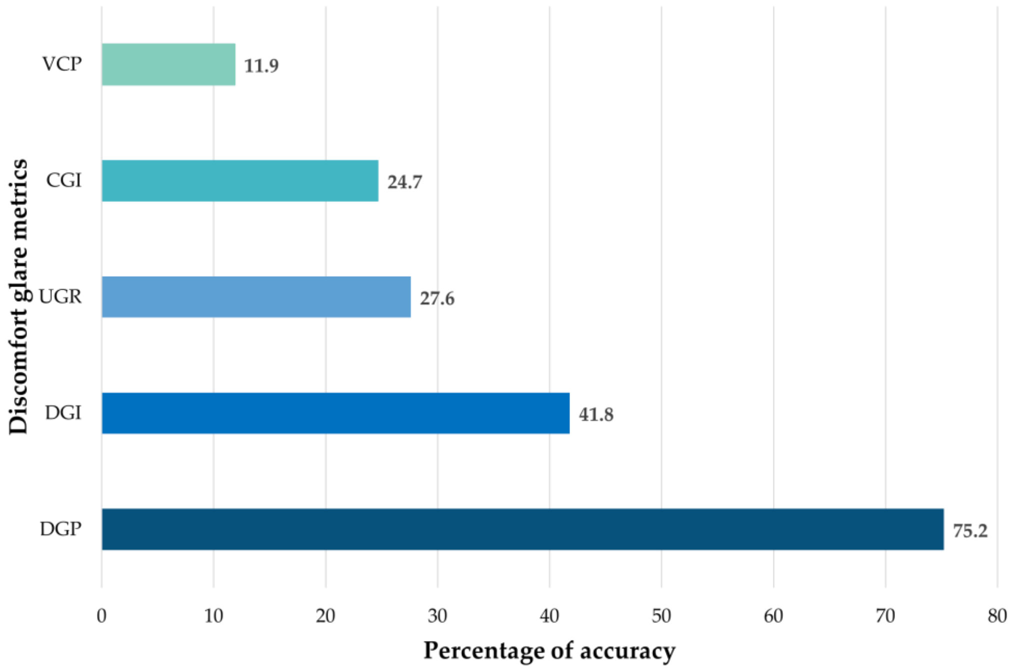



**Figure 8.** The accuracy rate of discomfort glare metrics in comparison with subjective data.

At first, the imperceptible glare scenes were analyzed and reported, which is illustrated in Figure 9. As can be observed from Figure 9, DGP shows a very high accuracy (36.4%) in the evaluation of imperceptible glare and DGI also has an acceptable accuracy (29.1%). Based on the study findings, it is evident that DGP and DGI are capable of suitable evaluation in imperceptible glare scenes. On the other hand, VCP, UGR, and CGI have a lower accuracy rate compared to DGP and DGI.

In perceptible glare evaluation, UGR has the most accuracy (33.1%). Accordingly, DGI and CGI show approximately the same result for the evaluation of perceptible glare. In the evaluation of disturbing glare, DGP has the highest accuracy rate (38.2%), followed by DGI (23%), CGI (18.9%), DGP (11.8%), and VCP (8.1%). Finally, for the evaluation of intolerable glare scenes, DGP has the highest accuracy rate (40.9%), and subsequently, CGI has the highest accuracy rate after DGP (38.4%). Among the five discomfort glare metrics, DGI has the lowest level of accuracy (1.7%) in the assessment of intolerable glare. Based on the accuracy rate analysis, existing glare indices have different evaluation performances in various conditions:

- DGP is the most reliable index in the evaluation of imperceptible, disturbing, and intolerable glare conditions, but its performance for assessing perceptible glare scenes is relatively weak. From the results, it is obvious that DGP has the highest correlation with human subjective evaluations to a large extent.
- UGR has the highest accuracy rate for evaluating perceptible glare scenes and has an acceptable performance in the evaluation of disturbing glare.
- DGI has very high accuracy in the assessment of imperceptible glare scenes, but it shows weak performance in disturbing glare evaluation.
- CGI has the best performance in the assessment of annoying glare and its accuracy rate for the rest of the glare scenes is low.
- Finally, VCP has the lowest accuracy rate in the evaluation of different glare ratings, and it confirms the previous findings that indicated that VCP is not suitable for assessing daylight glare.

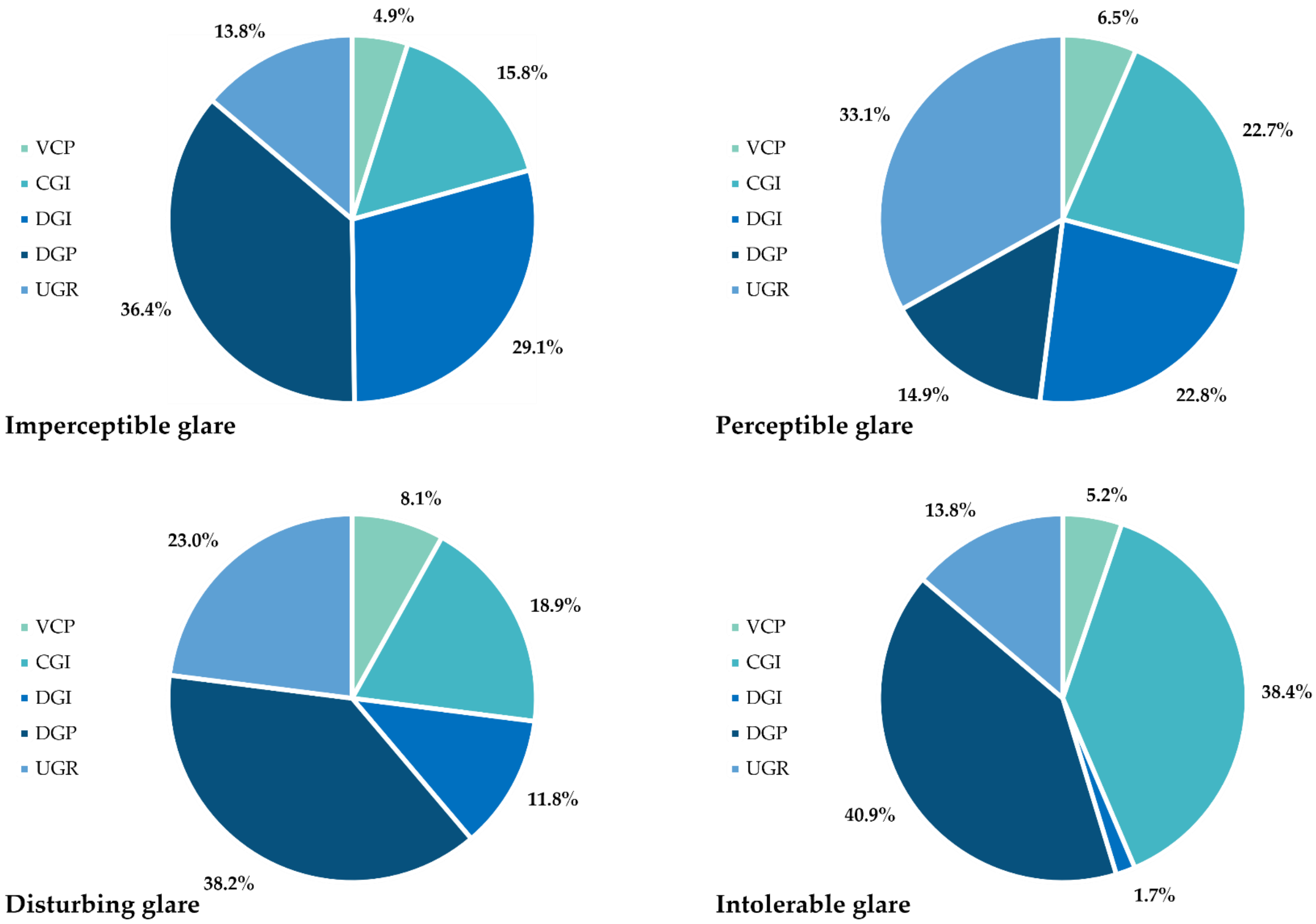



**Figure 9.** The accuracy rates of glare metrics in the evaluation of different glare scenes.

## 4. Discussion

### *4.1. Implications and Key Findings of the Study*

In contemporary architecture, the glass façade is so popular since it can remarkably minimize energy consumption in buildings and maximize daylight utilization as a natural energy. It is generally accepted that daylighting design and implementation in buildings can improve occupants' comfort, the efficiency of employees, and users' mental health [1,3,6,18,19,46,47,49,51,53,54,73]. However, it is necessary to consider occupants' visual discomfort due to the daylighting glare risks during the initial stage of design. Based on recent investigations, discomfort glare is a prevalent problem in many offices, due to the wide use of glazed façades [6,52].

So, various daylighting control systems have been developed to redirect or block the sunlight. Among different daylighting systems, light shelves have more capability to address visual comfort demands, along with enhancing energy efficiency due to their physical adaptation compared to fixed systems [34,71]; however, they can either be a great opportunity or a huge threat depending on their design [27,45–47,50,74]. With the advancement of shading device technology in office buildings, researchers have tended to conduct more research into daylighting glare and its related issues. Accordingly, a reliable metric is needed for evaluating glare in order to design an appropriate shading system.

Since the measured glare metrics should have an acceptable correlation with the human subject data, the agreement on the glare indices is complicated. Although many researchers have evaluated the current visual metrics to develop them, the existing visual metrics have contradictions in a similar level of glare. These conflicts have stemmed from the fact that glare is a subjective phenomenon [4,16,31]. Although many studies have been conducted into the validation of glare indicators, no clear guidelines have yet been provided. So, it is relatively difficult for the designer to select the appropriate glare index in various conditions.

From the study findings, it is clear that only one or two discomfort glare metrics were precisely aligned with the subjective human study data, and in some cases, none of the metrics were in agreement with the subjective evaluations. Our results support the previous research which stated that the visual metrics have wide contradictions in the evaluation of discomfort glare [16,18,56]. Each glare metric has its own weakness and is limited to specific indoor environmental conditions. This is because the position and the size of the glare source are not static during time intervals [34]. We confirmed that the accuracy rate of DGI in evaluating perceptible, disturbing, and intolerable glare is about 13.5%. This means that DGI overestimates glare scenes and shows a low accuracy rate in evaluating glare scenes. Although it shows a high accuracy rate in imperceptible glare scenes [23]. The results of this study can be added to the previous research because it presents the strengths and limitations of existing visual metrics.

### *4.2. Limitations and Future Research Recommendations*

The following recommendations practically express the suggestions of this research:

- According to the results, most of the current glare indices show a low correlation with human subjective data, and there is a high contradiction between different levels of predicted and perceived glare. Since glare is a kind of subjective phenomenon, the policymakers on building energy codes should be encouraged to involve more human-centered factors in regulating visual metrics, hence the contradictions are eliminated.
- For the subjective approach, we utilized a developed questionnaire to collect human subjective data. To yield a better outcome, it is recommended to use smart building sensors such as image-based sensing technologies and surveying methods simultaneously. Sensing technology helps to monitor building occupancy data and collect occupancy-related information more precisely.

The results guide architects and building designers to select suitable indices regarding the purpose of the project. As mentioned before, it is necessary to consider occupants' visual discomfort due to the daylighting glare risks during the initial stage of design, and designing an effective daylighting system is related to the building performance process, so we propose a roadmap to policymakers for making the best decisions in the process of building design in Figure 10.

The following limitations also can be addressed in future research:

- As mentioned before, our case study was located in a semi-arid climate and the research outcomes can be practical in similar climates. Further studies should confirm these novel findings by conducting research in similar climatic conditions.
- The main common feature among glare indices is their dependency on the occupants, although the main attention of this paper is on office buildings with fixed light shelves. Further research could be conducted to investigate the performance of glare indices in office buildings with dynamic light shelf systems to evaluate visual metrics according to changing conditions and compare the results with the current study's findings, since applying these metrics in other setups might not end with the same results.

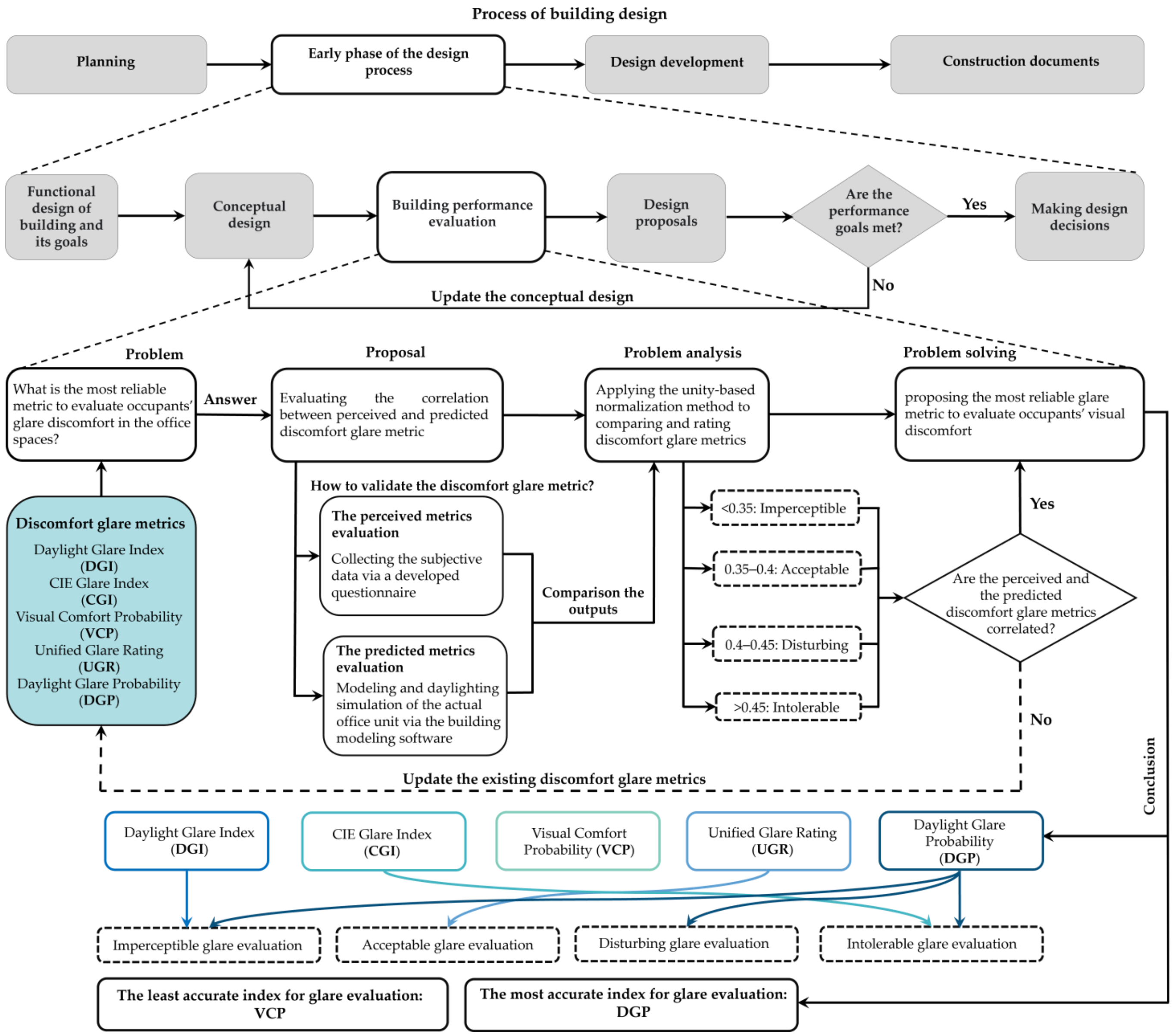



**Figure 10.** The proposed roadmap to policymakers for selecting the appropriate glare metrics in the evaluation of occupants' visual comfort.

## 5. Conclusions

The analysis performed in this research shows that the existing discomfort glare metrics need to be developed according to the subjective data to find the best correlation between the predicting and perceiving glare evaluations. In particular, the following key findings emerged from the study:

- According to the results, only one or two discomfort glare metrics are correlated with human subjective data in each stage, and in some cases none of the metrics are in alignment with the survey results. So, this finding supports the previous research which stated that the glare indices have wide contradictions in discomfort glare evaluations. There is no significant relationship between subjective and simulation-based analysis of discomfort glare metrics in different glare ratings.
- At almost all different levels of glare, comparing the subjective and simulation analysis of visual criteria indicated that DGP is the most accurate and reliable index for assessing glare and has the highest correlation with human subject data. However, some of the discomfort glare metrics in the special condition had better performance

in glare evaluation. For example, UGR had the highest accuracy rate for evaluating perceptible glare level, DGI was applicable for imperceptible glare assessment, and the best discomfort glare metric in assessing intolerable glare was CGI.

- Based on the obtained results from the comparison of glare metrics with surveying outcomes, VCP has the least correlation with subjective evaluation and its' assessment accuracy in each level of glare is very low. So, VCP is not appropriate for discomfort glare evaluation in offices with a light shelf system and needs deep research to consider suitable human-centered design factors for development in the future.
- The study indicated that there are highly significant differences between the subjective and simulation-based analysis of visual metrics in offices using light shelf systems. Although, for a more accurate investigation, it would be better to consider two or more glare indices simultaneously to alleviate this contradiction.

A set of recommendations is presented in this study that should be used by architects during the early design stage to create more efficient places to work.

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**Data Availability Statement:** Not applicable.

**Conflicts of Interest:** The authors declare no conflict of interest.

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