A COMPARISON OF FOUR DAYLIGHTING METRICS IN ASSESSING THE DAYLIGHTING PERFORMANCE OF THREE SHADING SYSTEMS

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ABSTRACT

The assessment of the daylighting performance of a design solution is a complex task due to the changing nature of daylight. A few quantitative metrics are available to designers to assess such a performance, among them are the mean hourly illuminance (MHI), the daylight factor (DF), the daylight autonomy (DA) and the useful daylight illuminance (UDI). Each of these metrics has a purpose, a set of criteria and limitations that affect the outcome of the evaluation. When to use one metric instead of another depends largely on the design goals to be achieved. Using Design Iterate Validate Adapt (DIVA) daylighting simulation program, we set out to examine the performance behavior of these four metrics with the changing dimensions of three shading devices: a horizontal overhang, a horizontal louver system, and a vertical fin system, and compare their performance behavior as the orientation changes of the window to which these devices are attached. The context is a typical classroom of a prototypical elementary school. Our results indicate that not all four metrics behave similarly as we vary the size of each shading device and as orientation changes. The lesson learned is that not all daylighting metrics lead to the same conclusions and that it is important to use the metric that corresponds to the specific goals and objectives of the design and of the daylighting solution. The UDI is the metric that leads to outcomes most different than the other three metrics investigated in this paper.

KEYWORDS

daylighting, daylight autonomy, daylight factor, mean hourly illuminance, useful daylight illuminance, louver design,

1. BACKGROUND

Building Illumination standards are largely based on visual performance requirements. Meeting the visual performance requirements under an electric lighting solution is a fairly straightforward task because of the constancy of electric light. Although there are many factors contributing to the quality of luminous environments, lighting design standards are almost entirely based on minimum illuminance requirements to be met in order for the observer to be capable of

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performing a certain visual activity [1]. In a daylighting scenario, the changing character of daylight adds complexity and difficulty in assessing the performance of a daylighting solution. Daylight prediction techniques can be difficult and complex as they deal with the temporal character of daylight. The problem is especially more complex when dealing with sunlight conditions. How does one evaluate indoor conditions under sunlight when the majority of the available assessment tools and benchmarks are based on the concept of sufficient illumination for visual task performance? When there is sunlight inside a room, light levels inside are likely much higher than any recommended minimum illuminance level [2, 3].

Daylighting metrics are grouped into two broad categories: the static metrics category and the dynamic metrics category.

a. Static Metrics:

Static metrics deliver performance judgement in terms of quantity of illumination inside a room at a specific time and date without providing a good assessment of how a specific design solution might perform throughout the year. The following metrics fall in this category:

Instantaneous Illuminance Metric

The instantaneous illuminance level is calculated using hand calculation methods or computer simulation codes. The calculation is performed for an ambient light level or a specific station point in the room and at a given time of day. Most hand calculation methods consider overcast sky conditions only, using coefficients of utilization that describe how much light compared to what exists outside a particular location receives given a room's dimensions and surface reflectances. When computer codes are used, other sky conditions include clear sky and sunlight. This metric of daylighting performance provides information that is very limited in space and time. In order for the designer to make design decisions regarding a particular design solution, several calculation iterations must be made to complete the analysis. This can be time-consuming and may or may not always be possible depending on the complexity of the design.

Daylight Factor

The daylight factor (DF) is defined as the ratio between the daylight illuminance level at a given point on a horizontal plane inside a room and the outdoor illuminance level on an unobstructed plane [4]. The daylight factor is comprised of three constituents, namely the sky component, the externally reflected component, and the internally reflected component, the sky component being the largest of the three components. Therefore, the DF may be influenced by the exterior environment outside the room as well as the reflectance of the inside surfaces in addition to the amount of daylight coming from the sky vault. DF is one of the oldest metrics in daylighting computations. This metric was developed for the purpose of eliminating the time factor in daylighting prediction by taking into consideration only the diffuse daylighting condition. Consequently, only the diffuse overcast sky may be used when applying this method of calculation because the luminous characteristic of an overcast sky in terms of luminance distribution is considered stable and unchanged. Consequently, the ratio between the inside illuminance at any given point and the outdoor daylight levels remains constant regardless of the time of day. The constancy of the DF is the main advantage in using this method. Because of its simplicity, the DF metric is the most used one in experimental studies that rely on physical scale models. The overcast sky condition in many locations is considered the least advantageous sky condition in terms of daylight availability, and it is often used as the standard design by most daylighting computer simulation. The principal disadvantage of this metric is, however, the fact that it can be used only under overcast sky conditions. Sunlight is an important characteristic of daylight, and ignoring it could lead to significant visual and thermal discomfort potentially experienced by the building occupants.

$$\text{DF}\ (\%) = \frac{E_i}{E_o} \times 100 \tag{1}$$

Where,

E_i = interior daylight level at a given point on a horizontal plane under overcast sky condition

E_o = exterior daylight level at on a horizontal plane under overcast sky condition

This metric is often used in daylighting design recommendation or daylighting codes whenever they exist because of its simplicity to understand and apply in design. The DF metric is a purely illuminance-based metric without any consideration of visual comfort of the building occupants. Some countries such as in France and the UK used the DF metric to legislate daylighting in schools [5]. In the case of the UK, levels up to 6% were prescribed in the 1970s for schools, only to find out later that such levels, if achieved on overcast days, may result in high glare and visual discomfort during the sunny days.

b. Dynamic Metrics

In the last decade, new concepts of daylighting metrics were developed. These computer-based calculations emerged primarily due to the increased power of computing. Unlike static metrics, dynamic computing is based on a time series of illuminance levels within a room under any sky conditions including sunny ones [6]. The calculations span the entire year or a user-selected period, and are based on solar radiation data at the location of the building. Three different but related metrics fall under this category of dynamic metrics, namely the mean hourly Illuminance (MHI), the daylight autonomy (DA) and the useful daylight illuminance (UDI) metrics.

Mean Hourly Illuminance

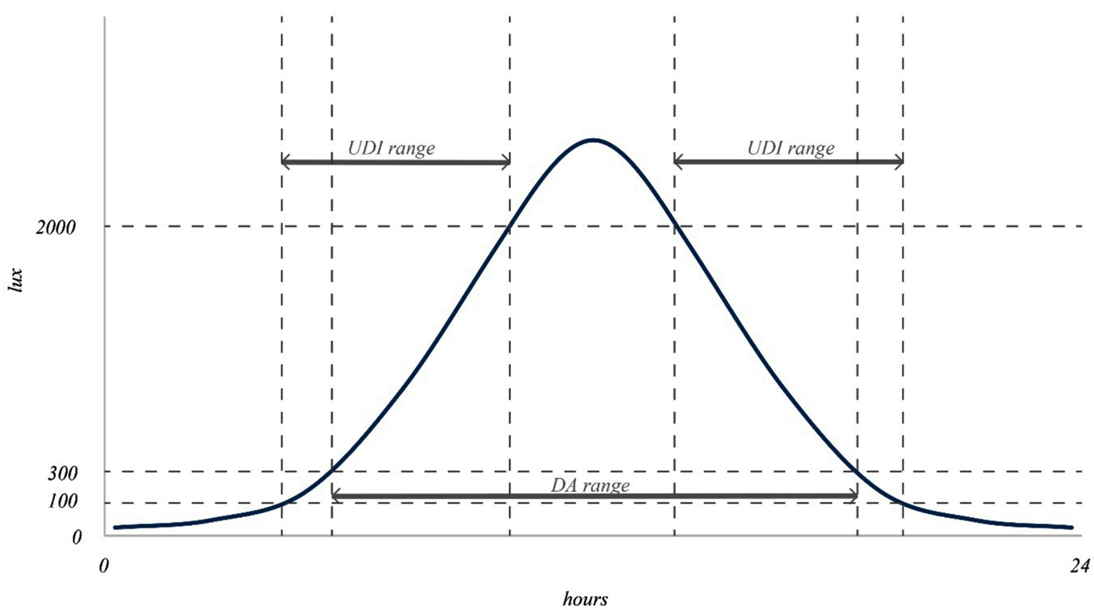
The mean hourly illuminance (MHI) represents the average illuminance level calculated at a given location, or as an average based on several prescribed locations inside a room. It represents the mean value of the total hourly illuminance levels in a room calculated at one or several preselected locations throughout a day, a month or a year [7]. This is a computer-based calculation whereby the mean is a statistically derived number of illuminance values based on the weather files available for that geographic location, using probabilistic occurrences of all sky conditions. What this metric provides is not an illuminance level at a given location in a room at a given time but rather provides information about the daylighting potential and possibilities of a design solution using one single number of illuminance level. This is both an advantage and a disadvantage of this method. It is an advantage because it gives an idea of how overall a particular design solution may be performing in general terms but is not specific enough to actually provide information about how this solution is performing at a given moment. Unlike the DF method, the MHI accounts for all sky conditions as well as for direct and diffuse illuminance inside the room but does not have any considerations of visual comfort issues.

$$\text{MHI} = \sum_{n}^{1} \frac{E_i}{n} \tag{2}$$

Daylight Autonomy (DA)

The Daylight Autonomy (DA) informs the user about the percentage of time within a given time frame daylight illuminance meets or exceeds a reference level inside a room at a given specific location or as an average level for that room. The cumulative hour-by-hour DA calculation is based on an illuminance threshold for a user-defined period of time (for example from 300 lux 8:00 AM to 5:00PM in the case of an office.) (Figure 1). DA varies in an inversely proportional manner with the selected threshold illuminance level. In other words, as the illuminance threshold increases, DA is expected to decrease and vice-versa. This concept was initially proposed in the 1980s [8], and subsequently improved [6, 9]. This new paradigm of dynamic daylight simulation was an important advance in the area of daylighting simulation particularly as it pertains to estimating energy savings from daylighting which is what this metric is mostly used for. This metric does not provide specific photometric performance information, but rather permits the user to determine the potential electric lighting energy savings by calculating the percentage of time the user may rely on daylighting given a pre-determined illuminance threshold. Generally speaking, this illuminance threshold is the needed ambient illuminance to perform a given task and can be set at various levels according to the electric lighting strategy being used. It would

FIGURE 1. User-defined Illuminance thresholds for the DA and UDI given a 24-hour cycle.



be reasonable to assume that as the quantity of daylight inside a room increases, DA would be expected to increase as well albeit not necessarily in the same proportions. Another advantage for the DA compared to DF metric is the fact that it considers all sky conditions of the specific location in so far as the weather data for such a location exist.

Useful Daylight Illuminance

The concept of Useful Daylight Illuminance (UDI) is based on the Daylight Autonomy. The UDI attempts to alleviate the significant drawback of many other metrics, namely their lack of consideration for visual comfort criteria [10]. Daylighting design has to deal with issues of excessive illumination that may exist at times, such as under sunlight conditions. Under the UDI the user is able to calculate the percentage of time, given a time frame (for example 8:00AM to 5:00PM) that the interior daylight illuminance in a room falls within a user-defined range (for example between 100 lux and 2,000 lux) (Figure 1). The UDI represents the annual occurrence of daylight illuminances falling within the given range. The lower end of the UDI range indicates that light levels below it are not useful for any task performance while the higher end of the range denotes that levels above that the upper limit potentially would cause too much visual or thermal discomfort and that in all likelihood the room occupants would find it necessary to alter the condition by pulling down blinds for example [11]. Light levels below the lower end and above the upper end of the range are consequently discarded during the daylighting performance analysis. The UDI is deemed to be a reliable measure for predicting glare from daylight because of its strong association with the daylight glare probability that assumes light levels above 2,000 lux are likely to induce high glare potential (DGP) [10].

2. RESEARCH PROBLEM AND HYPOTHESIS

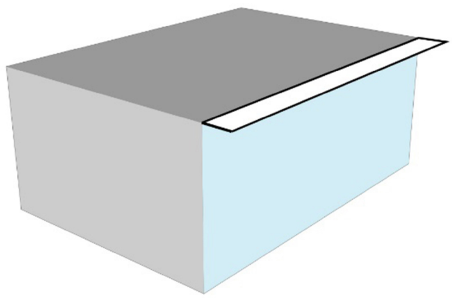
What is good daylighting and what metrics are appropriate in a daylighting analysis given the changing character of daylight are issues that designers constantly address. Our research question is do these various performance metrics lead consistently to the same conclusions and the same optimal architectural solutions? While one might easily guess the existence of a positive association between the relative size of the daylight apertures and illuminance-based metrics such as the DF or the MHI, such association may not be true all the time for the DA or UDI metrics that are based on calculating a percentage of time a certain daylight illuminance condition is met. Our hypothesis is that because of their inherent definitions, not all daylighting metrics lead to the same design solution.

3. RESEARCH METHOD

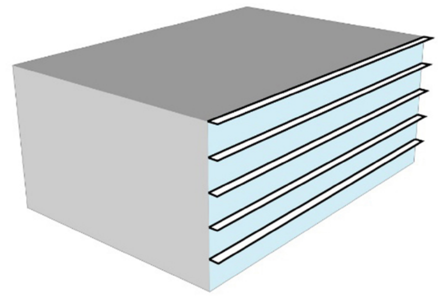
Given the inherent definitions of these four metrics, we set out to compare the performance outcome of three simple daylighting/shading systems using these four metrics. For our analysis we selected three types of shading devices that are ubiquitously found, namely a horizontal overhang, horizontal louvers, and vertical fins (Figure 2).

The Design Iterate Validate Adapt (DIVA) plug-in for Grasshopper/Rhino was used to evaluate the relationship between each of the four metrics and the size of these three daylighting devices. DIVA-for-Rhino is a highly optimized daylighting and energy modeling plug-in for the Rhinoceros.

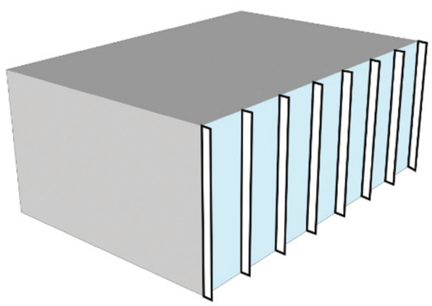
FIGURE 2. Three-dimensional view of the three daylighting systems tested.



Horizontal Overhang



Horizontal Louver System



Vertical Louver System

The simulated building consists of a typical classroom of an elementary school in South Korea. Its dimensions are 5 m (16.4 ft.) in depth, 7.2 m (23.6 ft.) in width, and a floor-to-ceiling height of 3.05 m (10 ft.). The parametric simulation input variables and outputs are shown in Tables 1 & 2, which include varying dimensions of the three shading devices and four given façade orientations assuming a fully glazed wall of the classroom to maximize the effectiveness of the installation of a shading device. The values of material reflectances and visual transmittance of the window are listed in Table 2.

TABLE 1. Input variables and outputs for simulation.

Input variables		Outputs
Louver	Horizontal/Vertical/Overhang	MHI DF DA (300 lux reference) UDI (100 lux ≤ E ≤ 2,000 lux)
Orientation	S/N/E/W	
Visible transmittance of glazing	0.65	

TABLE 2. Material properties for simulation.

Building property	Material's value	Value type
Wall	0.5	Material Reflectance
Ceiling	0.7	
Floor	0.2	
Louver	0.3	
Window	0.65	Visible Transmittance

Each shading system has five different parametric values, which enables us to evaluate the performance behavior of each daylighting metric relative to the changing dimensions of the shading device and to the orientation of the glass wall. The size of the shading devices is calculated as a percentage relative to the dimension of the glass wall to which they are attached (Figure 3). To calculate this relative size, we use the relative size of the shading device in relation to the total aperture. This is also known as the projection factor (PF) [12, 13, 14]. PF is defined as the ratio of the total depth of all louver slates or the overhang to the total height of the window in the case of horizontal devices, or the total width of all vertical fins to the total width of the window:

$$\text{Projection Factor (PF)} = \frac{\text{Total depth of shading device pieces}}{\text{Total height or width of aperture}} \times 100\% \tag{3}$$

In our simulation, the depth of the horizontal overhang varies between 0.5 m and 2.5 m, with 0.50 m increments. The depth of the horizontal or vertical slates of the louver system varies between 0.20 m and 1.00 m with 0.20 m increments, corresponding to projection factors as indicated in Table 3. All the louvers and vertical fins are fixed, forming a 90-degree angle with the plane of the window and spaced 0.60 m apart. We also investigated the impact of building orientation, namely East, West, South, and North. The particular location of Seoul, South Korea, was used, which corresponds to the ASHRAE climate classification zone 4A.

FIGURE 3. Projection factor of a shading device.

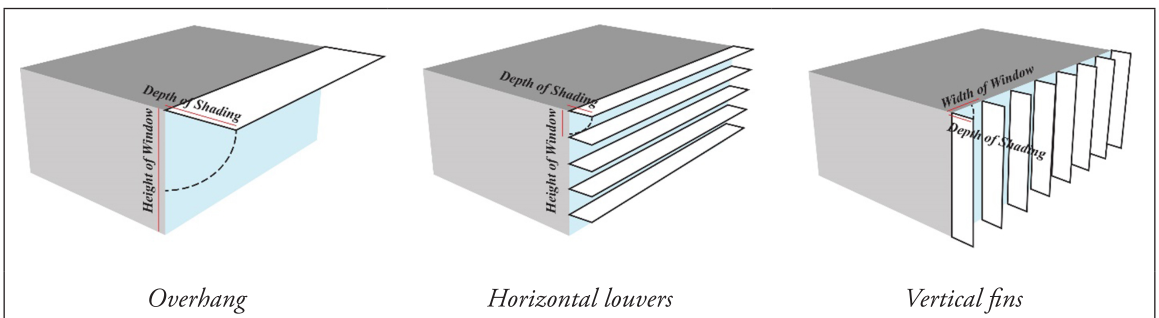


TABLE 3. Relative size (PF) of shading devices used in relation to the dimensions of the window wall.

Shading System	Size of Individual Shading Device (Meters)	Number of Devices	Projection Factor (%)
Horizontal Louvers	0.20	5	33.3
	0.40	5	66.6
	0.60	5	100
	0.80	5	133
	1.00	5	166
Horizontal Overhang	0.50	1	16.6
	1.00	1	33.3
	1.50	1	50
	2.00	1	66.6
	2.50	1	83.3
Vertical Fins	0.20	5	19.4
	0.40	5	38.9
	0.60	5	58.3
	0.80	5	77.8
	1.00	5	97.2

Daylighting Analysis:
The four metrics, namely the MHI, DF, DA and UDI are calculated using the DIVA daylight simulation program. The calculations are based on a room average of a user-defined grid system, in our case a 40-point grid as shown in Figure 4.

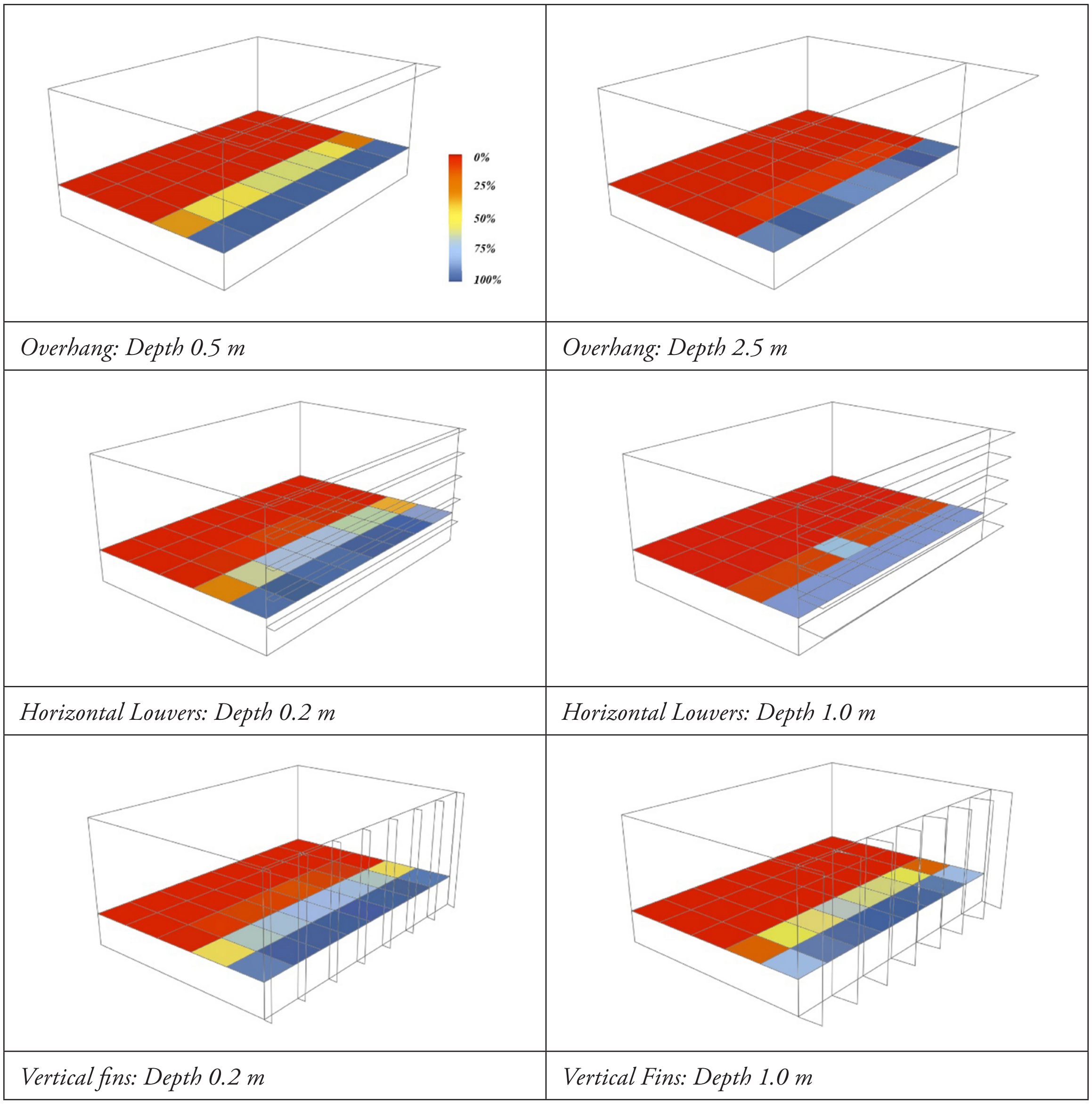
For the DA, a target value of 300 lux was assumed in our analysis. For the UDI range we selected a range between 100 lux and 2,000 lux (Figure 1).

4. RESULTS

4.1. Effect of horizontal louvers and orientation

Figure 5 illustrates the relationship between the mean DF, MHI, DA and UDI and the size of the horizontal louvers applied to a fully glazed facade as well as the effect of façade orientation. As a reminder, the DF value as well as the other three metrics were calculated using a 40-point average as shown in Figure 4. The results indicate a negative relationship between the mean DF and the depth of the louvers. The mean DF value for a fully glazed façade with no shading at all is 9 %, and the mean value for a 1meter deep louver (PF = 166%) is 1.5%. The results

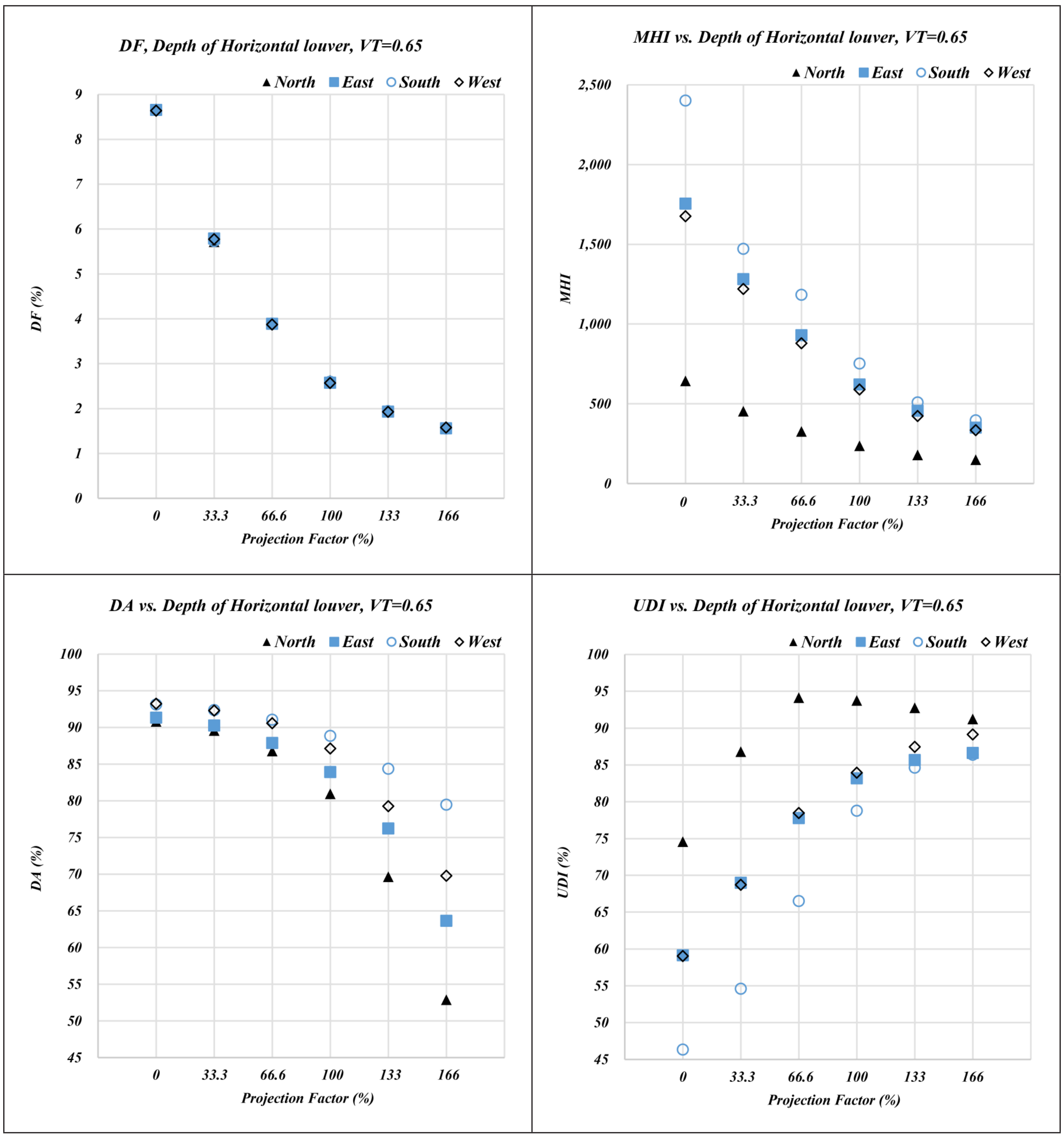
FIGURE 4. The 40-point grid systems used to calculate and compare the 4 metrics.



also indicate no noticeable difference between the four façade orientations as expected under an overcast sky. The results show a rapid DF decline as the depth of the louver slates increases from zero to 0.20 meters (PF = 33.3%). This decline becomes more moderate as the depth of the louvers increases beyond 0.20 meters. Furthermore, this relationship between louvers depth and DF is not linear but rather a curvilinear one suggesting that depth beyond a point is not as impactful.

The relationship between the annual mean hourly illuminance (MHI) and the depth of the louvers is also negative and not linear, with the largest decline occurring between louver depths ranging from 0.00 meter and 0.60 meter (PF = 100 %). The decline is more moderate when louver depth is in the region between 0.6 meter and 1.00 meter (100% < PF <166%). Unlike DF, orientation plays a significant role in the case of the MHI because this metric takes into account all sky conditions. South orientation leads to the highest value of HMI while the north orientation leads to the smallest values. On an absolute scale of illuminance levels, the south side is impacted more negatively than the north side. However, on a relative scale we notice similar declining proportions, where HMI loses close to 75% from all four sides as the depth of the louvers increases from 0.00 m to 1.00 m (Figure 5).

FIGURE 5. The relationship between the daylighting metrics, horizontal louver depth, and orientation.



Assuming a 300 lux target illuminance with regard to the Daylight Autonomy, we notice a negative relationship between the mean DA and the depth of the louvers. The decline in the DA is neither proportional to the louvers' depth nor is it the same for all facade orientations. It is more gradual from the south, east and west but much larger from the north façade. DA is calculated based on mean illuminance in the room and the the fact that direct sunlight component is included in its computations tends to give a distinct advatange to the south orientation as well as east and west orientations that let sunlight in. The north orientation is affected the most severely when using the DA metric.

The relationship between the UDI and the depth of the horizontal louvers follows a pattern different from the ones observed with the other three metrics. When the louvers are on the north façade, UDI values increase sharply when the depth of the louvers increases from 0.00 m to a depth of 0.40 meter (PF = 66.6 %). After a depth of 0.40 meter, we observe a gradual decline. From the three other orientations, we observe a continuous positive relationship between the UDI and the depth of the slates, with the south façade registering the smallest UDI and the east and west facades showing nearly equal UDI values. It is worth noting that UDI values on the north side of the building are higher than UDI values of the other three facades given the same louver depth. At first glance this seems illogical, but given the fact that a large portion of illuminance values exceeding 2,000 lux are excluded from the calculation of the UDI, this puts the facades of the building that receive sunlight at a disadvantage when using this metric.

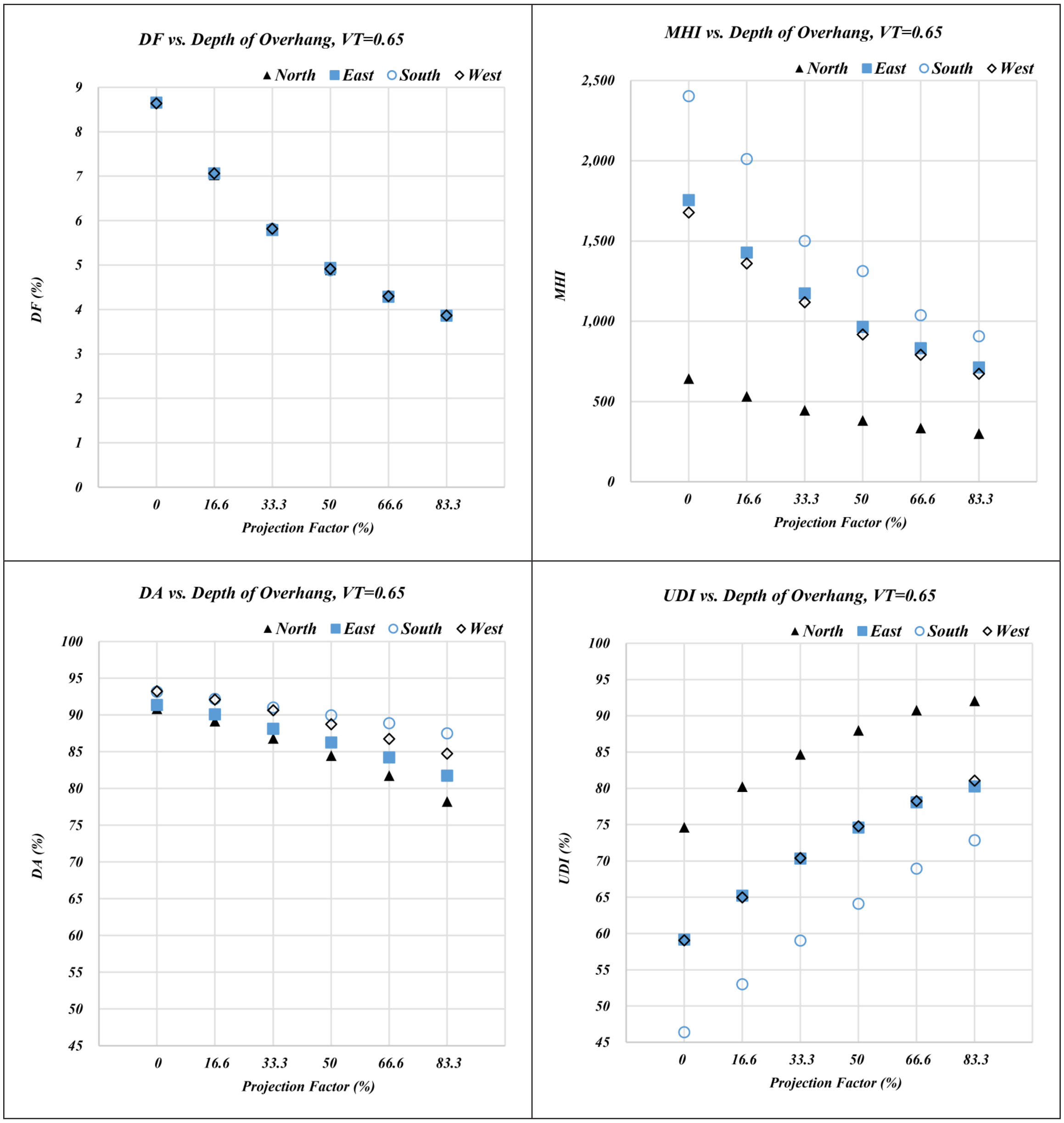
4.2. Effect of horizontal overhang and orientation

Figure 6 illustrates the relationships between the depth of a horizontal overhang and the 4 metrics we examined in our study. While DF, MHI and DA metrics exhibit a negative relationship with the overhang depth, the UDI exhibit a positive relationship. In addition to such a difference between the UDI and the three other metrics, we further observe a discrepancy among these various metrics in the way they are impacted by orientation. As expected, DF shows no difference between the various four orientations tested. The south orientation lead to the highest values of the MHI while the north orientation leads to the lowest MHI, with the east and west being nearly equal. A similar pattern to the MHI is also observed with the DA, although the difference this time between the south and north is not as severe as when using the MHI (Figure 6). Generally, the loss in DA is smaller and more gradual from all four orientations, with the south orientation resulting in the highest DA and the north orientation with the lowest DA. A window with no overhang has the highest DA (92%, based on 300 lux target illuminance). The reduction in MHI is very steep from the south, east and west orientations, but smaller on the north side. From the south façade, a loss of 45% in the MHI is observed as the depth of the overhang increases from 0.00 meter to 1.00 meter (PF = 33.3 %), and a loss of 66% is obtained as the overhang increases from 0.00 m to PF of 83.3%. From the north façade, MHI loses its maximum value as the overhang depth increases from 0.00 m to PF = 83.3% (or 2.5 meters). With the DF metric, the relationship is also negative and linear from all four orientations and are identical as expected. The Daylight Factor loses 30% of its value from a window with no overhang to PF = 33.3% overhang and nearly 50% of its maximum value as the overhang depth increases from 0.00 m to PF = 83.3 % (Figure 6).

4.3. Effect of vertical fins and orientation

Figure 7 shows the behavior of the four metrics in relation to the depth of vertical fins. A pattern similar to the horizontal louvers may be observed that is a negative and non-linear relationship

FIGURE 6. The relationship between the daylighting metrics, the depth of a horizontal overhang and orientation.

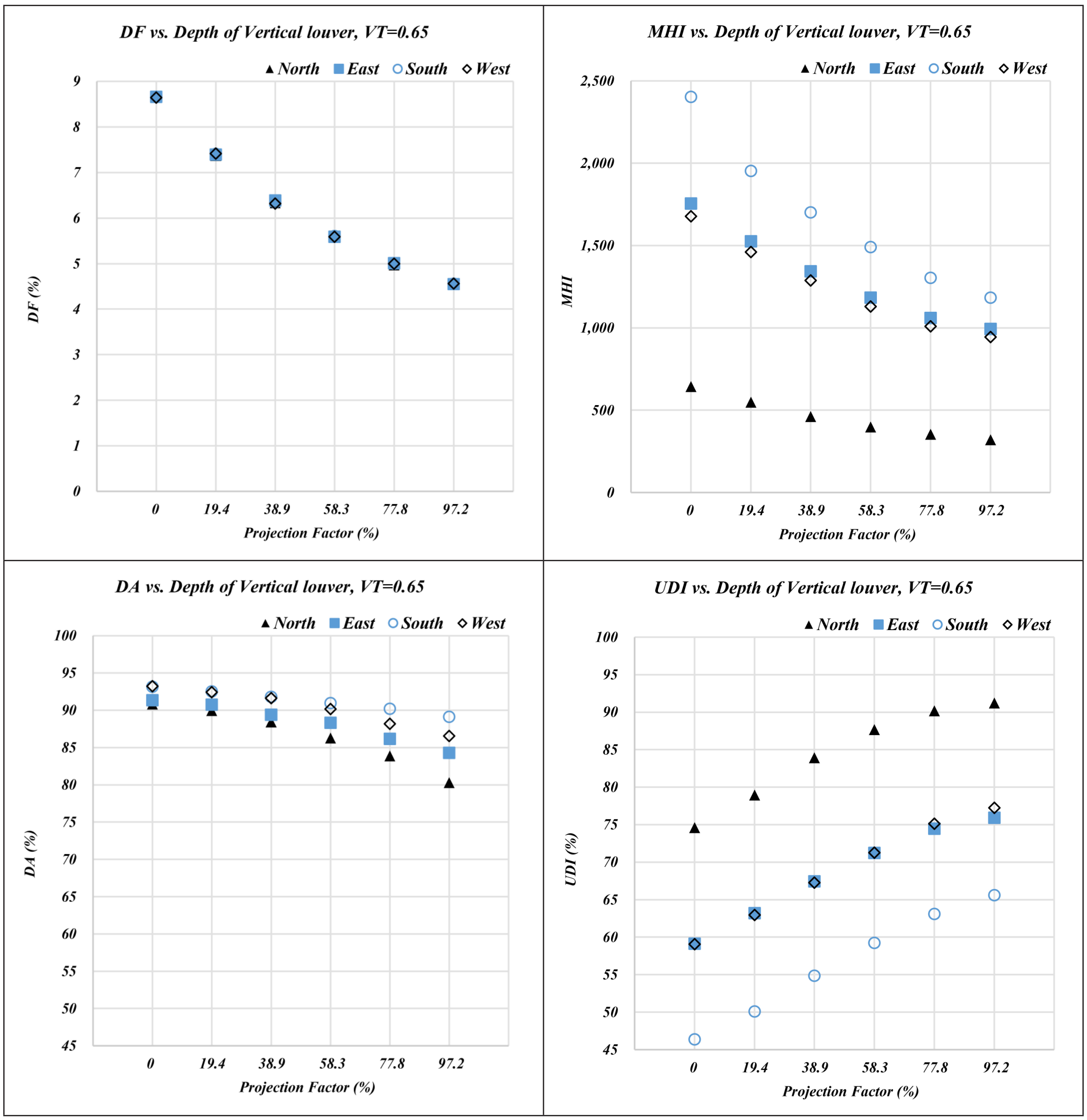


exiting between the three metrics, DF, MHI and DA but a positive and non-linear relationship exists in the case of the UDI. South orientation seems to be negatively impacted the most as the depth of the fins increases. Conversely, and much like with the other two shading devices previously tested, the north orientation displays the highest UDI values, much like in the case of horizontal louvers.

TABLE 4. Comparison of the behavior of the four metrics with the size of the 3 shading devices.

	Horizontal Louvers PF (%)		Overhang PF (%)		Vertical Fins PF (%)	
Metric	33.3	66.6	33.3	66.6	38.9	77.8
DF (%)	5.8	3.9	5.8	4.3	6.3	5
MHI (Lux)	1,450	1,250	1500	1050	1,700	1,300
DA (% of time)	93	90	92	88	92	90.5
UDI (% of time)	58	67	60.5	68	55	63

FIGURE 7. The relationship between the daylighting metrics, depth of vertical fins, and window orientation.



5. DISCUSSION

Our investigation shows that when using any given metric in daylighting studies it is essential to clearly state the objectives and the goals that need to be achieved by the design. Each of the four metrics that we tested measures different things and consequently neither do not necessarily lead to the same conclusions. What we learned in this study is that the DF, MHI and DA metric lead to similarly close conclusions, in that all three of them showed similar behavior as the size of three shading devices change. The three metrics also behaved similarly as orientation varies with the exception of the DF which showed no difference between the four orientations due to the fact that only the overcast sky condition applied to that metric.

What we found astonishing and one of the main lessons learned here is that the UDI leads to very different results by comparison to the three other metrics with respect to the size of the three shading devices and also in regard to façade orientation. And though the DA is a rather straightforward calculation of the percentage of time a given target daylight level is to be met, the UDI specifies a range of illuminance that is quite wide. Some levels within this UDI illuminance range may not necessarily meet the needed levels for task performance, and consequently, the designer may not necessarily know when the light fixtures are on or off. Unless the lowest end of the range is equal to the target illuminance for task performance, it is not always possible to determine how much electric energy is saved using the UDI. The main advantage of the UDI is its explicit consideration of visual comfort parameters and its close correlation with the Daylight Glare Probability [11].

6. CONCLUSION

In conclusion, if the goal of the design is to estimate energy savings resulting from a daylighting strategy, the DA would be the most appropriate metric. Because of visual comfort considerations, the designer may need to employ both the UDI and the DA simultaneously in order to achieve both the targeted energy savings and in order to meet the visual comfort concern. To do so, one can determine the percentage of time light levels are going to be above the reference illuminance level using the DA and at the same time determine the percentage of time those levels are not going to exceed discomfort levels by using the UDI metric. Another possible scenario is to have an illuminance range for the UDI where the lowest end is equal or exceeds the target illuminance level for the electric lights to be turned off. It is only by combining these two metrics that one can meet hopefully both the lighting energy reduction goals while maintaining visual comfort during a predetermined time period.

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