An index linked with luminous environment and energy saving for daylighting and shading design

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SUMMARY

Being healthy and energy saving have become two important principles of building development. Daylight is an influential factor with the characteristics of both photometry and radiometry. This study adopts a dynamic daylight metric, average daylight autonomy (Ave. DA300), with the benchmark for evaluating luminous environment in residential buildings. With this guideline, the Hong Kong public housing units is found that part of units lack of daylight, while some units have potential to save energy by compromising daylighting performance. Therefore, a new index, energy daylight rate (EDR), is proposed to help decide the best scenario of envelope design for both daylighting and shading purposes. The results show that opening a secondary window is an efficient way to bring more light in and lengthening overhang is an efficient way to block excessive sunlight. This new index is proved to help define proper building envelope design at the early stage.

INTRODUCTION

Light is a valuable resource, not only it brings people brightness and affects human circadian physiology, but also it enhances people’s productivity and satisfaction. Increased consciousness about satisfaction such as thermal comfort, acoustic comfort, as well as luminous comfort has attracted people’s attention to their living conditions. Nowadays, being healthy and energy saving have become two important principles of building development. Daylight is an influential factor as the characteristics of both photometry and radiometry. Irradiance brings solar heat gains, which transfer to building cooling load, while illuminance provides a specific luminous environment and affects energy usage of lighting system at the same time. Therefore, how to balance the energy consumption and daylighting performances becomes a critical issue, and three important questions should be addressed first: 1) should the energy be consumed as little as possible; 2) can the comfort level of luminous environment be quantified; 3) how to guide the energy-efficient daylighting design based on luminous comfort?

Hong Kong has a fruitful daylight resource for saving artificial lighting energy as the outdoor horizontal illuminance could reach to 10 000 lux for over 80% office hours in a year (Chung, 2003). Both the simulated and measured data showed the daily lighting energy savings could reach to 8 kWh in spring and summer (Li and Tsang 2005). The Electrical & Mechanical Services Department (EMSD Hong Kong 2014) reported that the annual lighting consumes 13% of the total electricity end-uses, which ranks the second following the space-conditioning 30%. Better utilization of daylight and better control of lighting, such as daylight harvesting systems and dimming control, could generate more lighting energy savings. However, daylight also brings radiation, and solar heat gain becomes cooling load which will increase 28% of the energy consumption for air-conditioning (AC) system unintentionally (Apte and Arasteh 2006). Hong Kong still suffers from an intense increasing of annual total electricity consumption with an average rate of 6.67% per year over last 40 years. Therefore, in order to achieve total energy-efficient objective, cooling load and artificial lighting electricity should be considered simultaneously when optimizing envelope design related to daylight.

To reduce the annual energy consumption, static or dynamic façade features are often adopted for envelope design. For an individual flat, the electricity savings could decrease from 40 to 28 kWh/m 2 when the angle of obstruction varied between 25° and 30° (Li and Wong 2007). With the optimized shading area of 7.84 m 2 based on Pareto method, the solution provides the 20.19% reduction in overheating. Regarding window position, the energy savings in electric lighting can be quantified as 30% at the back of the room (Acosta et al. 2016). Except for energy saving purpose, façade features (balconies, sunshades and reflectors) are recommended by Hong Kong government to incorporate in building development for enhancing luminous environment of residential units. To balance the energy consumption and daylighting performances and also answer the first question, it’s reasonable to minimize the environmental load under moderate comfort conditions.

Veitch and Newsham (1998) believes that people’s subjective perception of light should be quantified by objective metrics. Some researchers qualified the comfort as illumination level and some treat it as uniformity. While, most researchers believe offering comfort environment means reducing glare problem. With the development of climate-based daylight modeling (CBDM) technology and the continuous improvement of computer performance, cumulative effect of daylight on indoor luminous environment are put forward, namely daylight autonomy (DA) (Reinhart and Walkenhorst 2001), useful daylight illuminance (UDI) (Nabil and Mardaljevic 2005), annual light exposure (ASE) (CIE, 2004) and so on. A basic study lead by Reinhart and Weissman (2012) found that the spatial daylight autonomy (sDA) can
accurately representative the area in which students assessed as mean daylit area, with an error of around 7%. Based on this series of work (Reinhart et al. 2006; Mardaljevic et al. 2009; Nezamdoost and Wymelenberg 2015), the North American Institute of Illumination (IESNA) has incorporated the dynamic metrics sDA and ASE into the latest daylighting measurement methods (IES 2012). In 2016, the latest version of the US LEED Green Building Assessment System also includes these two metrics and legalise them as one of three standard methods of indoor lighting evaluation (Green Building Council 2016). At the same time, the Society of Light and Lighting (SLL) is studying the feasibility of using dynamic metric as a statutory evaluation metric (Littlefair 2015), and it can be seen that the characterization of subjective requirements with dynamic metrics has become a trend. Due to the dynamic metrics can only be obtained by numerical calculation, the quantitative process needs further simulation work.

In this study, the rest two questions mentioned above will also be answered. A dynamic daylighting metric, average daylight autonomy (Ave. DA<sub>300</sub>), will be first tested to quantify luminous comfort with the data from a questionnaire survey (Xue et al. 2014) and simulation work. The benchmark of this metric will be established for high-rise residential buildings. With this guideline, the daylighting performances of Hong Kong typical public housing units could be checked to decide whether they needs daylighting or shading. Several different scenarios will be built trying to meet the balanced daylighting and energy requirements. A new index, energy daylight rate (EDR), is then proposed to help decide the best scenario of envelope design.

**METHODS**

2.1 Questionnaire survey

A questionnaire survey was conducted in a public housing estate to obtain the residents’ subjective comfort feeling for the living room luminous environment. Participants chose the comfort level based on the Likert 5-point scale. The type of the buildings is selected as Harmony 1, which is the most famous type of public housing in Hong Kong. Questionnaires were coded and issued by mail, and 108 valid questionnaires were collected through collection boxes for further analysis. These coded questionnaires reveal the specific physical information, including floor level, orientation and shading devices of the living room. By searching further information from Housing Authority, each unit’s external obstructions could be known based on real location and surroundings.

2.2 Simulation set-up

The building model has 40 storeys and 16 units on each floor level according to the real conditions. To investigate the individual difference among the units, a group (3×3) of building blocks is built, which is closed to real condition (Figure 1a). The center block is the target building which the units are built in.

As there are 640 units in a single building block, it is essential to study the daylighting and energy performances with typical units. The typical models are built according to the characteristics of the units. Except for the orientation and floor level, the location of the neighbour rooms differs much when considering the self-shading. Therefore, the total 16 units in one certain floor is separated into two groups, namely inner ring and outer ring, and 8 units for each (Figure 1b). The units in inner ring are more sensitive to the self-shading than the ones in outer ring. However, the distance of the buildings is also an influential factor as it affects much about the angle of obstruction. In this case, the inner and outer rings’ units are modelled in the target building on 5, 15, 25 and 30 storeys facing 4 different orientations in a group of building blocks with the distance of 15 m, 25 m and 35 m for each other. In this way, there will be totally 96 combinations of different units. For each combination, the daylighting performance and the energy performance of the units will be simulated by Daysim and EnergyPlus respectively.

2.3 The Average Daylight Autonomy 300 lux

DA is a percentage of time that the target illuminance threshold level is met. It has been known as a dynamic daylight metric to evaluate the cumulative daylighting performance just like UDI and ASE. Based on this metric, another term, spatial daylight autonomy (sDA), which describes the qualified area, has been accepted as a new way for daylight evaluation by IESNA and LEED. sDA<sub>300</sub> reports the percentage of the space area that meets the target illuminance of 300 lux at least 50% of the occupied time. In this study, a further step of sDA is made to average the space DAs. The average DA<sub>300</sub> (Ave. DA<sub>300</sub>) which is the average value of the DA in the target plan, is proposed not only as a cumulative metric for assessing daylighting, but also a spatial metric to quantify residents’ luminous comfort.

2.4 Energy Daylight Rate

Owing to the characteristics of photometry and radiometry happen at the same time, when there is more daylight, daylighting performance and cooling load increase, while the energy consumptions of artificial lighting has a contrary effect. Aiming to consider the sum energy of lighting and AC, and also to evaluate the daylighting performance and energy performance at the same time, a parameter, Energy Daylight Rate (EDR), is proposed. The calculation is shown as equation 1.

\[
\text{Energy Daylight Rate} = \frac{\Delta \text{Total energy}}{\Delta \text{DA}_300}
\]

From the equation, the EDR can be both negative and positive. It will be the very best condition that the total energy consumption reduces while more daylight could be brought into the room. This new parameter can be used to check the effectiveness of the designs of daylightings systems and shading systems. According to the Building Energy Code of

![Figure 1. Simulation models: a) A Group of Building blocks in 40 storeys high; b) Layout and categories of the units in one certain floor](image)
Hong Kong, the COP of chiller at full load should be 2.8 Wth/Wel. In this study, the energy of AC is converted from the cooling load with the COP of 2.8 Wth/Wel.

RESULTS

3.1 Luminous comfort level by a dynamic metric

Based on the results from simulation work and questionnaire survey (Xue et al. 2014), the relations between objective daylight metric and subjective feeling is studied. Bivariate association between luminous comfort and Ave. DA_300 (Xue et al. 2016) is shown in Figure 2 (1: strongly dissatisfied; 2: dissatisfied; 3: neither dissatisfied nor satisfied; 4: satisfied; 5: strongly satisfied).

Figure 2. Bivariate association between luminous comfort and Ave. DA_300

As shown in Figure 2, Ave. DA_300 presents a strong relation with luminous comfort level. This trend can be described as narrow scope at the high comfort level side and wide scope at the low comfort level side. The value of this metric is relative concentrated from the residents with the highest luminous comfort level, and this scope becomes wider with the decreasing of the comfort level. In other words, for the widely accepted comfort environment, the value of Ave. DA_300 should not be too low, either not too high. The low value indicates the lack of daylight, while the high value means too much daylight which may bring glare, overheating and fading furniture problems to residents.

Referring to the thermal field, even in the most thermal comfort condition there still exist at least 5 % people who feel dissatisfied. That is to say the dissatisfied rate never goes below 5 %. If the benchmark is established like this, it is essential to find a threshold that guarantees 95 % of the satisfied units are included. The satisfied category was grouped with the luminous comfort of level 4 and level 5. Therefore, with the total satisfied number of 63, the comfort value of Ave. DA_300 ranges from 29.6 % to 57.8 %.

3.2 Comfort level in density buildings

Obtained from the climate-based daylight simulation, Ave. DA_300 is proved to represent the luminous comfort level from the real on-site survey. Based on the real model mentioned in section 2.2, 96 cases (4 orientations, 4 distance, 4 floor levels and 2 rings) are then built to study the units’ possible daylighting performance in density buildings. All of the Ave. DA_300 results in 96 cases are shown in Figure 3. Each subgraph contains 16 units in a certain ring and a certain distance among buildings.

From any subgraph in Figure 3, it can be easily concluded that a higher floor has a higher value of Ave. DA_300, no matter for inner units or outer units. The longer distance between the buildings also offers a better opportunity to receive the daylight as Ave. DA_300 increases with the increasing of the distance. Compared with units in inner ring, the ones in outer ring have a bigger value of Ave. DA_300 because they are less likely to be shaded by the building itself. From the data, the value of the outer units can be 25% more than the inner units. This is often the truth that the all these three factors, namely distance between buildings, floor levels, and inner or outer rings, reflect the condition of obstruction. When comparing the results among different orientations, the units facing west always obtain the highest Ave. DA_300 than other sides. While, the units facing north often have the lowest value of the Ave. DA_300. This is because the north units receive the least daily direct sunlight. The south units do not have the best performance as the solar elevation angle is too high. The reason that the west units and east units have different performance results from the position of the window, which is not fixed in the middle of the external wall. However, the difference among the orientations is acceptable as sunlight can still shine into the north units.

Considering the comfort benchmark of the Ave. DA_300, some bad conditions cases can be found refer to the results in Figure 3. Almost all outer ring units meet the standard value with the distance between buildings more than 15 m, except for few lower floor level units. For the inner ring units, all units under 25 floor level with the distance between buildings of 15 m could not reach the standard (Ave. DA_300 equals to 29.6 %), which means they could not receive enough daylight. Aiming to guarantee the condition of the inner ring lower level units, the distance between the buildings should be more than 35 m. However, in that condition, the outer ring high level units could...
beyond the upper benchmark very much (Ave. DA\textsubscript{300} equals to 57.8%), which may bring overheat problem.

Therefore, the façade of all units should not be the same. In other words, inner and lower units need to bring more light into the room, while outer and higher units need to block some light and save energy.

3.3 Optimization of windows (daylighting system)

To bring more light into the room, enlarging the openings on the wall is the most common way. Enlarging a single window and opening a secondary window are two different scenarios. To enlarge a single window for the living room, 5 cases are built according to the reference case. The aspect rate of the reference window is 1.25 and so do the other cases. The window to wall rate (WWR) of the reference case is 0.35 and the following cases are built with the WWR of 0.45, 0.55, 0.65, 0.75 and 0.85. The corresponding window to floor rates (WFR) are shown in Table 1. Another way to enlarge the window size is opening a secondary window for the living room. WWR is not available as new cases have an additional window on another wall, therefore, the WFRs of the new Case 6 to 10 are equal to the ones of Case 1 to 5 respectively, as shown in Table 1.

Table 1. Window openings with different dimensions (unit: m)

<table>
<thead>
<tr>
<th>Case</th>
<th>Single Width</th>
<th>WWR</th>
<th>WFR</th>
<th>Opening</th>
<th>Case</th>
<th>Single Width</th>
<th>WWR</th>
<th>WFR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>1.750</td>
<td>0.300</td>
<td>0.300</td>
<td>Reference</td>
<td>1.750</td>
<td>0.300</td>
<td>0.300</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1.875</td>
<td>0.400</td>
<td>0.400</td>
<td>6</td>
<td>0.625</td>
<td>0.625</td>
<td>0.625</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2.000</td>
<td>0.500</td>
<td>0.500</td>
<td>9</td>
<td>1.175</td>
<td>1.175</td>
<td>1.175</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>2.475</td>
<td>0.800</td>
<td>0.800</td>
<td>8</td>
<td>1.050</td>
<td>1.050</td>
<td>1.050</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>2.500</td>
<td>0.800</td>
<td>0.800</td>
<td>9</td>
<td>1.050</td>
<td>1.050</td>
<td>1.050</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>2.500</td>
<td>0.800</td>
<td>0.800</td>
<td>14</td>
<td>1.950</td>
<td>1.950</td>
<td>1.950</td>
<td></td>
</tr>
</tbody>
</table>

The two ways of changing window size has been presented, and the effective one should be selected by comparing the results together. To make the comparison clear, the results of units facing south orientations are presented in Figure 4.

From Figure 4, with the same value of WFR, opening additional window has obvious advantages in improving Ave. DA\textsubscript{300} than enlarging the single window. This is because the additional window is faced to west, and it could receive much more direct sunlight in the afternoon than the same area of south window. What’s more, it could also reduce the energy consumption of artificial lighting. About the solar heat gains, both two methods have a similar results as the opening areas of the window are the same. The advantage of the secondary window can be concluded as it bring more light to the poor daylighting condition area, while the other is not.

In these two scenarios, the energy of AC increases more than the reduction of artificial lighting. Considering both daylighting and energy performances, it is scientific and easy to evaluate these two scenarios by adopting the new parameter, energy daylight rate (EDR). The result is shown in Figure 5.

In the Figure 5, the slopes between the points are EDRs. When adopting daylighting system, the EDR should be as small as possible, even to the negative value. In other words, improving daylighting performance will lead to a relative increasing of energy consumption even a reduction. As seen from the figure, the EDR for opening additional window is smaller than enlarging as single window. This results from the similar energy performances and different daylighting performances. It means that to improve the Ave. DA\textsubscript{300} into the same level, a secondary window will add less total energy for the unit. Therefore, it can be concluded that opening an additional window is a better way than enlarging the single window. It’s better to open a second window in the living room, no matter how small it is.

3.4 Optimization of shading system

In the high-rise residential buildings in Hong Kong, some of the outer units and higher floor level units may need shading system to block more light into the room. To prevent direct sunlight and solar heat gains, most of the public housing are integrated with overhangs outside each units’ living room. To
optimize the performance of the overhang, two scenarios are proposed based on the dimensions of the configuration (Figure 6). Overhang’s length and tilted degree are studied and the results are presented.

![Figure 6. Configuration of an overhang](image)

In current public housing units, the overhang outside the living room is measured with the A of 0.375 m and B of 1.780 m horizontally. To study the different lengths of the overhang, models are built with the dimensions shown in Table 2. A case without overhang and three cases with longer overhangs are built without any outside obstruction. Four more cases are built according to the reference case to further study the tilted degree of the overhang. The overhang width (A) stays as 0.375 m in horizontal, and the edge points will be up and down with a certain slope. The selected slope degree are tilted up 20°, tilted up 10°, tilted down 10° and tilted down 20°. The detailed dimensions of the built overhangs are also shown in Table 2.

<table>
<thead>
<tr>
<th>Case</th>
<th>A</th>
<th>B</th>
<th>Tilted Degree</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>No overhang</td>
<td>0.375</td>
<td>1.780</td>
<td>20°</td>
<td>0.375</td>
<td>1.780</td>
</tr>
<tr>
<td>Reference (Norm)</td>
<td>0.375</td>
<td>1.780</td>
<td>10°</td>
<td>0.375</td>
<td>1.780</td>
</tr>
<tr>
<td>11</td>
<td>0.375</td>
<td>1.780</td>
<td>10°</td>
<td>0.375</td>
<td>1.780</td>
</tr>
<tr>
<td>12</td>
<td>0.375</td>
<td>1.780</td>
<td>20°</td>
<td>0.375</td>
<td>1.780</td>
</tr>
<tr>
<td>13</td>
<td>0.375</td>
<td>1.780</td>
<td>30°</td>
<td>0.375</td>
<td>1.780</td>
</tr>
</tbody>
</table>

Table 2 Overhangs with different dimensions (units: mm)

The two ways of optimizing overhang has been presented, and the effective way should be investigated by comparing the results together. In these two scenarios, the changing of AC energy is still more than the changing of artificial lighting. Considering both daylighting and energy performances, it is scientific and easy to evaluate these two scenarios by adopting the EDR. The result is shown in Figure 7.

In the Figure 7, the slopes between the points are EDRs for shading. When adopting shading system, the EDR should be as big as possible. In other words, compromising daylighting performance should lead to a relative decreasing of energy consumption as well. As seen from the figure, the EDR of changing overhang’s length is bigger than the other. It means that to reduce the same amount of total energy, lengthening overhangs will compromise less daylighting performance and luminous comfort. Therefore, it can be concluded that lengthening overhangs is a better way for shading.

**DISCUSSION**

As Hong Kong is situated just south of the Tropic of Cancer, all orientations could reach the direct sunlight. Then the wall in each direction should consider both luminous comfort and energy saving. In order to select the better scenarios and make the comparison clear, the results in section 3.3 and 3.4 only present the units facing south direction. The efficient ways for units facing other directions will be investigated in this section under basic condition without any shading.

With more daylight into the room, it can be concluded that the daylighting performance and AC consumption increase while lighting consumption decreases in all orientations. However, the changing values are not the same, which may lead to different efficient scenarios for units facing different directions. To select the better scenarios, the EDR method is adopted here again, and the results are shown in Figure 8.

In Figure 8a, the EDR results of daylighting scenarios for four typical units facing different directions are shown. Though the four reference case have different energy and daylighting performances, the daylighting scenario for bringing more light into the room is the same. Opening an additional window is a better way compared to enlarging the single window for all orientations.

In Figure 8b, the EDR results of shading scenarios for different directions could not lead to a unified conclusion. The scenarios of lengthening overhang for units facing west, south and east show a better performance than make the overhang tilted down. The EDR value should be as big as possible to decrease the energy consumption with the decrease of daylighting performance. However, the EDRs of the unit facing north are negative under both scenarios. In other words, adopting shading system for the units facing north will lead to an increasing in lighting energy, even to the total energy consumption. Therefore, this kind of units should use the internal shading instead of any shading scenario for envelope design.
CONCLUSIONS

In this study, a questionnaire survey of residents’ subjective feelings about luminous environment is first conducted. 108 cases are then simulated based on the real condition of the marked units to quantify the satisfaction of luminous environment with a dynamic metric, Ave. DA300. Then the benchmark of this metric is guided range from 29.6 % to 57.8% for high-rise residential buildings. With this guideline, 96 cases are built and simulated to study the influence of orientations, rings, floors, and distance between buildings on the units’ daylighting performance. The results found the façade of all units should not be the same.

To help decide the best scenario of envelope design for both daylighting and shading purposes, a new index, energy daylight rate (EDR), is proposed. Based on the simulation results, the units facing west and south always have higher values of Ave. DA300 and consumes more AC energy. The north units always obtain the lowest value of Ave. DA300 and the units facing east always use the least annual lighting energy. Opening an additional window is a better way than enlarging the single window for all orientations. It’s better to open a secondary window in the living room, no matter how small it is. Lengthening overhangs will compensate less daylighting performance and luminous comfort and it is a better way for shading than make overhang tilted down. Adopting shading system for the units facing north will lead to an increasing in lighting energy, even to the total energy consumption. These units should use the internal shading instead of any shading scenario for envelope design.

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REFERENCES


Figure 8. EDR (slope) in all orientations: a) daylighting scenarios; b) shading scenarios