https://doi.org/10.1016/j.enbuild.2016.02.026

Quantification of luminous comfort with dynamic daylight metrics in residential buildings

P. Xue [a], C. M. Mak [a,*], Y. Huang [a]

[a] Department of Building Services Engineering, The Hong Kong Polytechnic University, Hong Kong, China

*Corresponding Author: Tel.: +852 2766 5856; Fax: +852 2765 7198; E-Mail: cheuk-ming.mak@polyu.edu.hk

Abstract

This study was conducted with an idea that practical daylighting design and control should reduce the energy consumption without eroding residents' satisfaction with luminous environment. In this research, a dynamic daylight metrics average DA_{300} (Daylight Autonomy) and a static metric uniformity were tested to quantify occupants' luminous comfort by using statistical analysis with the data from questionnaire survey and climate-based simulation of 108 unit cases. These two metrics were found able to be complementary to each other and the benchmarks of uniformity level and Ave. DA_{300} are 0.112 and 29.6 % respectively. Luminous comfort zone was also proposed and the units with higher value of these two metrics, in comfort zone 2, have a great potential of energy saving by compromising daylighting performance. This research makes possible to predict residents' luminous comfort without the post-occupancy evaluation and guide the façade energy-efficient design at the early stage.

Keywords: Luminous comfort; Daylight autonomy; Uniformity; Statistical analysis; Comfort zone

1. Introduction

1.1 Energy-efficient design about daylight

The design for daylighting innovates continuously as there have been fruitful researches aiming to bring more light into the room [1]. Researchers create and improve optical units and systems, such as Sawtooth roof [2], light pipe [3], solar canopy illumination system [4], anidolic ceiling [5], prismatic glazing [6], skylight system [7], light shelves [8] and so on, to take advantage of the daylight benefits more intentionally. Daylight is a valuable resource that brings people close to nature, and appropriate exposure to daylight enhances people's satisfaction and productivity, affects people's visual perception and mood and promotes the circadian stimulus for hospital patients [9]. Apart from these, daylight could also lead to the reduction of electric lighting energy.

Hong Kong has a high potential of utilizing daylight for saving electric lighting energy as the outdoor horizontal illuminance exceeds 10 000 lux for over 80% of the normal office hours in a year [10]. Both the measured and simulated data showed the daily lighting energy savings could reach to 8 kWh in spring and summer [11]. Up to 2012, the EMSD (Electrical & Mechanical Services Department, Hong Kong) reported that the lighting still consumes 13% of the total electricity end-uses, which ranks the second following the space-conditioning 30% [12]. Better utilization of daylight and better control of lighting, such as daylight harvesting systems and dimming control, can generate more lighting energy savings up to 60% without consideration of the additional cooling energy benefits [13,14].

However, daylight has the characteristic of not only light, but also radiation. The solar heat gain becomes a problem which daylight brings unintentionally and it will be transferred as the cooling load that should be removed by air-conditioning system. Hong Kong city still suffers from the fact that the annual total electricity consumption of domestic sectors increased dramatically with an average rate of 6.67% per year over last 40 years [15]. Therefore, how to balance the conflicting energy consumptions of artificial lighting and air-conditioning is a major challenge in cooling-dominant climates. In order to achieve total energy-efficient objective, the minimum cost function should be adopted to balance the aspects of whole energy. The detailed methodology includes life-cycle cost [16], annual operating costs, and annual energy use [17]. However, the annual energy use is mostly concerned compared with the other two in research study. Cooling load and artificial lighting electricity should be considered simultaneously when optimizing annual energy-efficient design related to daylight [18].

To achieve the reduction of annual energy consumption, there exists two ways. The first one is to adopt static or dynamic façade features. It is reported that an ideal envelope design could reduce 33% of annual summed loads without consideration for daylighting [19]. 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° [20]. Rao and Tzempelikos [21] proposed a universal metric, Annual Load Based Energy Consumption (ALBEC) value, to evaluate overall building energy use of a certain design, and they found the combined shading system with daylight-linked continuous dimming lighting controls has the greatest potential to save energy. Park et, al. [22] proposed a Dynamic Daylight Control System (DDCS) that can be dynamically tuned to the different climates and sun positions to control daylight quality and distribution in the interior space, and it has a great potential for saving a significant portion of the energy. Yun et, al. [23] demonstrated the dynamic shading control with the dimming control of the lights is the best case for the east and the west facing buildings with the consideration of annual energy consumption. The Second way is adopting developed glazing. Selecting a glazing for window system is still crucial where both static and dynamic glazing have their own contradictions in offering a balance between visual and energy aspects. Compared to dynamic glazing, designing a static glazing window usually needs more substantial consideration of optimization [16] and the ultimate goal of a glazing system for energy savings is that it should possess higher transmittance in visible spectrum and lower transmittance in infrared region. Energy consumption of a building could greatly reduce by approx. 60% when introducing an intelligent glazed façade in the climate of Denmark [24]. Electrochromic evacuated glazing has also been proved advantageous in reduction of energy consumption and controlling solar gain [25]. Huang et, al. [26] concluded that the low-e glazing is the best choice considering both thermal and daylighting performance, while double-layer glazing performs the worst in cooling-dominant climates.

So here comes a question, should the annual energy consumption be as little as possible for energy-efficient designs? The optimization process often involves sacrificing on daylighting performance to open opportunity for energy performance in order to obtain an ideal energy balance. A new specific definition of daylighting combines daylight availability, occupant comfort and energy efficiency [27]. Therefore, a rather unambiguous response to that question is no and we propose here that the energy-efficient design should guarantee a satisfactory level of daylighting first.

1.2 luminous comfort

"Visual comfort" is a term that usually appears in the study related to (day)lighting performance and human psychology. However, the definition of visual comfort in a scientific or professional sense has not yet to be agreed upon. Some researchers qualified visual comfort as illumination level [28,29]; some treat it as luminance balance [30]; and some name it as the satisfaction with visual environment [31]. While, most of the researchers think providing visual comfort means reducing glare problem [23,32,33]. It seems all glare-based criteria, such as Daylight glare index (DGI) [34,35], Daylight Glare Probability (DGP) [36], and Unified Glare Rating (UGR) [37], are all studied to represent visual comfort. In fact, the satisfaction in our study is affected by many factors, such as physical environment, people’s feelings and their behaviors. So in order to make research more rigorous and comprehensive, we had already proposed another term "luminous comfort" in our previous study and investigated the key factors [38].

Luminous comfort is defined as the people’s satisfaction with the luminous environment, as subjectively evaluated by occupants. Hwang et, al. advocated there was significant correlation between the occupants’ satisfaction and luminance distribution [39]. Xue et, al. conducted a survey and presented that external obstruction is the major physical factor affecting luminous comfort, while the perception of uniformity is the major factor of residents’ feelings toward daylight. Façade features and human behaviors also have significant influences on luminous comfort [40]. To accelerate decision-making and realize the post-occupancy evaluation at the early stage, simulation in architectural lighting design, research and education is essential [41]. Can computer simulations be used to predict occupant luminous comfort and stimulate the design of energy-efficient buildings? Loonen et, al. [42] provided the positive answer and claimed that contemporary metrics are required to reliably evaluate the occupant comfort and building energy use.

1.3 dynamic metrics

The desired purpose of a metric is to combine various factors that will successfully predict better performance outcomes [43]. Illuminanation level, daylight factor, and illuminance uniformity are the most common static metrics used for studying physical models to test daylighting designs. However, considering the actual climate (the quantity and character of daily and seasonal variations of daylight) for a given building site together with irregular meteorological events, dynamic daylighting performance metrics are needed [44]. Daylight Autonomy (DA), Useful Daylight Illuminance (UDI) and Annual Light Exposure (ALE) have been proposed as dynamic or cumulative metrics in order to overcome static metrics' limitations [37,45]. DA was redefined by Reinhart and Walkenhorst [46] as the percentage of the occupied hours of the year when a minimum illuminance threshold is met by the sole daylight. UDI, proposed by Mardaljevic and Nabil [47], is defined as the fraction of the time in a year when indoor horizontal daylight illuminance at a given point falls in a given range. The range as its name suggests, neither too dark (100 lx) nor too bright (2000 lx). ALE is defined as the cumulative amount of visible light incident on a point of interest and is measured in lux hours per year. This metric is often an important prerequisite for the assessment and limitation of photochemical damage to objects and the criteria for museum are provided by CIE [48]. All these dynamic metrics could be obtained from climate-based daylight modeling (CBDM) and simulation.

The next step of the analysis is to decide what levels could be treated as adequate [49]. If these metrics are to ensure sufficient natural light to maintain the health or even indicate the energy use, criteria based on computer modeling should be first made [50]. Reinhart et, al. [27] has already discovered DA 300 lux (with DA 50% level) is in good agreement with the subjectively assessed mean daylit area. Therefore, the metrics still need further benchmarking when a set of metrics are tested to describe occupants' luminous comfort. In this research, metrics are first tested to describe occupants' luminous comfort by using statistical analysis with the data from questionnaire survey and simulation of 108 unit cases. It is expected to predict residents' luminous comfort and help decision-making without the post-occupancy evaluation. Then the benchmark of the metrics will be studied in order to guide the façade design at the early stage.

2. Methodology

2.1 Questionnaire survey

Hong Kong is the most densely city whose number of high-rise buildings ranks first all over the world. However, the regulations for ‘rights of light’ (window area not less than 10% of the floor area) do not ensure an acceptable daylighting in many residential building units [10]. As nearly 90% residents are most concerned about the daylighting performance of their living rooms and people have more activities in living room [51], a questionnaire survey was conducted among in a typical estate to obtain the residents’ subjective luminous comfort in living rooms [38]. Participants chose the comfort level based on the Likert 5-point scale, where level 1 means strongly dissatisfaction and level 5 representative strongly satisfaction. Participants were asked to answer the questions based on the annual average feeling under average weather conditions. The type of the buildings is Harmony I (Fig. 1a) which takes up half of the total number (293/586) of Harmony Blocks. However, Harmony Block ranks first in the total amount of public residential buildings in Hong Kong. All the blocks selected in the survey are all 40 stories and the floor area of each unit was between 45~60 m^2 in size. Coded questionnaires were issued by mail, and 108 valid questionnaires were returned to the authors through collection boxes (Fig. 2). These coded questionnaires provide the exact physical information of the participants’ units. This information includes orientation, floor level and shading devices of the living room (Fig. 1b). With further information of the exact location and surroundings, external obstructions could be known for each unit (Fig. 1c).

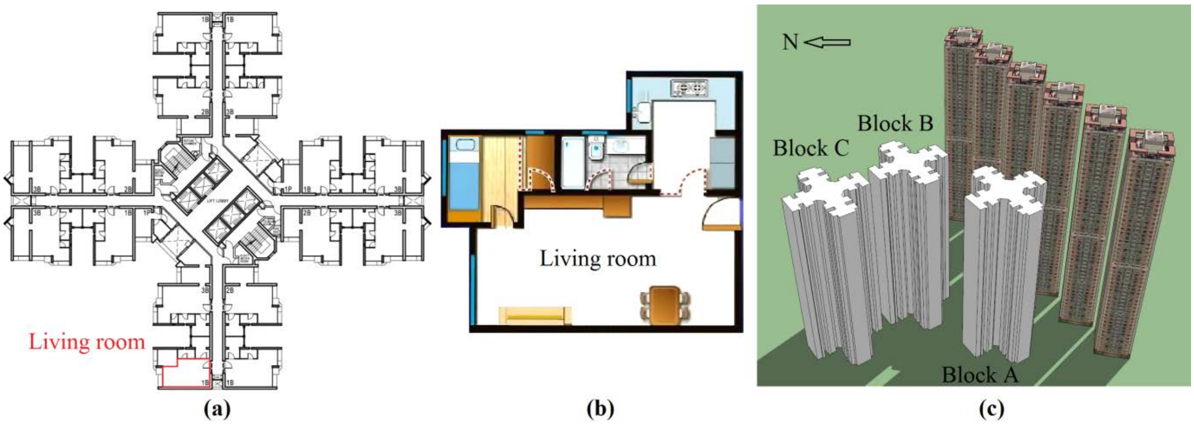


Fig. 1. Physical environment of the target units: 1 (a) building plan of HarmonyI; (b) layout of a living room; (c) location of the blocks

(a) (b)

Fig. 2. Conducting a questionnaire survey: (a) issuing the questionnaire; (b) collecting the questionnaire

2.2 Simulation set-up

2.2.1 Physical modeling

The model of the living room is based on the coded actual residential unit. Building plan and structural plan were brought from Housing Authority and Independent Checking Unit respectively, Hong Kong. The height of floor is 2.7 m (including floor layer), the floor area is 19.52 m^2, and the window-wall ratio of vertical façade is 0.354. The details of building construction, including structure and materials of wall, ceiling, floor and window are shown in Table 1. The reflectance of ceiling, wall and floor are 0.749, 0.549 and 0.300 respectively [52].

Table 1

Detailed data of building materials.

	Material	Thickness (m)	Conductivity (W/m K)	Density (kg/m^3)	Specific heat (J/kg K)
Exterior Wall	White mosaic tile	0.005	1.5	2500	840
	Cement render	0.01	0.72	1860	840
	Concrete panel	0.1	2.16	2400	657
	Gypsum plaster	0.01	0.51	1120	960

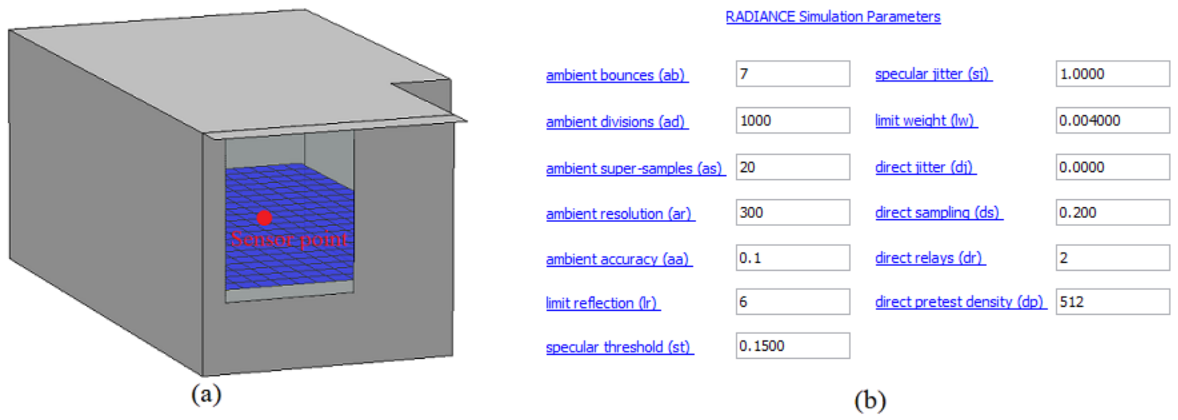
	Properties	Value
Glazing	Thickness (m)	0.006
	Solar transmittance at normal incidence	0.708
	Front side solar reflectance at normal incidence	0.075
	Back side solar reflectance at normal incidence	0.075
	Visible transmittance at normal incidence	0.753
	Front side visible reflectance at normal incidence	0.075
	Back side visible reflectance at normal incidence	0.075
	Infrared transmittance at normal incidence	0
	Front side infrared emissivity at normal incidence	0.84
	Back side infrared emissivity at normal incidence	0.84
	Conductivity	0.9

2.2.2 Computer modeling

In order to simulate the real condition of the units and obtain dynamic daylight metrics, climate-based daylight modeling (CBDM) is essential. CBDM is the prediction of various radiant or luminous quantities using sun and sky conditions that are derived from standard meteorological datasets [43]. Climate datasets are representative of the prevailing conditions measured at the site, and Hong Kong data was downloaded from Department of Energy, USA. Physical models were first built in SketchUp, since it could be imported into both Daysim and EnergyPlus easily, which were used in combination in this research. Daysim is a dynamic RADIANCE-based daylighting simulation program that uses the concept of daylight coefficients and the Perez sky model to predict the short-time-step development of indoor illuminance and calculate annual electric lighting energy consumption [46]. EnergyPlus is a new generation building energy simulation program, which is based on the state-space techniques and supported by Lawrence Berkeley National Laboratory [53]. Based on the fact that Hong Kong is in cooling-dominant climates and almost 60% residents do not use any heating system all over the year [26], annual electric lighting energy and cooling load are calculated by EnergyPlus.

2.2.3 Strategies

Illuminance is a key metric for the indoor lighting, and several regulations have made the criteria of lux level for rooms with different functions. The Code for Interior Lighting [52] gave a recommended 300 lux for moderately easy visual tasks, while the Lighting Handbook [54] provided a standard of 300 lux for bedroom. However, this is no regulation to offer an example for living room. In this research, the threshold level is set as 300 lux, and the artificial lighting system will be used when the illumination level drops below 300 lux. The illumination plane sensor was set in the middle of the room at the height of 0.85 m, as shown in Fig. 3a. As the model includes an overhang, the value of ambient bounces was set a little higher and calculation parameters used in simulation are shown in Fig. 3b.



RADIANCE Simulation Parameters

ambient bounces (ab) 7
ambient divisions (ad) 1000
ambient super-samples (as) 20
ambient resolution (ar) 300
ambient accuracy (aa) 0.1
limit reflection (lr) 6
specular threshold (st) 0.1500
specular jitter (sj) 1.0000
limit weight (lw) 0.004000
direct jitter (dj) 0.0000
direct sampling (ds) 0.200
direct relays (dr) 2
direct pretest density (dp) 512

(a)

(b)

Fig. 3. Simulation settings: (a) physical model of a unit; (b) calculation parameters

During the daylighting simulation, the lighting power density (LPD) was 10 W/m^2, according to local standards of building design [55]. The residents were considered to have no daylighting awareness, and the lighting control system was set to be ‘‘photosensor-controlled dimmed lighting system’’ which is a highly recommended lighting control type in IESNA Lighting Handbook. The user behavior type was set as active type in lighting control and passive type in blind control. This lighting system could express the energy savings potential of automated controls and the photocell dims the activated lighting when sensor’s illuminance reaches the 300 lux at daylight time (7:00 ~ 18:00). The ballast factor was set as 0.8. The simulation period was 1 year and the time step is 5 minutes. The assumption of the residents is two people live in a housing unit with one work outside and one stay at home. Refer to Building Energy Code of Hong Kong [56], the operation schedule of artificial lighting system and occupancy schedule are and presented in Fig. 4.

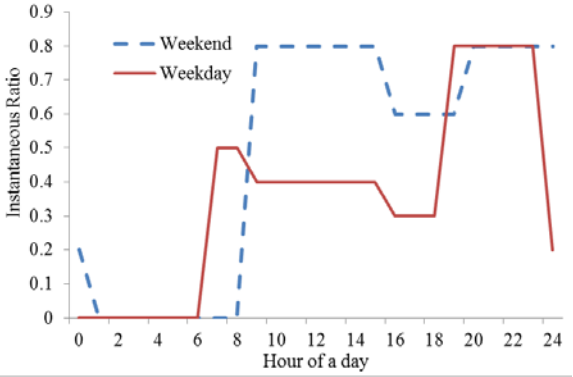


Fig. 4. Schedules setting for occupant

2.3 Statistical analysis

The luminous comfort obtained from questionnaire is quantified via dynamic metrics at the first step. Regression was further adopted to find the most parsimonious set of predictors and quantify the luminous comfort. To decide what satisfaction levels to consider ‘adequate’ easily, the reasonable range or benchmark of the metrics were provided learned from thermal comfort.

3. Results

3.1 Daylight metrics by luminous comfort levels

108 cases were built based on the information obtained from coded questionnaires. Simulation was conducted to reproduce the real condition of each unit and calculate the daylight metrics. The results of occupants’ luminous comfort (the last column) from survey and units’ daylight metrics (7 columns before the last one) from simulation are shown in Table 2. DA, UDI and ALE were selected as dynamic metrics and presented as the values of both sensor point (3 columns with the word “sensor”) and room average (3 columns without the word

"sensor"). The average values were calculated from 339 points in the plane of 0.85 m height. Since the threshold of the illumination level is 300 lux, the DA was shown as DA_{300} which means the average percentage of the time that illumination level above 300 lux of the whole room.

$$DA = \sum_i (wf_i \cdot t_i) \,/\, \sum_i t_i \in [0,1] \ \text{ with } \ wf_i = \begin{cases} 1 \ if \ E_{daylight} \geq 300 \ lux \\ 0 \ if \ E_{daylight} \leq 300 \ lux \end{cases} \qquad (1)$$

where t_i is each occupied hour from 7:00 to 18:00 every day in a year; wf_i is a weighting factor. Uniformity is a static metric and mostly defined as the ratio between the minimum value of the illuminance and the average illuminance. The simulation is running with Typical Meteorological Year climate data of Hong Kong. As the value of uniformity differs from time to time with the changing sun position, a relative fixed value is needed to representative uniformity. Therefore, in this paper, uniformity is considered to be only affected by the physical environment of the unit and the effect of the direct sunlight is ignored. The uniformity is calculated under the worst sky condition (overcast sky), and it can be then obtained from the results of DF.

$$U = \frac{E_{min}}{E_{average}} = \frac{E_{min}/E_{outdoor}}{E_{average}/E_{outdoor}} = \frac{DF_{min}}{DF_{average}} \qquad (2)$$

where $E_{outdoor}$ is the outdoor illuminance on a horizontal plane with unobstructed hemisphere of overcast sky; DF_{min} is the lowest DF value of all the calculation points; $DF_{average}$ is the average DF value of the room.

Table 2

The occupants' luminous comfort and units' dynamic metrics obtained from survey and simulation.

Cases	Block	Floor	Orientation	DA_{300} (Sensor)	UDI (100~2000) (Sensor)	ALE (Sensor)	Ave.DA_{300}	Ave. UDI (100~2000)	Ave. ALE	Uniformity	Luminous comfort
1	Block A	1	West	66	84	2500807	54.85	73.84	3964895	0.131	4
2	Block A	2	South	52	81	1345096	45.73	73.25	2570451	0.179	4
3	Block A	2	North	51	82	1295777	41.45	72.56	2038456	0.161	4
4	Block A	5	West	72	87	2741686	61.36	74.1	4761300	0.138	4
5	Block A	7	North	55	83	1411646	43.29	72.95	2360890	0.144	4
6	Block A	9	East	36	76	1006747	33.85	64.06	1812893	0.161	3
…	…	…	…	…	…	…	…	…	…	…	…
103	Block C	35	North	60	88	1870502	55.63	75.56	3261364	0.130	2
104	Block C	36	West	54	82	1627898	48.42	69.67	3662796	0.145	3
105	Block C	38	South	45	79	1337179	41.89	66.09	3227742	0.155	4
106	Block C	39	East	57	84	1721204	50.02	71.14	3509782	0.128	4
107	Block C	40	South	62	86	1797354	55.27	73.1	4619382	0.180	3
108	Block C	40	South	62	85	1735659	54.1	72.54	4488999	0.149	4

With these results, the relations between luminous comfort and daylight metrics could be further studied. Bivariate associations between luminous comfort and three dynamic metrics and one static metric are shown in Fig. 5. The three dynamic metrics' results of the sensor are not shown in this figure, as they have almost the same trend with the values of the average ones. Another reason is people feel the environment as a whole instead of feeling at one point, and the result in Section 3.2 also confirmed this fact that the results of the center sensor is not a key factor of luminous comfort.

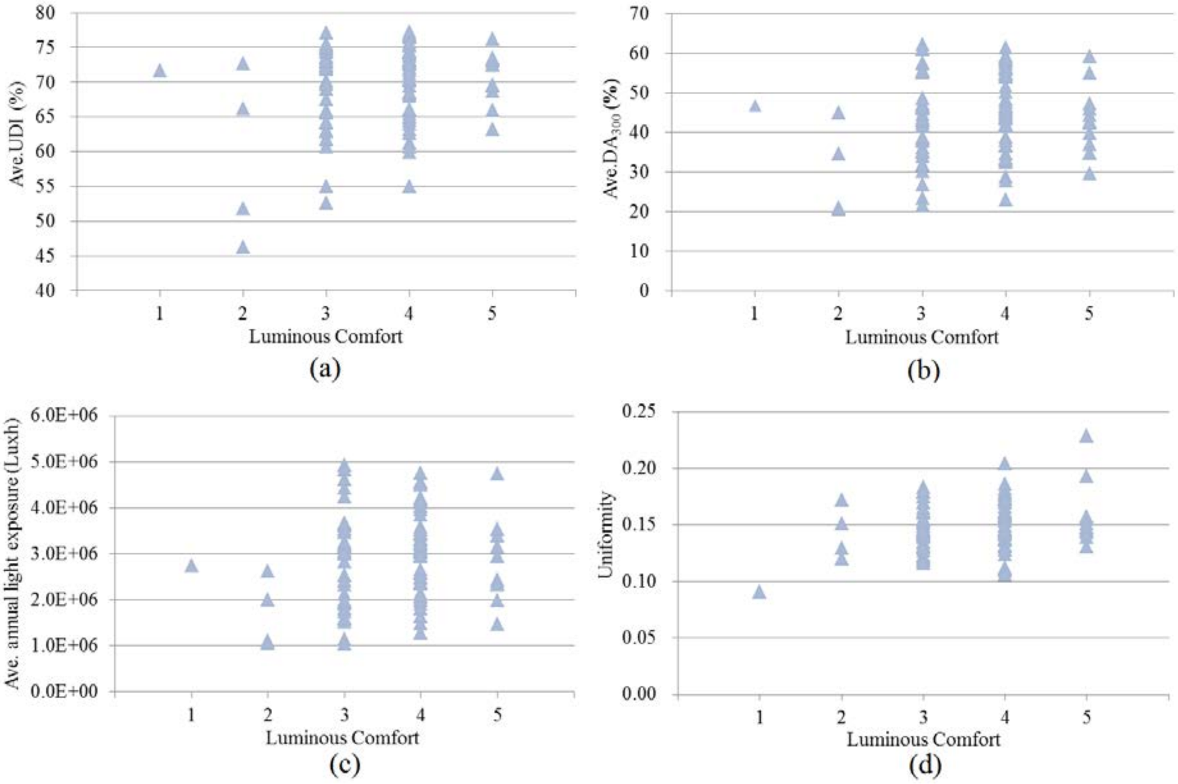


Fig. 5. Bivariate associations: (a) luminous comfort and average UDI; (b) luminous comfort and average DA_{300}; (c) luminous comfort and ALE; (d) luminous comfort and uniformity

(1: strongly dissatisfied; 2: dissatisfied; 3 neither dissatisfied nor satisfied; 4: satisfied; 5: strongly satisfied)

As shown in Fig. 5, Ave. UDI, Ave. DA and Ave. ALE present similar relations across the luminous comfort level. This trend can be described as wide scope at the low comfort level side and narrow scope at the high comfort level side. The values of these metric have a relative narrow scope from the residents with the highest luminous comfort level, and this scope becomes wider with the decreasing of the comfort level. In other words, the values of these three dynamic metrics should not be too high, either not too low. The low value indicates the lack of daylight, while the high value means too much daylight. Too much daylight may bring problems to residents, such as overheat, glare, fading furniture, etc. However, in order to decide the reasonable range of these metric, further analysis are conducted as following.

Compared with the dynamic metric, uniformity shows an obvious linear relation with luminous comfort. Low uniformity results in low comfort level, and high uniformity level increase the possibility of higher comfort level. A reasonable explanation of the unit with the lowest comfort level is the poorest uniformity, though the results of other three dynamic metrics seem in reasonable ranges. However, not all the points can be explained with only one metric or one figure, and the luminous comfort must be influenced by combination effect of a set of predictors.

3.2 Quantification of luminous comfort

Stepwise regression was used to qualify residents' luminous comfort. Luminous comfort was set as the dependent variable, and seven metrics were tested as the predictors. The result of regression is shown in Table 3.

Table 3

Coefficients of regression

Model 2	Standardized	***t***	Sig.
	Beta		
(Constant)		0.022	0.359
Uniformity	0.207	2.172	0.016
Ave. DA_{300}	0.193	2.024	0.023
UDI	-0.343	-1.034	0.303
DA_{300}	-0.311	-1.070	0.287
ALE	-0.057	-0.388	0.699
Ave. UDI	-1.168	-0.834	0.406
Ave. ALE	0.005	0.039	0.969

Dependent variable: luminous comfort
Predictors: (Constant), uniformity, Ave. DA_{300}
Excluded variables: UDI, DA_{300}, ALE, Ave. UDI, Ave. ALE

Model 2 was generated and then selected (R = 0.313, F = 5.693, $P < 0.05$) due to its superior outputs (Table 3). The result shows uniformity and Ave. DA_{300} are key factors of luminous comfort (Table 3), which means these two metrics decide residents' satisfaction with luminous environment most. The other 5 metrics are excluded from the regression model. As can be seen in Table 3, these two metrics all had significant P-values and a positive relationship with luminous comfort. The standardized beta reveals the relative influence of these factors. Essentially, Uniformity has greater influence than Ave. DA_{300}. Though 108 cases is a huge number for simulation work, it is still hard to build a regression formula for luminous comfort. Compared with 108 cases, the level of comfort also seems a little dispersed and not continued. This part of study could not offer an empirical formula for the luminous comfort, but it tells that uniformity and Ave. DA_{300} decide residents' luminous comfort most and the benchmarks of these two metrics should be studied.

3.3 Benchmark of the metrics

The importance of the benchmark is not only a standard for building envelope design, but also an indication that decides when adopting shading system to compromise daylighting performance and saving total energy or adopting daylighting system to increase daylighting performance.

3.3.1 Benchmark decided by percentage

From Fig. 5d, it is easy to draw a conclusion the value of uniformity should be as high as possible. Referring to the thermal field, there exist at least 5 % people who feel dissatisfied even in the most thermal comfort condition. That is to say the comfort never gets below 5 % dissatisfied. So if we make the benchmark like this, it is essential to find the value that guarantees 95 % of the "satisfied" units above it. The "satisfied" category was grouped with the luminous comfort of level 4 (satisfied) and level 5 (strongly satisfied). The "dissatisfied" category was grouped with level 1 (strongly dissatisfied) and level 2 (dissatisfied) and the "moderate" category was grouped with the result of level 3. Therefore, with the total "satisfied" number of 63, the benchmark of uniformity is 0.112 and the benchmark of average DA_{300} is 29.6 % (Fig. 6).

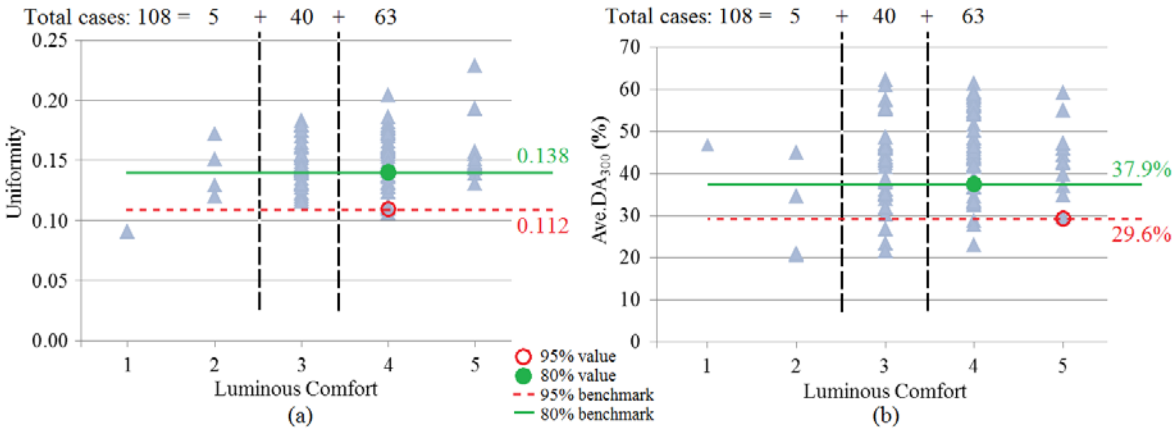
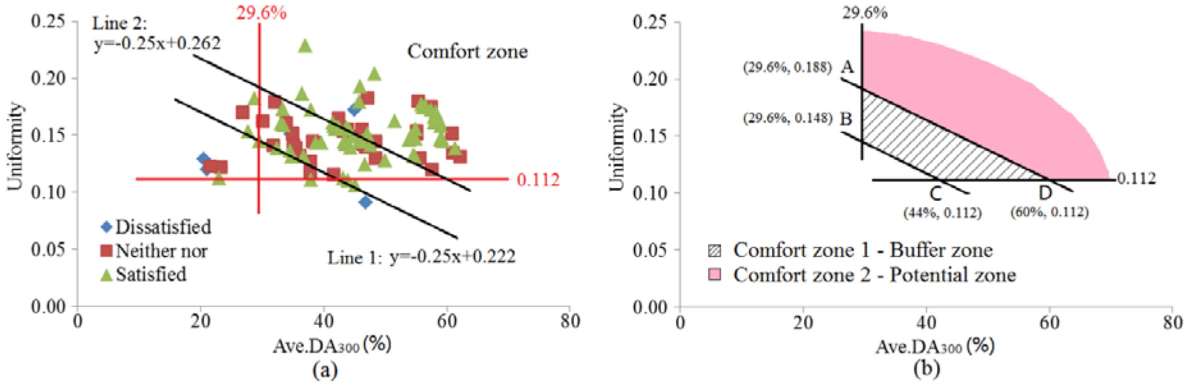


Fig. 6. Two percentage standards of benchmarks: (a) uniformity; (b) average DA_{300}

However, the standard often comes stricter than the guarantee condition. Just like the thermal standard, it requires at least 80% of the occupants be satisfied [57]. If learning from thermal standard and increasing the benchmark to meet top 80 % people's requirement, the lower limiting value of uniformity will increase to 0.138 and the lower limiting value of average DA_{300} increase to 37.9 % (Fig. 6).

3.3.2 Benchmark decided by comfort zone

As uniformity and Ave. DA_{300} show great influence on luminous comfort, the 108 cases can be drawn on one coordinate graph of these two metrics (Fig. 7a).Three categories are shown in different colors and shapes.



(a) (b)

Fig. 7. Luminous comfort zone: (a) benchmark with cases; (b) zones with thresholds

As seen from Fig. 7a, the Line 1 can be easily recognized with the point data. This line ‘BC’ in Fig. 7b was regressed and described in the figure. The formula can be also transformed as:

$$Ave.DA_{300} = (-4U + 0.888) \times 100\% \tag{3}$$

It is can be seen that most of the “dissatisfied” cases are excluded under this line and almost all the “satisfied” cases are included above this line. This important line also shows that uniformity and Ave. DA$_{300}$ can make up for each other. A higher uniformity value can make up the low value of Ave. DA$_{300}$ and vice versa. With the benchmark of 0.112 for uniformity and the benchmark of 29.6 % for average DA$_{300}$, as mentioned in last section, a comfort zone was figured out. However, this comfort zone has no upper threshold.

The only line “BC” is not adequate enough for benchmarking the metrics as the point can be either below or above it. The points above the line can be explained as they have potential to compromise daylighting performance to save energy. However, when compromising daylighting performance, the point may go down the benchmark line. Therefore, it is necessary to build another line as a higher benchmark and compose a buffer zone with line ‘BC’.

Since uniformity and Ave. DA$_{300}$ can be complementary to each other, another parallel line was then found as line ‘AD’. The formula can be transformed as:

$$Ave.DA_{300} = (-4U + 1.048) \times 100\% \tag{4}$$

This line is decided by some of the “satisfied” cases in the relatively concentrated area though. With this line, a comfort zone 1 (buffer zone) is drawn in Fig. 7b. The coordinates of four vertexes were also calculated and shown in the figure. It is easily to tell that most of “satisfied” cases are included in this comfort zone. However, there are still many cases left out of comfort zone 1. In this case, the rest of the comfort zone was defined as comfort zone 2 (potential zone). In comfort zone 2, housing units have abundant daylight and higher value of these two key metrics, uniformity and Ave. DA$_{300}$. In other words, the units in this zone have potential to compromise daylighting performance to save annual energy.

4. Discussion

The average results of the performance and preliminary analysis are provided in this part. Details of the single units are also studied to check our metric benchmarks and prove the energy-saving potential.

With the simulation results, units are grouped by 4 categories, namely block, orientation, floor and self-shading. 108 cases are distributed in 3 blocks, 4 orientations and 4 floor levels. In each floor, there are 16 units as shown in Fig. 1a. Among them, 8 are outer ones which have two external walls and 8 are inner ones which are easily shaded by the building itself. The numbers of the cases from block A, B and C is 23, 34 and 51 respectively. 19 cases face to north, 33 cases face to west, 28 cases face to east and 28 cases face to south. 28 units are below 11th floor, 19 units are between 11th to 20th floor, 27 units are between 21th to 30th floor and 24 units are above 30th floor. The number of the inner units is 57 and the one of outer units is 51. The summary of average daylighting and energy performances is shown in Fig. 8.

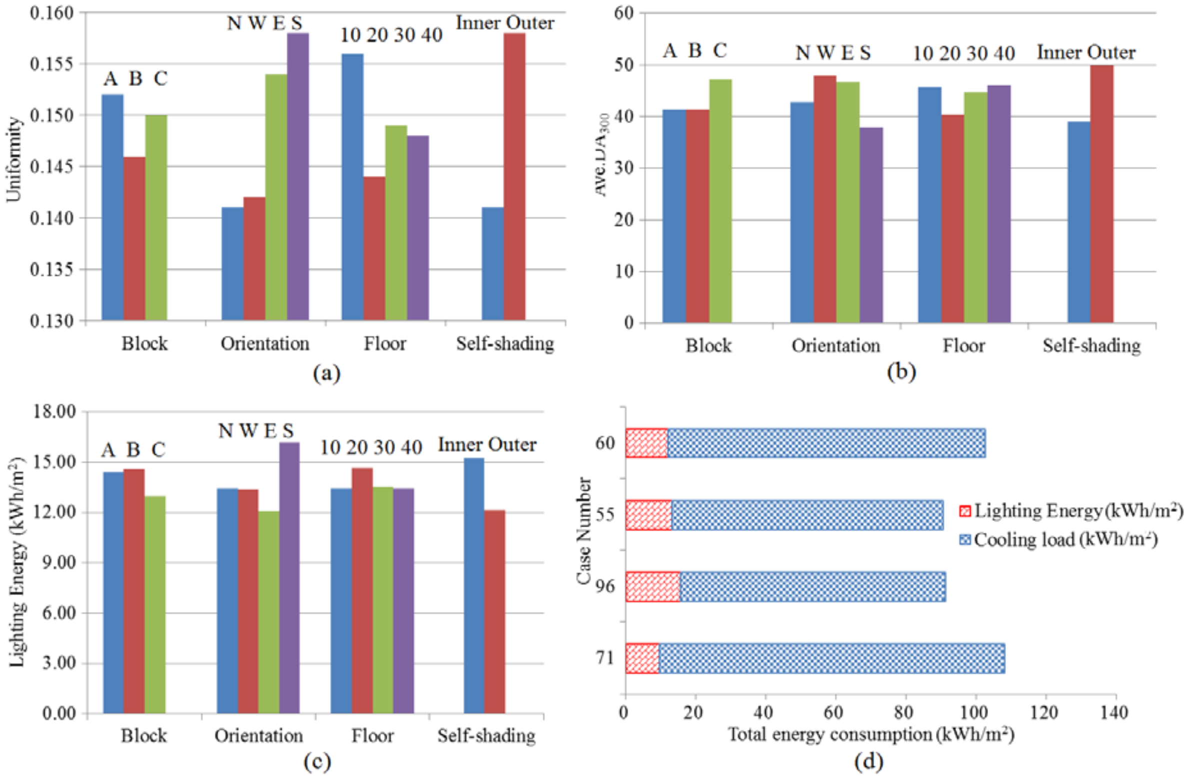


Fig. 8. Summary of daylighting and energy performances: (a) uniformity; (b) average DA_{300}; (c) light energy consumption; (d) comparison of cases

As seen from Fig. 8, the block B has the lowest uniformity and consumes the most lighting energy. This is because block B has a relative bad location with no obstruction in east orientation only. This result indicates that the location affects daylighting and energy performances very much. Units facing south have the highest uniformity, lowest Ave. DA_{300} and consume much lighting energy. This result may be due to the Hong Kong special geographic information, and the units facing south may receive no direct sunlight in summer time. Units with higher floor have higher uniformity values, while no obvious difference occurs in Ave. DA_{300} and lighting energy. However, the units from 11th floor to 20th floor show the conflictive data, this may be due to the relative less amount of total sample compared with the four categories. The explanation makes sense when it comes to inner and outer units. It can be easily recognized that the inner units have a bad condition of daylighting and use more lighting energy. On the contrary, the outer units have a better daylighting condition and consume less lighting energy. Therefore, the self-shading or the obstruction has a great influence on the daylighting and energy performances. However, the annual energy use contains not only lighting energy consumption, but also the cooling load which needs to be removed from the room. Cooling load, which containing conduction through building envelope, people heat, lights' heat and solar radiation, was calculated by EnergyPlus. To ensure only one of the two metrics changes at a time, four cases were further studied to check the metric benchmarks and prove the energy-saving potential (Table 4).

Table 4

Energy performances and detailed information of selected cases

Case	Block	Floor	Orientation	Luminous comfort	Ave.DA_{300}	Uniformity	Comfort zone	Lighting Energy (kWh/m^2)	Cooling load (kWh/m^2)
71	Block C	11	South	5	57.38	***0.172***	2	9.6311475	98.352
96	Block C	32	East	5	35.92	***0.172***	1	15.655738	75.335
55	Block B	39	West	5	***48.42***	0.130	1	13.002049	77.354
60	Block C	3	South	4	***48.24***	0.204	2	12.079918	90.232

Case 71 and Case 96 have the same value of uniformity but different Ave. DA_{300} so that one is in the comfort zone 2 and the other is in zone 1. Case 71 with much higher Ave. DA_{300} value could save lighting energy, but too much daylight also brings solar heat that transfers to cooling load. In this result, case 71 has 18.7 % more total energy consumption than Case 96 (Fig. 8d). Case 55 and Case 66 have similar values of Ave. DA_{300} but different uniformity so that one is in the comfort zone 1 and the other is in zone 2. Case 60 with much higher uniformity value saves lighting energy, but the luminous comfort level is lower than the other. What's more, Case 60 receives much solar heat and generates much cooling load, therefore it consumes 13.2 % more energy than case 55.

The comparison of these four cases show the higher value of uniformity and Ave. DA_{300} could not guarantee the luminous comfort and may also increase the annual energy consumption. In other words, uniformity and Ave. DA_{300} are indication metrics for energy-efficient residential buildings and the units with higher value of these two metrics have great potential of energy saving by compromising daylighting performance.

5. Conclusions

Luminous comfort is proposed to be considered before the energy-efficient design. Two metrics, uniformity and Ave. DA_{300} were proved to be the key factors of luminous comfort by analysis of the data from both questionnaire survey and climate-based simulation. These two metrics can be complementary to each other and the benchmarks of them were also studied. In residential buildings, the uniformity level should be above 0.112 and the threshold of Ave. DA_{300} is 29.6 %.

Luminous comfort zone was also proposed to provide a detailed standard for energy-efficient design. The units with higher value of these two metrics, in comfort zone 2, have great potential of energy saving by compromising daylighting performance. This research makes possible to predict residents' luminous comfort without the post-occupancy evaluation and guide the façade design at the early stage. However, the practical degree of energy saving should be studied later with reference case not only the comparison with different units. In the future, the optimization of energy-efficient design and the choosing of the daylighting or shading systems can be decided according to the benchmarks of the metrics.

Acknowledgements

Many thanks to building owners and occupants for their responses. This work was supported by the Hong Kong Environment and Conservation Fund under Grant ECF 23/2011.

References

[1] Gago EJ, Muneer T, Knez M, Köster H. Natural light controls and guides in buildings. Energy saving for electrical lighting, reduction of cooling load. Renewable and Sustainable Energy Reviews 2015;41(0):1-13. doi: http://dx.doi.org/10.1016/j.rser.2014.08.002

[2] Heras MR, Jiménez MJ, Isidro MJS, Zarzalejo LF, Pérez M. Energetic analysis of a passive solar design, incorporated in a courtyard after refurbishment, using an innovative cover component based in a sawtooth roof concept. Solar Energy 2005;78(1):85-96. doi: http://dx.doi.org/10.1016/j.solener.2004.05.019

[3] Rosemann A, Kaase H. Combined daylight systems for lightpipe applications. International Journal of Low-Carbon Technologies 2006;1(1):10-21. doi: 10.1093/ijlct/1.1.10

[4] Rosemann A, Mossman M, Whitehead L. Development of a cost-effective solar illumination system to bring

natural light into the building core. Solar Energy 2008;82(4):302-10. doi: http://dx.doi.org/10.1016/j.solener.2007.09.003

[5] Linhart F, Wittkopf SK, Scartezzini J-L. Performance of Anidolic Daylighting Systems in tropical climates – Parametric studies for identification of main influencing factors. Solar Energy 2010;84(7):1085-94. doi: http://dx.doi.org/10.1016/j.solener.2010.01.014

[6] Laouadi A, Saber HH, Galasiu AD, Arsenault C. Optical model for prismatic glazing (1415-RP). HVAC&R Research 2013;19(1):63-75. doi: 10.1080/10789669.2012.736812

[7] Acosta I, Navarro J, Sendra JJ. Daylighting design with lightscoop skylights: Towards an optimization of shape under overcast sky conditions. Energy and Buildings 2013;60(0):232-8. doi: http://dx.doi.org/10.1016/j.enbuild.2013.01.006

[8] Xue P, Mak CM, Cheung HD. New static lightshelf system design of clerestory windows for Hong Kong. Building and Environment 2014;72(0):368-76. doi: http://dx.doi.org/10.1016/j.buildenv.2013.11.017

[9] Acosta I, Leslie RP, Figueiro MG. Analysis of circadian stimulus allowed by daylighting in hospital rooms. Lighting Research and Technology, 2015. doi: 1477153515592948.

[10] Chung TM. Daylighting in Hong Kong: Potential and problems. Lighting Research and Technology 2003;35(1):39-41.

[11] Li DHW, Tsang EKW. An analysis of measured and simulated daylight illuminance and lighting savings in a daylit corridor. Building and Environment 2005;40(7):973-82. doi: http://dx.doi.org/10.1016/j.buildenv.2004.09.007

[12] Hong Kong Government.. Hong Kong Energy End-use Data; 2014. Retrieved from: http://www.emsd.gov.hk/emsd/e_download/pee/HKEEUD2014.pdf

[13] Köster H. Daylighting controls, Performance and Global Impacts. Sustainable Built Environments. V Loftness,D Haase, New York: Springer;2013.

[14] Kamaruzzaman SN, Edwards R, Zawawi EMA, Che-Ani AI. Achieving energy and cost savings through simple daylighting control in tropical historic buildings. Energy and Buildings 2015;90(0):85-93. doi: http://dx.doi.org/10.1016/j.enbuild.2014.12.045

[15] Ma Z, Wang S. Building energy research in Hong Kong: A review. Renewable and Sustainable Energy Reviews 2009;13(8):1870-83.

[16] Hee WJ, Alghoul MA, Bakhtyar B, Elayeb O, Shameri MA, Alrubaih MS, et al. The role of window glazing on daylighting and energy saving in buildings. Renewable and Sustainable Energy Reviews

2015;42(0):323-43. doi: http://dx.doi.org/10.1016/j.rser.2014.09.020

[17] Shan R. Optimization for Heating, Cooling and Lighting Load in Building Façade Design. Energy Procedia 2014;57(0):1716-25. doi: http://dx.doi.org/10.1016/j.egypro.2014.10.142

[18] Lartigue B, Lasternas B, Loftness V. Multi-objective optimization of building envelope for energy consumption and daylight. Indoor and Built Environment 2014;23(1):70-80. doi: 10.1177/1420326x13480224

[19] Futrell BJ, Ozelkan EC, Brentrup D. Optimizing complex building design for annual daylighting performance and evaluation of optimization algorithms. Energy and Buildings 2015;92(0):234-45. doi: http://dx.doi.org/10.1016/j.enbuild.2015.01.017

[20] Li DHW, Wong SL. Daylighting and energy implications due to shading effects from nearby buildings. Applied Energy 2007;84(12):1199-209. doi: http://dx.doi.org/10.1016/j.apenergy.2007.04.005

[21] Rao S, Tzempelikos A. Daylighting and Thermal Assessment of Combined Dynamic Shading Systems on Energy Consumption in Educational Buildings. ASHRAE Transactions 2014;120(1):1-10.

[22] Park D, Kim P, Alvarenga J, Jin K, Aizenberg J, Bechthold M. Dynamic daylight control system implementing thin cast arrays of polydimethylsiloxane-based millimeter-scale transparent louvers. Building and Environment 2014;82(0):87-96. doi: http://dx.doi.org/10.1016/j.buildenv.2014.07.016

[23] Yun G, Yoon KC, Kim KS. The influence of shading control strategies on the visual comfort and energy demand of office buildings. Energy and Buildings 2014;84(0):70-85. doi: http://dx.doi.org/10.1016/j.enbuild.2014.07.040

[24] Liu M, Wittchen KB, Heiselberg PK. Control strategies for intelligent glazed façade and their influence on energy and comfort performance of office buildings in Denmark. Applied Energy 2015;145(0):43-51. doi: http://dx.doi.org/10.1016/j.apenergy.2015.02.003

[25] Ghoshal S, Neogi S. Advance Glazing System – Energy Efficiency Approach for Buildings a Review. Energy Procedia 2014;54(0):352-8. doi: http://dx.doi.org/10.1016/j.egypro.2014.07.278

[26] Huang Y, Niu J-l, Chung T-m. Comprehensive analysis on thermal and daylighting performance of glazing and shading designs on office building envelope in cooling-dominant climates. Applied Energy 2014;134(0):215-28. doi: http://dx.doi.org/10.1016/j.apenergy.2014.07.100

[27] Reinhart CF, Weissman DA. The daylit area – Correlating architectural student assessments with current and emerging daylight availability metrics. Building and Environment 2012;50(0):155-64. doi: http://dx.doi.org/10.1016/j.buildenv.2011.10.024

[28] Yener AK. A method of obtaining visual comfort using fixed shading devices in rooms. Building and Environment 1998;34(3):285-91. doi: http://dx.doi.org/10.1016/S0360-1323(98)00024-9

[29] Oral GK, Yener AK, Bayazit NT. Building envelope design with the objective to ensure thermal, visual and acoustic comfort conditions. Building and Environment 2004;39(3):281-7. doi: http://dx.doi.org/10.1016/S0360-1323(03)00141-0

[30] Frascarolo M, Martorelli S, Vitale V. An innovative lighting system for residential application that optimizes visual comfort and conserves energy for different user needs. Energy and Buildings 2014;83(0):217-24. doi: http://dx.doi.org/10.1016/j.enbuild.2014.03.072

[31] Konis K. Evaluating daylighting effectiveness and occupant visual comfort in a side-lit open-plan office building in San Francisco, California. Building and Environment 2013;59(0):662-77. doi: http://dx.doi.org/10.1016/j.buildenv.2012.09.017

[32] Hua Y, Oswald A, Yang X. Effectiveness of daylighting design and occupant visual satisfaction in a LEED Gold laboratory building. Building and Environment 2011;46(1):54-64. doi: http://dx.doi.org/10.1016/j.buildenv.2010.06.016

[33] Shen E, Hu J, Patel M. Energy and visual comfort analysis of lighting and daylight control strategies. Building and Environment 2014;78(0):155-70. doi: http://dx.doi.org/10.1016/j.buildenv.2014.04.028

[34] Ochoa CE, Capeluto IG. Evaluating visual comfort and performance of three natural lighting systems for deep office buildings in highly luminous climates. Building and Environment 2006;41(8):1128-35. doi: http://dx.doi.org/10.1016/j.buildenv.2005.05.001

[35] Lee ES, Tavil A. Energy and visual comfort performance of electrochromic windows with overhangs. Building and Environment 2007;42(6):2439-49. doi: http://dx.doi.org/10.1016/j.buildenv.2006.04.016

[36] Wienold J. Dynamic simulation of blind control strategies for visual comfort and energy balance analysis. Proceedings of Building Simulation;2007:1197-204.

[37] Ochoa CE, Aries MBC, van Loenen EJ, Hensen JLM. Considerations on design optimization criteria for windows providing low energy consumption and high visual comfort. Applied Energy 2012;95(0):238-45. doi: http://dx.doi.org/10.1016/j.apenergy.2012.02.042

[38] Xue P, Mak CM, Cheung HD. The effects of daylighting and human behavior on luminous comfort in residential buildings: A questionnaire survey. Building and Environment 2014;81(0):51-9. doi: http://dx.doi.org/10.1016/j.buildenv.2014.06.011

[39] Hwang T, Jeong TK. Effects of indoor lighting on occupants' visual comfort and eye health in a green

building. Indoor and Built Environment 2011;20(1):75-90.

[40] Xue P, Mak CM, Cheung HD, Chao JY. Post-occupancy evaluation of sunshades and balconies' effects on luminous comfort through a questionnaire survey. Building Serv. Eng. Res. Technol. In press. doi: 10.1177/0143624415596472

[41] Navvab M. Opinion: Simulation in lighting design and research. Lighting Research and Technology 2014;46(2):92-.

[42] Loonen RCGM, Loomans MGLC, Hensen JLM. Towards predicting the satisfaction with indoor environmental quality in building performance simulation. Proceedings of Healthy Buildings 2015 Europe. In press.

[43] Mardaljevic J, Heschong L, Lee E. Daylight metrics and energy savings. Lighting Research and Technology 2009;41(3):261-83.

[44] Reinhart CF, Mardaljevic J, Rogers Z. Dynamic daylight performance metrics for sustainable building design. Leukos 2006;3(1):7-31.

[45] Carlucci S, Causone F, De Rosa F, Pagliano L. A review of indices for assessing visual comfort with a view to their use in optimization processes to support building integrated design. Renewable and Sustainable Energy Reviews 2015;47(0):1016-33. doi: http://dx.doi.org/10.1016/j.rser.2015.03.062

[46] Reinhart CF, Walkenhorst O. Validation of dynamic RADIANCE-based daylight simulations for a test office with external blinds. Energy and Buildings 2001;33(7):683-97. doi: http://dx.doi.org/10.1016/S0378-7788(01)00058-5

[47] Nabil A, Mardaljevic J. Useful daylight illuminance: a new paradigm for assessing daylight in buildings. Lighting Research and Technology 2005;37(1):41-57. doi: 10.1191/1365782805li128oa

[48] CIE TC-3-22. Control of damage to museum objects by optical radiation. Technical Report, 2004, CIE, Vienna.

[49] Reinhart CF, Wienold J. The daylighting dashboard – A simulation-based design analysis for daylit spaces. Building and Environment 2011;46(2):386-96. doi: http://dx.doi.org/10.1016/j.buildenv.2010.08.001

[50] Tregenza P. Opinion: Climate-based daylight modelling or daylight factor? Lighting Research and Technology 2014;46(6):618. doi: 10.1177/1477153514557602

[51] Cheung HD. Daylighting performance assessment methods for high-rise residential buildings in a dense urban environment. Ph.D. thesis, Department of Building Services Engineering, The Hong Kong Polytechnic University, Hong Kong, 2006.

[52] Chartered Institute of Building Services Engineers. The SLL Code for Lighting; 2012.

[53] Hong TZ. Comparisons of HVAC Simulations between EnergyPlus and DOE-2.2 for Data Centers. Lawrence Berkeley National Laboratory; 2009. Retrieved from: http://escholarship.org/uc/item/2dq2w3b3

[54] Rea MS. The IESNA lighting handbook : reference & application. 9th ed. New York: Illuminating Engineering Society of North America; 2000.

[55] Hong Kong Government. Code of Practice for Energy Efficiency of Building Services Installation; 2012. Retrieved from: http://www.emsd.gov.hk/emsd/e_download/pee/BEC_2012.pdf

[56] Hong Kong Government. Performance-based Building Energy Code; 2005. Retrieved from: http://www.emsd.gov.hk/filemanager/en/content_724/pb-bec.pdf

[57] American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). ASHRAE Standard 55-2010: Thermal Environment Conditions for Human Occupancy. Atlanta: ASHRAE, 2010.

Tables & Figures Captions