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Quantification of luminous comfort with dynamic daylight metrics in residential buildings

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A R T I C L E I N F O

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A B S T R A C T

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.

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 lx 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].

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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 and Jeong 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 and Weissman [27] have already discovered DA 300 lx (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