Renewable and Sustainable Energy Reviews 74 (2017) 959–968

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A review of daylighting design and implementation in buildings

Ing Liang Wong

School of Engineering and Built Environment, Glasgow Caledonian University, 70 Cowcaddens Road, Glasgow, G4 0BA, UK

ARTICLE INFO

Keywords:
Daylight
Daylight factor
Glazing
Daylighting system
Window
Skylight

ABSTRACT

Daylighting design has become prevalent in modern buildings in the effort to create a more sustainable living environment. Past and recent bodies of research emerged are mainly focused on the different methods of predicting and measuring daylight level and various range of daylighting technologies available. Despite a wide range of developed and commercially available daylighting systems have been reported, their applications have been limited by a lack of studies on their utilisations and high initial costs. Computer simulations have been frequently used in the past to investigate daylighting performance due to reliable and accurate predictions. However, additional simulation time and variable level of skills and knowledge required are major drawback of computer simulations. This paper includes and pools information on all major daylighting design topic in the built environment. The study critically reviews and compares daylighting design principles, strengths and weaknesses of different range of daylighting systems and calculation methods, such as, scale model with artificial sky, full scale model for field measurement, numerical modelling and manual calculation procedures with the aid of diagrams or tables. Such information could be of useful for engineers, researchers and designers to assess the suitability of applying these systems and technologies in different building types and examine the potential of energy and cost savings.

1. Introduction

The sun is the biggest source of light and energy on earth and the light we received today comes from the sun in two ways: either directly as sunlight, or modified and redistributed by the atmosphere as diffuse skylight. The light from the sun not only enables us to see, but provides energy and power to the whole ecosystem on earth. The combination of the direct sunlight and the diffuse skylight can be defined as daylight [1]. The quality and intensity of daylight vary according to geographical latitude, season in a year, time of day, local weather, sky conditions, and building geometry. In the UK, the availability of daylight is crucial as we cannot rely on direct sunlight alone for lighting the interiors of buildings [2]. Despite artificial lighting has long being used to supplement lighting in the interiors of buildings, reports suggest negative effect of artificial lighting on health [3–8]. Using natural light, it can help to maintain a good health, cure some of the medical ailments [9], and reduce psychological sadness related to the Seasonal Affective Disorder [10,11]. Compared to artificial light, daylight offers better conditions for seeing as it contains consistent alterations of intensity, direction and spectral composition; thus, it brings positive implication biologically and physiologically to all living things on earth [12], such as, as natural means for human body to produce vitamin D [11] and hormone [13]. The advantages of daylighting designs and applications in the built environment have been largely documented. Despite various methods used to measure and predict daylighting performance have been reported in the past, most daylighting technologies and methods used are tailor-made or designed for specific cases only. By contrast, this paper includes and pools information from different literature sources and databases (such as, Elsevier, Taylors and Francis, and Springer), compares different methods and strategies for predicting or measuring daylight level, and examines the strengths and weaknesses of different daylighting technologies. Such information would be of useful for engineers, researchers and designers to assess the suitability of applying these systems and technologies in different building types and examine the potential of energy and cost savings.

2. Daylighting as an alternative to artificial lighting

Artificial lighting contributes to significant carbon emissions and as a result, leads to global warming. Literature revealed that electric lighting consumes up to 40% of the annual building energy consumption [14,15], 20–30% of the total energy use in commercial buildings [16], one third of the electricity bill [17] or 35% of the total electric load in conventional office buildings [13]. In built environment, we benefit from solar energy in various ways, such as, heating and lighting. Passive solar energy design in buildings, which uses building elements for collecting, storing and distributing solar energy, is becoming important. Space heating and daylighting are the most direct and

E-mail addresses: IngLiang.Wong@gcu.ac.uk, xijiayu@hotmail.com.

http://dx.doi.org/10.1016/j.rser.2017.03.061
Received 11 July 2016; Received in revised form 24 February 2017; Accepted 9 March 2017
1364-0321/

Nomenclature

A	total area of enclosing room surfaces, in m^2
A_g	glazed area of windows (excluding frames or obstruction), in m^2
DF_{ave}	average daylight factor, in %
DF_{winave}	average daylight factor for vertical window, in %
DF_{sklave}	average daylight factor for skylight, in %
ERC	Externally Reflected Component (unitless)
FC	correction caused by the remoteness of a point illuminated by natural light from an opening (unitless)
FR	correction factor for window framing (unitless)
GL	daylight transmission coefficient of the glass (unitless)
IRC	Internally Reflected Component (unitless)
M	maintenance factor, allowing for the effects of dirt
MF	correction factor for window dirt (unitless)
MG	activity coefficient of the study site (unitless)
R	average reflectance of surrounding room surfaces, area A
SC	Sky component (unitless)
T	transmittance of glass, including the effect of dirt
θ	angle of visible sky, measured in section from the centre of the window opening, in degree

efficient way of passive solar energy design approach. Daylighting, which is an important strategy in modern architecture by which natural light can be brought into a room via building opening to replace or supplement artificial lighting, can contribute to the reduction of the building energy consumption and enhance visual comfort [18–20]. The exploitation of daylight has been recognised as a valuable means of achieving energy efficiency in buildings and improving visual quality of interior building spaces. Previous studies indicated that, by employing daylighting, reduction of 223 million tonnes of CO_2 emissions [21,22] or 24,000 MW of energy demand [23] could be achieved. However, excessive daylight exposure could cause glare, overheating problems and thermal discomfort to building occupants. Surveys show that, the luminous comfort of building occupants is affected by the quality of daylighting [24,25]. The benefits of daylighting can only be realised if visual needs and comfort criteria are carefully considered in building design [26]. Duncan and Hawkes [27] discussed passive solar energy design for non-domestic buildings, highlighting the importance of lighting energy consumption in non-domestic buildings and the potential of daylight for meeting lighting demands. The opportunities for exploiting daylight in non-domestic buildings have been examined, as well as the factors that needed to be considered if exploitation of daylight was to be successful [24]. Methods and guidance for good daylighting design have also been discussed, which include examples, explanations and practical exercises of how daylight can be successfully used in a variety of building types [28,29].

Daylight in a building does not by itself lead to energy saving. Daylighting can only contribute to cost and energy savings if lighting control strategies or photo sensors can be integrated to dim or switch off artificial lighting when sufficient daylight is available. The use of various control strategies, such as, manual, timed and automatic lighting controls has also been explored. Building Research Establishment (BRE) [30] and Chartered Institution of Building Services Engineers (CIBSE) [31] provided guidance on different types of lighting control suitable for various types of installation. Despite lighting energy savings and subsequent payback period as a result of lighting control application are difficult to assess [32,33], potential energy savings for different types of daylight responsive dimming technologies can be accurately predicted using computer software and validated by field measurements [33–35]. Reduction of artificial lighting energy inside building spaces using lighting controls was revealed in studies [34]. For examples, annual lighting energy savings of more than 5000 kWh [35] were predicted for a high-rise building or up to 41.5% [19] for a large space industrial building. However, lack of simplified evaluation tools, which are capable of providing information on the suitability and the cost-effectiveness of daylighting, can still be considered as one of the main reasons why building professionals are reluctant to incorporate daylighting features in their design [34].

3. Measurements, estimation and predictions of daylight performance

It is difficult to characterise indoor daylighting because of the numerous design parameters that have to be considered, such as, view factor, aperture size and room depth [36]. Nevertheless, experiments, numerical studies and simplified procedures are common methods used to determine interior illuminance. In early 1980s, BRE had developed simplified procedures to characterise lighting performance in the interiors of day lit buildings [30]. The amount of daylight inside a room can be measured by comparing it with the total daylight available outside the room. This ratio is called daylight factor (DF), which can be measured in percentage (%). Two types of DF can be calculated: DF at a given position (Point DF) and DF over a given floor area (Average DF, DF_{ave}). DF can be accurately determined by Eq. (1), which is expressed as the ratio of indoor daylight illuminance to outdoor daylight illuminance under the standard overcast sky [2,13,22,28,30,37–41].

$$DF = \frac{Indoor\ illuminance\ from\ daylight}{Horizontal\ unobstructed\ outdoor\ illuminance} \times 100\% \quad (1)$$

The value of DF depends on building types, window sizes, frames and position, types of glazing, transmission characteristics of glazing, cleanliness of glazing, and interior room surface reflectance [30]. DF can be measured using scale model with artificial sky [38] or field measurement in a real building [42]. It can also be predicted using computer simulation programs or calculated using simple manual procedures [2]. DF is made up of three principal components: sky component, internally reflected component and externally reflected component [2,12,28,36,37], which can be calculated separately and added together. These components can be calculated using Building Research Station (BRS) daylight table, Waldram Diagram, BRS Daylight Factor Protractors [2], pepperpot diagram [28] or numerical formulas [37]. The resulting DF need to be corrected to allow for deterioration of room reflectances, types of glazing, dirt on glass and the window frame [37]. The calculated DF excludes the effects of building orientation or direct sunlight from both indoor and outdoor illuminance [38,39], whilst the overcast sky on which it is based is very much a worst-case condition.

Point DF can only be used once the window size, shape and position have been decided, which may be too late to alter glazing areas at this stage. It is higher near the openings, but decreases significantly further away from the openings [42]. Compared with Point DF, DF_{ave} is easier to calculate and considerably less dependent on window shape and position, as it can be simply related to glazing area [38]. Derived from Eq. (1), DF_{ave} is the ratio of average interior illuminance to external global horizontal illuminance under standard overcast sky conditions [38] and can be used to represent the arithmetic mean of DF obtained throughout the room [2]. To date, DF is still the most frequently used parameter to characterise the daylight situation in a building [22]. Almost all national standards and international directives recommend DF as criteria for sufficient daylight quantity assessments [43]. Minimum values of DF_{ave} are normally recommended for different building interior spaces, ranging from less than 2% (artificial lighting dominates daytime appearance) to more than 5% (fully day lit where daytime artificial lighting rarely needed). Such recommendations have been widely discussed in a number of publication, such as, DETR Good