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A REVIEW OF DAYLIGHTING DESIGN AND IMPLEMENTATION IN BUILDINGS

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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.

Keywords: daylight, daylight factor, glazing, daylighting system, window, skylight

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

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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 to 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 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 24000MW 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].

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

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 Practice Guide 245, The Code of Practice on daylight (BS 8206 Part 2), CIBSE Window Design Manual and BREEAM [28,38,44,45]. DF_{ave} can be calculated based on the theory of the split-flux principle that divides the flux entering the interior through window over its lower parts of the room surface areas and total internal surface areas [46], which can be determined by Eqs 2 to 5 [13,28,29,36-38,40,47-50].

$$DF_{ave} = \frac{A_g \theta T}{A\left(1 - R^2\right)} \tag{2}$$

$$DF_{ave} = \frac{TMA_g \theta}{A\left(1 - R^2\right)} \tag{3}$$

$$DF = DF_{winave} + DF_{sklave} \tag{4}$$

$$DF = \left(SC + ERC + IRC + FC\right) \times MF \times FR \times GL \times MG \tag{5}$$

A variety of aids and methods used for calculating the availability of daylight and the effect of sun shading is shown in Table 1. These mainly refer to indicators developed to quantify the amount of skylight or sunlight reach a window. Majority of these indicators are less suitable and rarely used nowadays since they still involve plotting obstruction from reference points using transparent direction finder and building layout plans with different scales. Such aids and methods have actually posed a difficulty for architects, where Poole [51] has called for the need to standardise calculation method for providing consistent and practical guidance for designers and engineers.

Performance indices other than DF used to assess the daylight performance and availability inside buildings have been discussed, compared and critically analysed [28,29,41,44,49,52]. It was concluded that, DF is the most frequently used indices and widely accepted by international standards, despite improvement has been done by developing other indices [13,41,43]. However, one significant weakness of DF is that it is not suitable for direct sunlight calculation and the calculation was highly influenced by building properties [13]. To overcome the limitations of DF for direct sunlight calculation, Vertical to Horizontal illuminance (VH Ratio) has been used as a function of the light decrease on a vertical plane (41,52); while Daylight Autonomy (DA) has been used to measure how a certain illuminance level can be maintained by the use of daylight alone and can be expressed as a percentage of occupied time, either annually or on a month-by-month basis [46].

Daylight prediction indicators	**Assessments**
Waldram diagram	Vertical sky component
BRS daylight factor protractors	Sky component
BRS daylight table	Sky component
Sun-on-ground indicators	Availability of sunlight on the ground at the equinox
Sunlight availability indicators	Probable sunlight hours
Skylight indicator	Vertical sky component
The no-sky line rule of thumb	Availability of direct light from the sky
Sun path indicators	Availability of sunlight at particular times of day and year

Pepperpot diagram	Percentage of total skylight

Table 1 A summary of different methods used to determine the availability of daylight in buildings

Parameters, such as, depth, size and area of a room, window or roof light are critical at the initial design stage and limitations to room parameters were studied. Advice on suitable design and position of windows and rooflights [28], practical guidance on daylighting design and calculations of optimum window size and average daylight factor [46] have been provided for architects at different stages of the RIBA Plan of Work. In order for a room to be successfully day lit, it has been discussed that $\frac{L}{B}+\frac{L}{H}$ must not exceed $\frac{2}{(1-R_b)}$, where L is depth of room (front to back), B is breadth of room (along the window wall), H is height of window head above floor level, and R_b is the average reflectance of surfaces in the half of the room remote from the window [28,45,49,50,53,54].

Apart from room and opening parameters, a wide range of factors, such as, site layout, building orientation and geometry, window parameters, availability of sunlight or skylight, and adjacent obstruction have to be considered and examined carefully in order to effectively apply daylight in a building space [12,24,28,29,49,55]. Table 2 summarises these factors in three categories: site layout, building geometry and opening parameters. A useful guidance on how a good site layout planning can contribute to achieving good daylighting and sunlighting in buildings has been provided [29]. It highlights good practice to site layout planning and contains methods to quantify access to sunlight and daylight within a layout.

Categories	Factors affecting daylight performance
Site layout	External obstructions (existing buildings and trees)
	Overshadowing
	Building orientation
Building geometry	Balconies and overhangs
	Extension to the existing building, which is perpendicular to window
Opening parameters	Window sizes and parameters (height of window head from floor level)
	Roof light parameters

Table 2 Factors which influent the availability of daylight in buildings

Effective window design is essentially part of energy-conscious building design. BRE Digest 309 can be used to assess visual and energy impacts of window design [2]. It is the simplest method of daylighting design involving alteration to window parameters or glazing type to receive optimum daylight in building spaces [34,56]. It is also necessary to consider occupation density, room configuration and building type in order to reach a right balance between daylighting strategies and the climate [57]. Analysis shows changes to façade design and configuration could impact on daylighting performance level in office buildings [58]. Li and co-researchers [45,59] had identified building area and orientations, window area, glass type, shading and external obstruction as five key factors affecting the daylighting performance level of office buildings and residential flats in subtropical Hong Kong. Sky conditions, façade orientation, obstruction and transparency ratio of window glazing are other factors affecting daylighting performance [60]. Distance from the adjacent buildings and height of adjacent buildings influence the amount of direct and diffuse daylight reaching the windows as well [11]. Visible sky angle and no-sky line position are two methods used to measure the impact of external obstruction on the amount of daylight received in a room [49,55]. Simulations show significant energy saving by altering building parameters (room and window sizes) and layout as well as implementing electric lighting management [32].

4. Innovative daylighting systems

In the last 30 to 40 years, different daylighting technologies have been developed to improve daylighting performance in building interiors. Littlefair and colleagues from BRE have been pioneering the work in developing daylighting design strategies and technologies in buildings [29,54,61]. They have looked that both design and technological approaches, such as, layout and parametric changes to building designs as well as the application of daylight 'harvesting' technologies. Also known as daylighting system, these are actually devices located near or at the openings of building envelope, which can reflect and redirect incoming natural light flux into interiors for improving lighting conditions [1]. Two common types of daylighting systems are side-lighting and top-lighting [22,62]. Conventional vertical window opening is a common example of side-lighting; while opening in the roof or ceiling element of buildings is an example of top-lighting. Daylight can be delivered into a building through conventional vertical windows, clerestory windows or rooflights as well as a number of remote distribution systems [31,49]. For a conventional vertical window, light levels drop off rapidly when the distance from the window increases. The greater the depth of a room, the poorer it is illuminated by daylight [18]. Al-Obaidi and Rahman [63] critically investigate optimum design requirements of top-lighting system, which conclude that system type, sky condition and human comfort are significant factors. Designs with top-lighting must be examined carefully as potential overheating resulting from inappropriate top-lighting design should also be avoided [22,64]. To minimise this problem, innovative daylighting systems, which contain new components and technologies, have been developed to bring sunlight deeper into building interiors; whilst reducing overheating problem [65]. Littlefair [61] discussed more than 30 types of innovative daylighting systems, which can be divided into two categories: light guiding system (LGS) and light transporting system (LTS). LGS and LTS sometimes also referred to fenestration and core systems respectively [66]. LGS is a simpler daylighting system which can reflect and direct sunlight to the back of a room, where least sunlight can be received. LTS is more complex, which can collect, transport and distribute sunlight to inner zone in a commercial building with no access to wall or roof opening. The daylighting strategy in this type of building involves daylight penetration, distribution, protection and control [57]. Both types of the daylighting systems can be used to improve daylight distribution in building space and to control direct sunlight [54]. Despite previous research to improve natural illumination within buildings, particularly, the deep floor plan buildings with minimum daylight penetration, it has been focused mostly on office buildings, not industrial buildings, where lighting is a major electricity consumer [19].

4.1. Light Guiding Systems

Simple and inexpensive modification of window glazing and shading devices was able to significantly improve daylighting quantity and quality for visual comfort [67]. Conventional sun-shading devices, such as, solar screens [68], roller blinds and venetian blinds [69] are commonly used in buildings because they are relatively inexpensive and easy to use [70,71]. However, these conventional devices block out natural light and reduce amount of light penetrating into buildings, which would affect the light distribution in the buildings [12]. Compared to these conventional devices, more advanced devices, such as, LGS have been developed to reduce excessive solar gain without reducing the transmission of diffuse skylight. LGS are simple and easy-to-apply technologies developed to reflect, refract or deflect sunbeams from exterior into interiors with room depth of less than 10m from the building facades. LGS can be integrated into existing windows or roof lights to modify or supplement them [61], improve light distribution in the room as well as reduce glare and overheating that may occur adjacent to window opening. Excessive incoming solar radiations that reach the interiors adjacent to windows can be reflected and redirected by LGS to the ceiling and redistributed within the room.

Light shelves [12,24,54,61,67,69,72-85], fixed louvres [61,69,84], light directing louvres or glass [11,84], and light guiding shade [86] are some examples of LGS, which can be mounted at the upper part of a typical window to provide solar shading and glare control to occupants adjacent to the window, while allowing daylight into the room. These systems, which can be fitted either internally or externally, increase core illuminances under certain well defined conditions when the sun shines onto the windows for a particular season of the year [61]. Another line of development has been the curved slat profiles [61,69,74,78], variable angle configured slats [87], compound parabolic concentrating (CPC) reflective window blind system [88], highly reflective lamellas with retro-reflection [11], anidolic solar blind [89], and semi-transparent acrylic profiles [90]. These systems can be applied inside double glazed units and have been developed to deal with different incidence angles with minimum maintenance requirement. Adjustable or flexible systems that can be used to track the sunlight at different angles, such as, blinds with different slat angles [67,71,91,92], reflective, mirrored or translucent louvres [11,24,54,61,69,70,80], reflective window sills [61], combined prismatic louvre and reflective blind system [11,70], holographic films on movable louvres [80], movable louvre variable-area light-reflecting assembly (VALRA) system [93], transparent shading device [94], and sun-tracking prismatic system [95] were also discussed. Such configurations are much capable of admitting sunlight more uniformly throughout the room space, compared with the fixed systems. For daylighting systems to be more effective at shading and redirecting light, supplementary shading devices may be required, but it will increase cost and reduce light input [80]. Transparent insulated materials [18,96-104], prismatic films [24,54,61,69,74,76,78,80,84,105], holographic films [61,80], laser-cut light deflecting panel (LCP) [61,64,84,86,106-109], and phase change material (PCM) [110] are more advanced technologies that can be applied to window glazing, without the need of having supplementary shading devices. These systems can also be used as sun shading devices by controlling sunlight through reflection; while allowing sunlight through from specific angles [80] or combine usage of solar radiation and thermal qualities [18]. The practicality of some of these systems however, depends on the adaptation of the building façade to the system tilted at certain angle only. For example, laser cut light deflecting panels perform best at angle from 20º to 40º [109]. A new type of solar and light control device with retro-reflecting slats can select and direct solar radiation, avoiding direct radiation and glare discomfort and up to 70% daylighting autonomy [111].

Innovative types of skylights installed on the building roofs were presented and can be categorized into active and passive skylight [112]. Active skylights contain mechanical components with the ability of tracking the azimuth path of the sun; while passive skylights are less complex with no tracking system. Common types of skylights include shed-type rooflight [113], skylight contained glass, sunscreen and light-directing layer [114], skylights made of several glazing systems [115], skylight with prismatic glazing [61], toplight systems with various shapes [116], rooflight made of glass, thermoplastic or glass reinforced polyster [117], and optimized lightscoop skylight with a curved shape reflector [61,118]. Studies show an increase of between 5% and 10% in DF for shed-type rooflight or lightscoop skylight [118]. A higher level of useful daylight illuminance could be achieved when a rooflight to floor area ratio is between 0.15 and 0.20 [119]. A rooflight area of up to 20% of the total building floor area could contribute to more than 1000 lux of illuminance in horizontal plane (117). Reflecting mirrors were also used to reflect and redirect sunlight from the top of a light well into lower floors in a multi-storey building in Japan [120]. Table 3 shows a list of different LGS which have been developed and identified according to the constructions and the types of materials used.

Light Guiding System	**Tilt-able**	**Solar shading**	**Ease of application**	**Ease of maintenance**	**Thermal reduction**	**Allow view**
Light guiding shade	No	Yes	Window	Easy	Yes	Yes
Reflective blinds	Yes	Yes	Window	Easy	Yes	Limited
Venetian blinds	Yes	Yes	Window	Easy	Yes	Limited
Movable blinds	Yes	Yes	Window	Easy	Yes	Limited

Light shelves	No	Yes	Window	Easy	Yes	Yes
Prismatic louvers	Yes	Potential	Window	Easy	Yes	Limited
Mirror systems	No	Yes	Fixed louvre	Difficult	Yes	Limited
Prismatic glazing	No	Potential	Window & roof	Difficult	Yes	Limited
Translucent louvers	Yes	Yes	Window	Difficult	Yes	Limited
Transparent insulated glazing	No	Potential	Inside double glazing	Easy	Potential	Limited
Toplight on roof	No	No	Roof	Difficult	Potential	Limited
Solar screens	No	Yes	Window	Difficult	Yes	Limited
Skylight on roof	No	No	Roof	Difficult	Potential	Limited
Lightscoop skylight	No	No	Roof	Difficult	Potential	Limited
Shed-type rooflight	No	No	Roof	Difficult	Potential	Yes
Holographic films	No	Yes	Inside double glazing	Easy	Potential	Yes
Active modular glazing panel	No	Yes	Window	Easy	Yes	Yes
Three-layered rooflight	No	No	Roof	Difficult	Potential	Limited
Façade panels with PCM	No	Potential	Inside double glazing	Easy	Potential	Limited

Table 3 Strengths and weaknesses of light guiding systems presented by previous researchers

4.2. Light Transporting Systems (LTS)

It is increasingly difficult to provide required daylight for daily activities using LGS alone due to increase in building density and complexity of internal building layout [121]. More advanced daylighting technologies, such as, LTS, can be used for transporting and distributing daylight. LTS offer opportunities for reliable daylight into core zones of multi-storey buildings [122]. In contrast to LGS, LTS can be applied to rooms with the depth of more than 10m, as the systems collect, redirect, transport and distribute the daylight into the space of the rooms. Light pipes and anidolic daylighting systems are examples of LTS. A light pipe is also known as light duct [123] or tubular daylighting device [112,124] and can be used to collect sunlight directly from building façade, transferred to the core zones in the building optically by a series of mirrors inside the pipe. Two types of light pipes are reported: vertical and horizontal light pipes [24,54,61,76,81,85,86,123,125-130]. The light pipe acts as transmission network [122] and guides the collected light beams, either several stories vertically down the building with light distribution system on each floor; or through building fabric or ceiling horizontally into interior zones without access to window opening. Despite light pipes may be capable of spanning distances of greater than 30m within buildings, they are limited in their applicability due to the pipe diameters, which cannot generally be more than 20 times smaller than their length [131].

Different light pipes available commercially in the market are manufactured by Monodraught Ltd, Solatube International Inc., Velux, and Doel Corp and have different characteristics and applications [122]. Table 4 shows the existing innovative type of LTS, developed and manufactured using different technologies. The performance of different light pipes installed in a test room and a living room was evaluated and the results show the light pipes can provide visual comfort and energy saving if carefully designed [122]. When the solar elevation was low, light pipe performance decreases due to multiple reflection losses within the pipes [86]. Heliostat tracking system, which tracks, collects and concentrates solar radiations with lenses or mirrors

[11,54,61,76,84], CPC trough and linear Fresnel lens [132] and primary parabolic collector [10], which capture and concentrate sunlight, can be applied to the aperture of light pipes to enhance the sunlight collection. More sophisticated materials, such as, fibre optics, solid acrylic, microprisms, metal tube, hollow mirrored or prismatic pipes, mirrored pipe coupled with deflecting sheet, and silvered aluminium sheet with 95% reflectivity were used as advanced light pipes to enhance the light distribution [10,76,84,123,124,126,128,130,132,133]. Shao and Callow presented light rods of small diameter and can be bended by up to 90º, which have higher transmittance than light pipes of similar aspect ratios [131]. Sedki and Maaroufi developed Polymethylmethacrylate (PMMA) fibre optic wires with dimension of not more than 3mm used inside a light pipe together with a parabolic solar concentrator for effective light collection and reflection to provide illumination to underground basement [134]. Despite its cost effectiveness and reliability of providing high level of illumination, the performance of the system was limited by issues, such as, melting of PMMA in high temperature. Francini and colleagues developed a prism light guide structure, which was as reliable as light pipe with fibre optics, but cheaper (124).

Innovative daylighting system	**Manufacturers**	**Countries**	**C/D/P**	**Installation**
Heliostat and sun pipes systems	Heliobus	Switzerland	C	1995
Heliostat with an ultra-sunlight concentrator	Sunportal	South Korea	C	2012
Heliostat with light guide with prismatic materials	Arthelio	Germany	D	1998
Fresnel lenses and fibre optic	Himawari	Japan	C	Early 1970s
	Parans	Sweden	C	2004
Fresnel lenses and light pipe	Hybrid Solar Lighting	USA	D	2013
Fresnel lenses and liquid light guide (Solux)	Bomin Solar Research	Germany	P	2001
Skylight with mirrors and light duct	Sundolier	USA	C	2004
Skylight with curved mirrors	SunCentral	Canada	C	2013
	Solar Canopy Illuminance System	Canada	D	2010
Heliostat with Fresnel lenses and light guide (Universal Fibre Optics project)	EC Energy Programme	EU	P	2002
Parabolic concentrators and horizontal light guides	ADASY	European EUREKA	P	2012
Sun pipe with dome	Solatube	International	C	1987
Anidolic ceiling system	LESO-PB	Switzerland	P	1990
Sun pipe, sun catcher	Monodraught	UK	C	1995
Sun tunnel systems with dome and rectangular pipes	Velux	Denmark	C	2005
Solarspot with dome and mirrored hollow light pipes	Syneco	UK	C	unavailable

Table 4 A summary of commercialized (C), demonstrated (D) and prototyped (P) light piping systems

The concentrated light transported along the light pipes, is then distributed into the interior building zones by means of special luminaires or emitters, such as, specialised triangular arrangement of LCP [135] or transparent light tubes [11]. Anidolic daylighting system, which is a shorter version of light pipe, contained curved daylight collectors, were constructed using the principles of CPC to enhance the daylight collection and distribution [89,136-139]. The systems comprised of light ducts integrated into ceilings for guiding daylight into building space and can achieve a DF of more than 3% at a point up to 6m from building façade

[137]. Anidolic daylighting system with its light pipe made of high reflective plastic and mirror coating could provide illumination to rooms of 40m^2 [140]. The integration of anidolic daylighting system and electro-chromic glazing in building façade can achieve optimal control of the daylight flux in an office room [141].

Although a large number of daylighting systems are available in the building industry today, their usage is limited for reasons, such as, high initial cost, maintenance and variability in their performance parameters. In most cases, the systems are also tailor-made, require detailed design and only used in some high profile projects for marketing, where cost is irrelevant [66]. A summary of strengths and weaknesses of both LGS and LTS is shown in Table 5. Beltran and colleagues [85] compared the performance of light shelves and light pipes, where they concluded that light pipes are more efficient than light shelves. Despite the overall aperture area of best shelf design was approximately the same as light pipe aperture (1.1m^2), light pipes had more than twice the reflective surface area of the light shelves. Light pipes can achieve seven hours of work plane illuminance of more than 200lux per day, compared to four hours for light shelves [85]. Light pipes however, are expensive, requires maintenance [61] and the performance can be constrained by overcast sky conditions and changeable solar altitudes. Despite light pipes cannot be properly used to substitute windows due to changeable weather conditions, the light pipes can present electricity energy saving alternatives for permanent artificial lighted rooms in buildings, such as, in windowless zones [142].

Daylighting system	Strengths	Weaknesses
Light guiding system	Easier to implement and apply to window opening; Easier to maintain; Cheaper compared to LTS	Lower efficiency compared to LTG [85]; Practicality depends on tiltable angle of system [109]; Subject to external obstruction; Potential view obstruction; Some LGS may require high demand of user participation [90]
Light transporting system	Higher efficiency with longer hour of workplane illuminance [85]; Minimum external obstruction; Applicable to buildings with complicated design	Expensive and require modification to building interior [61,124]; Higher maintenance rate [61]; Performance constrained by overcast sky conditions and changeable solar altitudes; Light leakage from roof penetration [143]

Table 5 A summary of strengths and weaknesses of both light guiding and transporting systems

5. Methods of investigating daylighting in buildings

The daylighting performance of buildings can be assessed using various methods, ranging from manual design tools with simple charts to more sophisticated computer-based design tools. Approximately 50 methods were identified ranging from those which were solely manual to those requiring mainframe computers for implementation [24]. Various methods on daylighting predictions discussed in the past are scale building models with simulators [44,49,116,144], mathematical or analytical modelling [71,91,126,145-

149], full scale models or mock-ups for field measurement [19,35,37,49,67,71,91,92,111,115,141] and computer simulation software [18,19,23,26,33,35,37,46,49,59,67,68,91,92,111,115;116,118,132,141,149-156]. Table 6 shows the strengths and weaknesses of these methods as reported in literature. Among all methods discussed, full scale models or mock-ups are most costly to implement due to degree of difficulty in façade configurations and technological integration. Despite the process is usually time-consuming, the results are often realiable and practical as it involves actual technologies and materials in the real sky conditions [49]. Scale models are smaller version of building models, which are usually built in desired scales and similar to architectural models. The benefits of scale models are that, they are easier and cheaper to build and the models are easily made and handled [49]. However, the difficulty of building a daylight scale model is not less than building a traditional architectural model. Certain rules and considerations, such as, geometry, elimination of light leaks, material choice and inclusion of furniture in models, etc. need to be carefully integrated when building a daylighting model in order to obtain results that are as accurate as possible (157).

Methods	**Strengths**	**Weaknesses**
Scale models	Visualize daylight performance; Assist decision-making process for appropriate design option [49]; Built in desired scales; Studies can be undertaken using artificial sky to represent a specific time, date and latitude [49]; Built at all design stages [49]; Easier and cheaper than real building; Models can be created and handled easily [49]; Apply sensors/ camera inside model; Façade configurations and geometrical changes can be easily made [49]	Rules and considerations in model building [157]; Over-estimated illumination [13]; Issues with sky simulators [13]
Mathematical models	Easier and quick to calculate even without specific design details (eg. average DF)	Accuracy needs to be validated and tested compared to experiments
Full scale models/ mock-ups	Visualize daylight performance in true sky conditions; True representation of actual design [49]; Real building and systems under real sky conditions; Ability to use real and accurate materials within buildings [49]; Suitable for complex LGS which cannot be replicated at scale [49]	Large and expensive [49]; Difficult, time consuming and costly to implement technologies; Façade configurations not easily interchange-able; Most assessment limited to real sky conditions [49]; Models should be weather-proofed and orientated correctly if located outdoors [49]
Computer simulations	Cost effective; User-friendly interface [90]; Three-dimensional rendering [49]; Easier analysis with variable parameters and complex models; Ability to perform annual simulation [158]; Provide 'preview' of daylighting effect [90]; Dynamic visualization, such as sun animations and time lapse [49]	Speed of software rendering [159]; Accuracy needs to be validated and tested compared to experiments [160]; Calculation errors; Certain programs require skillful and well-trained users [13]; Input quality affects accuracy [156]; Output needs careful expert interpretation [156]

Table 6 Strengths and weaknesses of the various methods used to investigate daylight performance

Building energy simulation programs are valuable tool in the design stage of new buildings to assess potential daylight savings by performing parametric studies of varying windows and shading devices for optimization of building energy performance [154]. Computer simulation programs are effective in offering design support, due to the capability of involving large number of design parameters and performing daylighting performance analysis on detailed and scenario-based cases. Simulations allow accurate comparisons within the levels of experimental uncertainties, provide practical and computationally efficient solutions for energy performance assessment of daylighting applications, and enable the researchers to focus on improving building designs to obtain best results. Survey revealed that, 79% of the respondents who considered daylighting aspects in their building design had used computer simulations; whilst the use of scale models among daylight specialists has fallen substantially since the use of computer simulation programs can generate more accurate results [161]. Previous studies show that, the simulation results matched well with the results obtained from field measurement, indicating the reliability of the computer software [19].

Despite computer simulation programs was frequently used during the design development stage, the complexity of the programs and insufficient program documentation have been identified as weaknesses of the existing computer simulation programs. Such level of complexity increases the amount of time required for calculations and only those with reasonable skills and knowledge would be able to perform the calculations. Daylight simulation developer community is still very fragmented with approximately 42 daylight simulation programs have been used [161]. One of the earliest issues with daylight simulation software was the problems of interface and creation of models due to the speed of rendering software [159]. However, with the advance in simulation technology, most commonly used lighting simulation programs today have photo-realistic rendering programs, which could inform on how the actual building might perform [13]. Improvement to shortcomings of the lighting simulation regarding accuracy, calculation of few parameters, long computational times, simple scenarios and disconnection from whole building simulation has been reported [156]. Minimum accuracy between measurements and simulation was reported as around 20% and one of the main difficulties is how to acquire reliable measurements of reflectivity from surroundings. Integration of lighting simulation within whole-building simulation is still under development. Progress is needed for the complexity required in lighting simulation to be useful in energy calculations [156].

Works to develop user-friendly programs to enhance daylighting simulations have been reported. Kota et al. [152] discussed the integration of Building Information Modeling (BIM) tool with daylighting simulation programs, such as, RADIANCE, DAYSIM, ADELINE, and Ecotect for easier file input and to reduce the need for the tools to define building geometry in a three dimensional (3D) coordinate system. Other integrated simulation programs, such as, Relux, LighTools, SolidWorks, Lightscape, Microstation, RadioRay and DIALux were also used to provide 3D view of building models [42,132,159]. Fakra et al. [36] developed a new model to introduce simulation code into CODYRUN software, which was simple, user-friendly and can reduce calculation time. Gagne et al. [150] and Andersen et al. [26] combined fuzzy rule-based system with a simulation program, Lightsolve, to develop an interactive expert system for providing design guidance in improving daylighting performance in the early design stage. While every simulation tool is unique and has its own limitation, most researchers had either integrated different simulation tools, used more than one simulation tools to perform daylighting studies for better results, or compared them with experimental or measured results for validation [19,68,92,111,115,149,153,154]. Daylighting and thermal simulation programs were integrated to evaluate the impact of lighting energy savings on global building energy consumption [18,33], where a 50% to 80% reduction to artificial lighting energy consumption was reported [33]. Table 7 shows various daylighting computer simulation tools used in the past, in which RADIANCE, ADELINE, Ecotect, DOE, EnergyPlus, and DAYSIM are the most frequently used simulation programs.

Programs/ tools	Assessment	References
Dialux	Prediction of daylight illuminance	[91]
Lightsolve	Provide design guidance to users to improve daylighting performance	[26,150]
RADIANCE	Ray-tracing lighting simulation for UNIX computers	[11,18,19,46,67,68,95,111,115,116,141,142,153,155,162]
ADELINE (Superlink/ Radlink/ Superlite)	3D simulation program to evaluate the potential lighting energy savings of replacing artificial lighting with daylighting	[32,92,115]
Ecotect	Evaluate the performance of solar and lighting control devices, as well as daylighting performance of possible building orientations and shading strategies	[19,111,142,153]
CODYRUN	Indoor daylighting value calculation	[36]
DAYSIM 3.0	Evaluate daylight conditions in a building	[11,19,68,151,160,162]
DOE-2.1	Simulate energy performance of daylighting control systems	[34,154,164]
Photopia	Accurate prediction of performance of light pipes compared to analytical method	[149]
BIM-based simulation tool	Development and validation of a prototype to integrate Revit with RADIANCE and DAYSIM	[152]
EnergyPlus	Model daylighting performance of a high-rise residential building with severe sky obstruction	[59,154,160]
LightTools/ SolidWorks	Creation of 3D models to simulate fibre optical daylighting system	[132]
IES VE (6.1.1)	Analysis covers solar, energy, lighting data, cost and value, egress, computational fluid dynamics and mechanical parameters	[40,149]
Relux	Creation of 3D model to calculate DF	[42]
SkyCalc	Daylight calculation of photocontrols with skylighting	[23]
Autodesk VIZ 4	Daylight modelling in ray-tracing and radiosity lighting algorithms	[94]
SPOT	Optimizing the placement and orientation of photo sensor	[160]
Lightscape	Creation of 3D model to calculate DF	[159]
RadioRay	Creation of 3D model to calculate DF	[159]
Microstation	Creation of 3D model to calculate DF	[159]

Table 7 A summary of various computer simulation programs used to evaluate daylighting performance

Both computer simulations and measurements offer different possibilities and drawbacks, which vary according to the characteristics of the code or the artificial sky/ sun used [144] and large discrepancies between the real and simulated sky conditions were predicted [116]. It was concluded that the inconclusive experimental results might due to uncertainties related to daylighting system's optical properties, imperfect geometry, accuracy of the simulated sky conditions, and difficulty in comparing measured with simulated data. Further work is needed to remove the uncertainties [149]. Scale modelling can be effectively and accurately used to evaluate the impact of daylighting for a particular case study. Scale building models with various types of shading devices can be easily created and orientated for simulation under different sky conditions and sun positions either using a solar simulator or under a real sky condition [45,144,157]. Gagne et al. [150] and Kazanasmaz [91] predicted daylight illuminance with the application of fuzzy logic algorithm, whilst, Kim and Kim [71] used linear regression models to determine the fluctuation range of outdoor daylight illuminance.

6. Conclusions

Despite daylight can contribute to occupants' sense of well-being, excessive daylight could pose overheating problem to occupants [44]. It is essential to ensure that effective daylighting control systems are in place to prevent unwanted daylight and thermal discomfort. Daylight can also be properly incorporated into a building to offset the electrical lighting energy consumption using innovative daylighting systems. Despite many innovative daylighting systems are currently available in the market, there is very little information on how or where these daylighting systems can be best utilised [112]. Previous research [163] suggested that, daylighting systems should be tailor-designed and made to suit different circumstances, instead of designing a generic daylighting system which could overcome all challenges at once. This may, however, pose a limitation to the application as each technology is unique and requires the input of specific knowledge and technical expertise. An effective daylighting system should be able to avoid any visual discomfort, which is frequently caused by conventional lighting installations [31]. The main challenges that could prevent their widespread application are high initial costs, utilisation difficulties and application limitations [163]. Among the methods available to study daylight performance, it can be concluded that each has its own strengths and weaknesses, with full scale models being the most effective but also most expensive. With the advance in computer technology, computer-based simulation studies can also offer cost-effective solution and accurate predictions to daylighting performance. The methods are ideal especially at the initial stage of the studies or building design, prior to the application of more expensive real technologies or systems. The simulated results however, have to be validated by experimental or measured results. To increase the accuracy and reliability of the simulation studies, it is suggested that a longer measurement periods is recommended to allow rigorous comparison with simulations [149] and more works should be expected in the future to develop more accurate and reliable computer programs.

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

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