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Daylight Performance of Toplighting: An Overview

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Abstract

Abstract Novel and advanced daylighting strategies and systems can noticeably decrease artificial lighting consumption and considerably improve light quality in the interior environments. In modern architecture, employment of rooflights is prevalent since they transmit daylight into deep plans or spaces lacking facade. Although, the use of this system is more common in temperate and cold climates, because of its severe thermal effects, it can be used in all the climates by innovative design strategies. Proper design of rooflights can significantly reduce energy use of lighting, heating, and cooling. Accordingly, the present study was designed to present an overview of toplighting field surveys conducted between 1984 and 2021. In this review study, analytical methods, efficient design parameters, and their effects on daylight and energy performance of the rooflights were investigated. These parameters include rooflight and indoor environmental conditions. Reviewed studies have utilized various methods such as analytical formulae, computer simulation, and experimental designs to investigate performance of the rooflight. The key point is finding or designing a proper state of toplighting in order to increase energy efficiency of the building while improving visual comfort. Also, studying effective rooflight design parameters presents practical guidelines for future studies.

Keywords: Toplighting; Skylight; Atrium; Design parameter; Daylight performance

1. Introduction

In the last decades, considering the world's environmental issues such as carbon emissions, global warming, and sustainable design, proper use of daylight in buildings has become a significant solution in order to achieve energy efficiency by reducing lighting, heating, and cooling loads. It is noteworthy that, energy consumption of artificial lighting in office buildings accounts for up to 35% of total electricity consumption (Koster, 2012). In addition to artificial lighting, daylight has other advantages such as its quality and variability. Results of a study on peoples' reactions to indoor environments indicated that, long-time working under artificial lighting is injurious to health while working under daylight results in less stress and discomfort (Ruck, 2000; Fazeli et al., 2019).

From ancient times, rooflights have frequently been used to transmit daylight into the interior spaces and achieve homogeneous lighting. The use of rooflight is more common in modern architecture because of its aesthetic and energy-saving aspects (Al-Obaidi et al., 2014). Rooflights can be classified into active and passive rooflights. Active rooflights operate by mechanical systems tracing the sun position, while passive rooflights are less complicated (Sharp et al., 2014).

According to Treado et al. (1984), skylights are the most efficient fenestrations in the field of daylighting, as the entire room can be adequately illuminated utilizing only 2% of the ceiling surface. They also affirmed that, skylights are more efficient than windows, both in terms of illumination and uniformity. Many studies (Laouadi and Atif, 1998; Garcia-Hansen et al., 2002; Yoon et al., 2008; Sher et al., 2019) have shown that, proper design of rooflight significantly reduces energy use of lighting, heating, and cooling. They indicated that, shape and glazing type of rooflights could remarkably influence energy efficiency of rooflights. However, there are some disadvantages regarding application of roof lights. For example, low-altitude sunrays penetrate less in winter, and high-altitude sunrays penetrate more in summer, which in turn causes overheating, thermal discomfort, and extreme cooling loads that limits the use of rooflights in tropical and subtropical climates (Falt et al., 2017).

Daylighting is considered with various aspects such as lighting, heat gain, energy consumption, and visual comfort. Proper daylighting can directly reduce the energy consumption required for lighting, cooling, and heating. Visual discomfort, referring to pain or fatigue in or around the eyes, is a subjective reaction to the quantity and quality of light. Glare, a kind of visual discomfort, can occur when the amount of light is excessive or when there is an intense luminance in a visual scene. Some controlled direct sunlight may be required to provide a dynamic visual environment. And completely trying to obstruct direct sunlight will lessen the visible sky, and hence diffuse light, thus a designer will have to keep the balance of direct and indirect sunlight, dependent on climate and building type (Zeinalzadeh et al., 2021).

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Therefore, this study was conducted aimed at reviewing previous researches about rooflights in order to provide a strong background and practical guidelines for further researches. Different studies have been done with different analytical methods about design parameters of roof lights and interior spaces to investigate daylight penetration between 1984 and 2021. The indices used in literature are described in table 1.

Table 1

Description of the indices used in literature

Index	Definition	Reference
Indices for assessing the quantity of light		
Illuminance	the total luminous flux incident on a surface, per unit area. It is measured in lux (lx)	(Carlucci et al., 2015)
Daylight Factor (DF)	the ratio of the indoor daylight illuminance at a point within the enclosure to the outdoor illuminance at that point at the same time	(Carlucci et al., 2015)
Daylight Autonomy (DA)	percentage of annual daytime hours that a given point in a space is above a specified illumination level	(Carlucci et al., 2015)
Spatial Daylight Autonomy (sDA)	percentage to which a desired area receives a minimum daylight illuminance level, at least 300 lux, for a specified fraction of operating hours per year	(Carlucci et al., 2015)
Useful Daylight Illuminance (UDI)	percentage of the time in a year when indoor horizontal daylight illuminance falls between 300-2000 lux	(Carlucci et al., 2015)
Skylight Well Efficiency (WE)	percentage of the average illuminance ratio at the bottom and the top opening of the skylight well	(Acosta et al., 2013b)
Indices for assessing glare		
Luminance	a photometric measure of the luminous intensity per unit area of light travelling in a given direction. It describes the amount of light that passes through, is emitted from, or is reflected from a particular area, and falls within a given solid angle	(Carlucci et al., 2015)
Discomfort Glare Probability (DGP)	a probability that an occupant will be dissatisfied with the visual environment. Relationship between DGP and subjective glare ratings: – Imperceptible Glare <0.35 – Perceptible Glare 0.35 – 0.40 – Disturbing Glare 0.40 – 0.45 – Intolerable Glare >0.45	(Carlucci et al., 2015)
Annual Solar Exposure (ASE)	percentage of floor area that receives at least 1000 Lux for at least 250 occupied hours per year	(IESNA, 2013)

(Carlucci et al., 2015; Acosta et al., 2013b; IESNA, 2013)

2. Research Methodology

In this research, an overview of field surveys carried out on toplighting between 1984 and 2021 is presented. These papers were selected by searching for the keywords including toplighting, rooflight, skylight, clerestory, roof monitor, lightscoop, sunscoop, atria, atrium, and light well in the title, abstract or author-specified keywords among the ISI journals.

In this review study, analytical methods, efficient design parameters, and their effects on daylight and energy performance of toplighting are investigated. Different studies have used different parameters that often coincide or have similar parameters with different methodologies. These parameters were categorized into two major parts: rooflights and indoor environmental conditions. Previous studies have utilized various methods such as analytical formulae, computer simulation, and experimental designs to investigate performance of the rooflight. First, a brief review of rooflights is provided. Second, general conclusions on different parameters are summarized and discussed in separate sections. Third, the studies are summarized based on year, case study, objectives, study type, the issue of analysis, variable parameters, used simulation program, used measurement tool, as well as sky condition, and studied indices, as shown in Table 2. Finally, limitations and recommendations for future studies are presented.

3. A Brief Review of Rooflights

The rooflight transmits daylight into centre of the buildings with a deep plan or limited openings in exterior walls. This fenestration system is a critical section of a building's exterior cover, because it is confronted with most of external environmental conditions. Rooflights are more common in temperate and cold climates as they receive much heat from sunrays (Al-Obaidi et al., 2014).

3.1 Evolution of the rooflights throughout history

From ancient times, daylight has influenced lives of the humans by making the difference between night and day and by openings or windows as the first dwellings were built (Sheppard and Wright, 1984). The windows used on outer surface of the buildings have been more important so far, but the rooflights transmitting daylight into core parts of the buildings had a significant influence on plan form of glorious homes in the 17th and 18th centuries. This solution allows the architects having more creativity in designing of central areas. In the 19th century, after industrial revolution and growth of economic issues in structure, the decrease in the floor-to-floor height resulted in less daylight penetration from vertical window. Furthermore, the increase in the number of workplaces and so more demand for light has expanded the use of rooflights (Baker et al., 1993).

The early rooflights were simple such as Florence cathedral with vertical windows under the dome (Fig. 1). The illumination of the inside temple is much lower than the outside. This increase results in a feeling of "concentration" and peace. Through the opening, sunlight illuminates inside of the dome and distinguishes the prominent decorations and details of the semi-gloomy interior. Although there are many prominent decorations, they do not produce a bright contrast of shade and shadow when the interior lighting is imperturbable. This method of lighting produces a solemn and impressive effect and emphasizes the feeling of vast space inside the temple. In the condition of low brightness for the ceiling and walls, low level lighting in the interior can provide a gloomy feeling. In this atmosphere, the top of the dome filled with sunlight is emphasized. Through the windows at the bottom of the dome, only a few light streams to the top of the dome, therefore the dome looks very high and the spiritual feeling is stronger. Colourful glasses have been used to present various colourful views relying on the visual and spiritual manifestation of light. The light that filters through a colored glass can change the hue of the base color of the surface on which it falls. With the advancement of technology in the 19th century, fully glazed domes or glazed barrel vaults emerged. A worthy example is the Soane Museum with different shapes and sizes of rooflight devised to transmit daylight deep into the spaces (Fig. 2). When the sun shines in, it creates the feeling that the roof is flying upwards in the sky. Rooflights admits a large quantity of light, which fills the interiors with light and allows the decorations on the ceiling and walls to be clearly seen. Decorations on the wall creates a pattern of shadow and light at a very small scale. This generates an attractive pattern that changes continuously as the sun moves in the daytime. This kind of texture helps in scattering diffused light (Philips, 2004).

Fig. 1. Interior view of the dome of the Florence cathedral, Florence, Italy. (URL1)

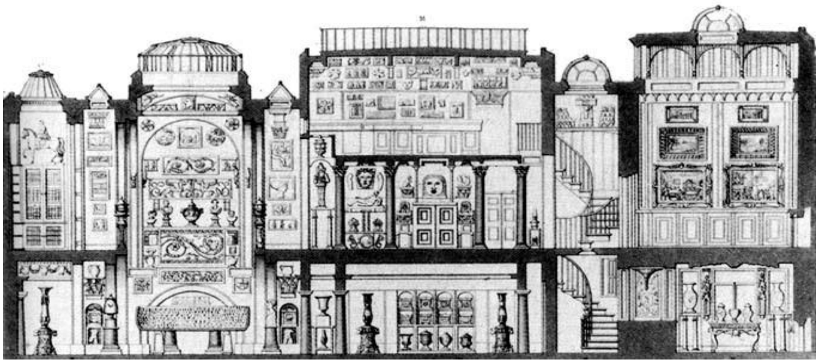

Fig. 2. Section through the Soane Museum, London, England. (URL2)

3.2 General forms of the rooflights

Climate types, design requirements, thermal comfort, and building functions influence selection of a rooflight form substantially. According to the assortments done by CIBSE (1999) and Lam (1986) and other types of rooflights mentioned in other studies (Kim and Chung, 2011; Acosta et al., 2013b; Asdrubali, 2003; Acosta et al., 2012; Acosta et al., 2015), the rooflights are categorized into four major types based on position of the openings.

3.2.1 Skylight

As described by Kim and Chung (2011), a skylight is an opening on a horizontal or sloped roof surface with different glazing covers, which can be flat, pyramid, dome, barrel vault, and ridge (Fig. 3). There is another type of skylight called lightwell skylight, which has a horizontal opening but is placed on a prism as a reflector avoiding direct sunlight to the interior (Acosta et al., 2013b) (Fig. 4).

3.2.2 Shed roof

According to CIBSE (1999), the shed roof, as the cheapest solution, with a ridge form and linear openings on it has many flaws and is almost abolished today (Fig. 5).

3.2.3 Clerestory

The clerestory has a vertical or inclined one-sided opening standing out of the roof surface. It transmits daylight, redirecting it to the below spaces (Garcia-Hansen et al., 2002). Sawtooth, lightscoop, and sunscoop are subsets of these rooflights differentiated based on opening side and reflector form. When the reflector is tilted, the clerestory is called sawtooth (Fig. 6). This type usually faces north that blocks direct light and allows diffusion of light without glare. It has been widely used in public and industrial places such as factories, warehouses, and museums because of its ability to avoid direct sunlight from precious objects or industrial equipment (Asdrubali, 2003). If the opening is oriented towards open sky, the clerestory is called lightscoop, or if the opening is oriented towards sun path, it is called sunscoop (Acosta et al., 2012).

Fig. 3. Different glazing shapes of a skylight (Kim and Chung, 2011)

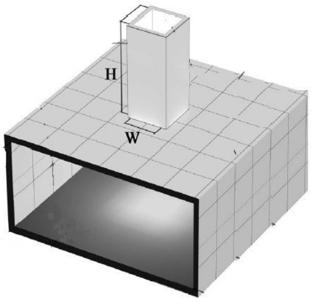

Fig. 4. Lightwell skylight (Acosta et al., 2013b)

Fig. 5. Section of the shed roof (CIBSE, 1999)

Fig. 6. Section of the sawtooth (Asdrubali, 2003)

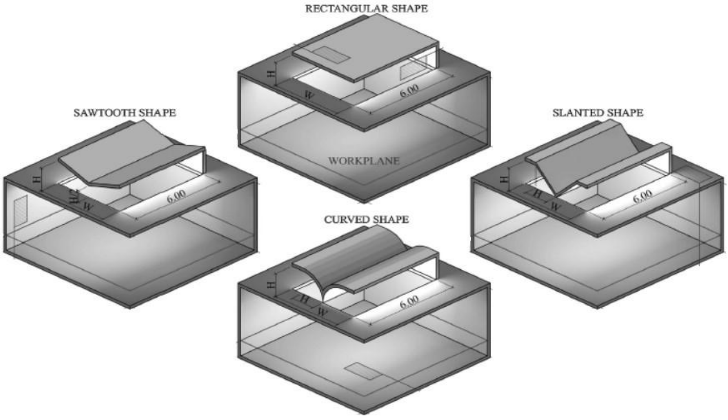

Fig. 7. Different reflector forms of a roof monitor (Acosta et al., 2015)

3.2.4 Roof monitor

It is a projected section of the roof with both north and south openings. It transmits daylight towards the below spaces. Common form of the roof monitors has a flat roof. However, different shapes of the roof such as slanted, sawtooth, and curved can be set (Fig. 7). These reflectors redirect light towards the below spaces and provide a homogeneous distribution of light (Acosta et al., 2015).

4. Effective Parameters on Toplighting

In this section, the effect of various design parameters on toplighting is reviewed. This section demonstrates how daylight performance and energy efficiency are amended by implementing appropriate strategies and appropriate design parameters. To evaluate performance of the rooflight, different analytical methods such as experimental designs (scale models, real cases), computer simulation, and analytical formulae have been used.

4.1 .Rooflights

Various aspects of a rooflight such as its type, configuration, and material have been studied that can be considered during schematic design stage. Furthermore, suitable rooflight features should be selected according to the site latitude, climate, and architectural requirements.

4.1.1 .Types of the Rooflight

Boubekri (1995) analysed three kinds of rooflight on the roof of an atrium and indicated that, flat skylight receives more illumination along with the problem of overheating and monitor roof provides more homogeneous distribution of the light on the four walls than the sawtooth system. Dewey and Littlefair (1998) investigated flat, northlight, shed, sawtooth, monitor, and dome rooflights on a room and found that, monitor roof provides the most homogeneous illumination and dome skylight transmits the least illumination. They also found that, the space between rooflights is relative to reflectance of surfaces. Sharples and Shea (1999) studied different atrium roof forms including flat, east-west sloping A-frame, and south-sloping mono-pitch, and expressed that the south-sloping mono-pitch form had the least effect on illumination of the atrium walls. However, roof form has a negligible effect under overcast sky conditions. Garcia-Hansen et al. (2002) analysed skylight, roof monitor, and clerestory for daylight performance (using illuminance and daylight factor (DF) indices). They expressed that, energy saving for cooling loads is high first for the clerestories, followed by the roof monitors and the skylights in the second and third ranks. Regarding the daylight, skylights are suggested for cloudy skies, clerestories for clear skies and roof monitors are suitable under variable sky conditions. Laouadi et al. (2002) studied different shapes of roof skylight including flat, pyramid, and ridge in terms of thermal and energy performance. Both the pyramid and ridge form had more solar heat gain ratio than flat form. They also studied the effect of different types of glazing, including double and triple clear/tinted glazing with or without low-E coatings on cooling, heating, and annual energy consumption in different shapes of skylight and different shapes of atrium including enclosed, three-sided, and linear. Laouadi and Atif (1998) demonstrated that, the dome skylight further transmits low-altitude light and it less transmits high-altitude light than the flat skylight; therefore, it is more efficient at low latitudes. Another study indicated the same feature for the barrel-vault skylight (Laouadi, 2005). Yoon et al. (2008) investigated different configurations of the rooflight including a skylight with vertical or splayed wells, clerestory in the form of north-facing without diffusing baffles, or south-facing with diffusing baffles. By providing a 2% daylight factor, skylights with vertical wells cause the highest total energy saving than other types, because they have the least glazing area to provide a 2% daylight factor.

Kim and Chung (2011) suggested two rooflight systems, north-facing sawtooth and monitor roof, instead of pyramid skylight, aimed at improving daylight performance (using illuminance index) of an existing museum room, and analysed their different glazing heights and transmission efficiencies. They proposed the sawtooth roof system with 3-meter glazing height and 60-70-80 % of transmission efficiency and monitor roof system with 2-meter glazing height and 70-80 % of transmission efficiency. In another study, Kim and Seo (2012) proposed a monitor roof system with 1-meter glazing height and 80-90 % of transmission efficiency or 2-meter glazing height and 60-70-80-90 % of transmission efficiency. Leung et al. (2013) analysed two proposed solutions, semi-silvered reflective Elero louver system, and laser cut panels, aimed at improving daylight performance (using illuminance and luminance indices) of a north-facing clerestory in an existing office building. The louver system was selected because of better daylight performance and glare obstruction. Al-Obaidi et al. (2017) designed and evaluated an integrated daylighting system consisting of skylights combined with a dynamic shading system and fibre optic daylighting system that meet illumination need in a common library room without aperture on its facades. Cabeza-Lainez et al. (2019) proposed and investigated a south-facing sawtooth system with diffusing baffles instead of existing plastic pyramid skylights to improve daylight performance (using illuminance index) of classrooms in Denmark.

4.1.2 .Configurations of the rooflight

In a Mediterranean climate, optimal skylight area -to -floor area ratio providing energy efficiency, adequate daylight, and glare protection has been reported to account for 5–10% (Motamedi and Liedl, 2017). Two studies (Laouadi and Atif, 1998; Parent and Murdoch, 1989) with different analytical methods, experimental and analytical formulae, respectively suggested that, height -to -width ratio of the dome skylight is proportional to -light penetration and uniformity. A survey (Acosta et al., 2013b) about lightwell skylights conducted under overcast sky conditions as the worst lighting condition specified that, the spacing between lightwell skylights is proportional to their width -to -height ratio. Concerning the skylight wells, skylight well efficiency (WE) has an inverse ratio with height -to -width ratio of the skylight well (Acosta et al., 2013b; Boubekri and Anninos, 1995; Tsangrassoulis and Santamouris, 2000) and the more the skylight well angle, the less the skylight well efficiency (WE) (Parent and Murdoch, 1989; Boubekri and Anninos, 1995). Results of a study on the three reflector forms of a lightscoop demonstrated that, curved shape has better daylight performance (using daylight factor (DF) index) than rectangular shape, while the sawtooth shape had the worst performance (Acosta et al., 2013a). Other studies have proved that optimal height -to -width ratio of a lightscoop is equal to 4/3 (Acosta et al., 2012; Acosta et al., 2013a), and proper spacing between them should be equal to or more than ¾ of rooms□ height (Acosta et al., 2012). According to Laborda et al., (2015), opening on the east or west side of a clerestory provides higher average daylight factor than opening on its north or south side. Results of a study on four reflector forms including sawtooth, curved, rectangular, and slanted for a monitor roof indicated that, rectangular shape has poorer performance (using daylight factor (DF) and daylight autonomy (DA)indices). Independent from shape of the reflector, more efficient height -to -width ratio of a monitor roof is equal to one, and the spacing between them to rooms□ height is proportional to height-to-width ratio (Acosta et al., 2015). Furthermore, minimum ratio of the monitor roofs□ height to the atriums□ height for achieving sufficient level of illumination in adjacent spaces of the atrium has been reported as 3/8 (Ghasemi et al., 2015). Comparison of the skylights with or without structural elements showed that, they have a marginal effect in reducing daylight level under overcast sky conditions. Under clear sky conditions, they increase illuminance in north and east atrium walls and decrease illuminance in south and west atrium walls (Sharples et al., 2015). A recent study by Fang and Cho (2019) investigated skylight design variables on a gable roof of a single-storey building using useful daylight illuminance (UDI) index. Results indicated that the skylight located near the roof ridge has better performance, horizontal and vertical skylights are suitable in hot and cold climates, respectively, and north orientated skylights have the best UDI. Bugeat et al. (2020) studied the effect of the installed mirrors on the light well top in the five regions with various latitudes (0◦-60◦). Results showed that these solar redirecting mirrors are specifically efficient for low latitudes .

Henriques et al., (2012) designed an innovative domed form pavilion covered with triangular panels (Fig. 8). Directions and angles of the panels' apertures are investigated to find suitable configurations providing high illumination and low glare in different situations considering season, sky condition, and time of the day. El-Abd et al., (2018) (Fig. 9) analysed parameters of a skylight, visual transmittance and opening ratio of its panels under clear sky condition for most times of the year. They showed that, optimal configurations cause more than 50% decrease in the overlit area and reduce glare, while causing low increase in the daylit area.

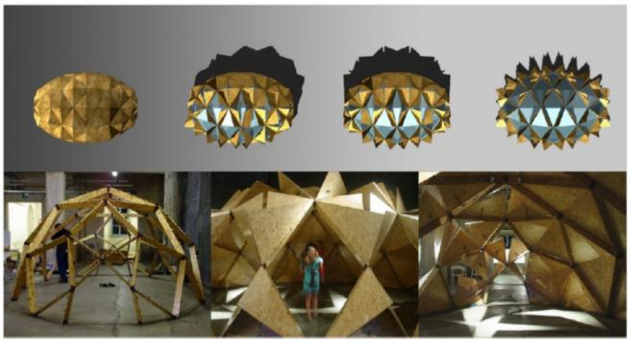

Fig. 8. The TetraScript pavilion concept and prototype, presented at the Beyond Media Festival, Florence. (Henriques et al., 2012)

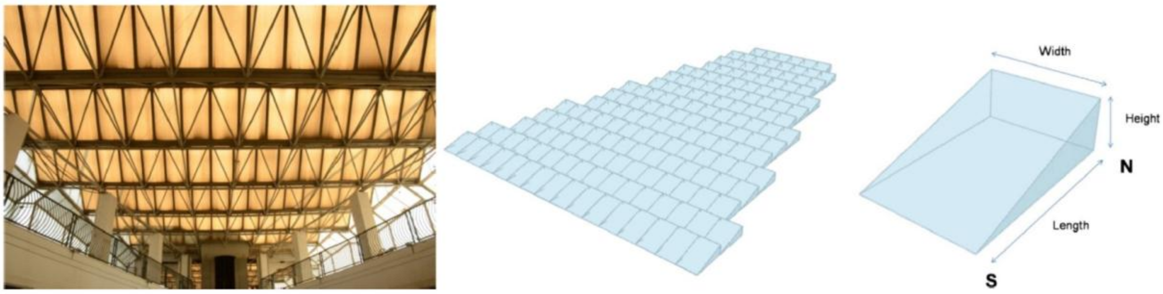

Fig. 9. Skylight configurations of Grand Mall (El-Abd et al., 2018)

4.1.3. Materials used for the rooflights

Falt et al. (2017) proposed an advanced gas-filled triple skylight with rotating mid layer (Fig. 10). The skylight acts as a thermal insulator when the mid layer is horizontal, and acts as a cooler in case of slanted mid layer, which allows gas circulation. Comparison of two types of glazing, translucent and transparent, set on a barrel-vault skylight proved that, translucent vault skylights transmit more and less diffuse light on sunny and overcast days, respectively (Laouadi, 2005). In a study, glare performance of two types of glazing including fritted glass and electrochromic (EC) glass was evaluated under clear and overcast sky conditions using daylight glare probability (DGP) index. It was proved that, electrochromic glass could control the glare more efficiently while providing better view clarity (Malekafzali et al., 2017). Galal (2019) used a survey to assess the various atrium top materials using useful daylight illuminance (UDI), special daylight autonomy (sDA) and annual solar exposure (ASE) indices. It was found that lighting requirements were achieved for photovoltaic and Low-E glass but not for tinted and reflective glass. Another research investigated the optimal area ratio of photovoltaic materials over the skylight glass to improve the daylight performance (using daylight autonomy (DA) and useful daylight illuminance (UDI) Indices) for six cities in China (Fan et al., 2020). In a study investigating the impact of dielectric crossed compound parabolic concentrator (dCCPC) panel as the material of skylight in 14 cities, Tian et al. (2019) reported that the dCCPC skylight caused increases of artificial lighting energy consumption in all cases, but it was just suitable in hot climates by decreasing total annual energy consumption.

The laser cut panels are another efficient material used in pyramid skylights with the splay angle ranging between 45 □-55 □, obtaining much light at high solar zenith angles and less light at low solar zenith angles. Therefore, they are more efficient at low latitudes (Edmonds, 1993; Edmonds et al., 1995) (Fig. 11).

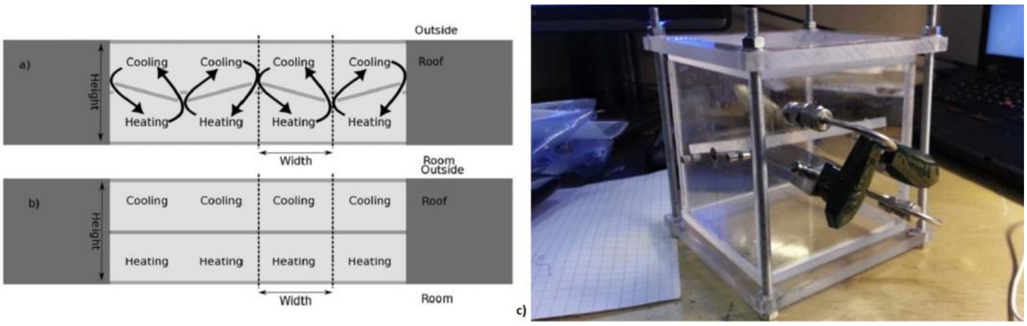

Fig. 10. Skylight in cooling mode (a), and in insulating mode (b), the 10 × 10 × 10 cm³ test skylight (c) (Falt et al., 2017)

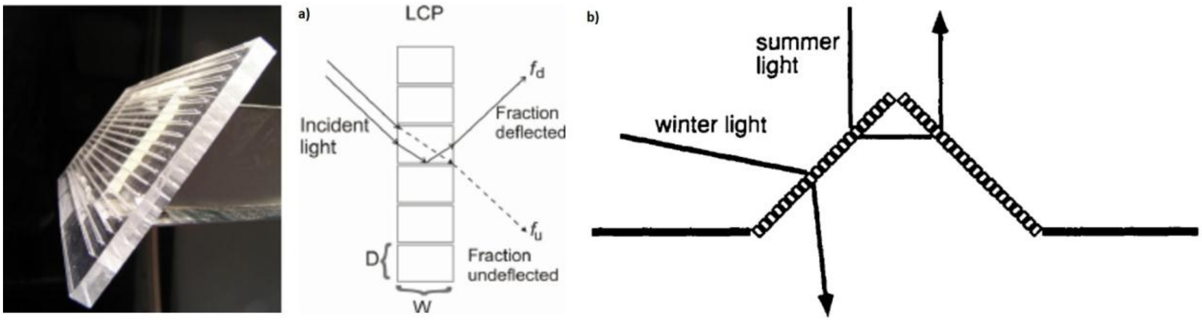

Fig. 11. A laser cut louvre panel (a), Angular-selective skylight produced by assembling four laser-cut panels over the aperture to form a pyramid (b) (Edmonds, 1993); Edmonds et al.,1995)

4.2. Indoor environmental conditions

Due to solar trajectory, not all sides of interior spaces may receive the same illumination. The south-facing spaces receive the most amount of daylight in most times of the year, and east-facing spaces receive it in June (Sudan et al., 2017). In addition to geographical directions, particularly in deep atriums, upper half of the atrium adjacent spaces receives excessive light, and bottom half of them receives low light (Al-Turki and Schiler, 1997). Moreover, the difference in daylight quantity between the spaces near and far away from the atrium border is less on lower floors (Du and Sharples, 2011a).

4.2.1. Configuration of interior spaces

Well index (height (width + length)/2 × length × width) is the most significant indicator of daylight levels in atriums with the same rooflight and surface reflectance so that, the higher the well index, the lower the illumination (Iyer-Raniga, 1994; Calcagni and Paroncini, 2004; Samant and Yang, 2007; Mohsenin and Hu, 2015). Furthermore, in atriums with interior balconies, well index and balcony depth are the most remarkable factors in daylight potential (Kim G. and Kim J.T., 2010). In addition to Well Index (WI), the relationship between other parameters like the PAR (Plan Aspect Ratio: well width/well length) and the SAR (Section Aspect Ratio: well height/well length) and daylight performance has been studied. The SAR has almost an inverse linear relationship with Daylight Factor (DF) (Yi et al. 2009; Lau and Duan, 2008), while there is an almost direct linear relationship between the PAR and DF on upper parts of the wall. In addition, there is an almost inverse linear relationship between the PAR and DF on lower parts of the wall (Du and Sharples, 2011a; Du and Sharples, 2010b; Du and Sharples, 2011b).

Results of a study on double atriums indicated that, less central atriums receive more daylight, and rectangular atriums act better than square and circular ones (Huang et al., 2015). Rastegari et al. (2020) analysed experimentally daylight performance (using illuminance, daylight autonomy (DA) and useful daylight illuminance (UDI) Indices) of Kaveh Glass office building (Well Index: 1/8 and well width/well height: 0/34) in Tehran. Then through simulation, optimum amounts for well index and well width/well height were assessed to be 1/3 and 0/5, respectively.

Alraddadi (2004) studied daylight performance of a stepped section atrium under a sloped north-facing roof opening using daylight factor (DF) index. He demonstrated that the stepped section atrium provides a significant improvement in light penetration despite a 30% reduction in the volume of this type of atrium than typical one. Gradually increasing opening area from top to bottom of the atrium walls is another strategy to increase daylight performance of lower levels (Iyer-Raniga, 1994; Matusiak et al. 1999; Cole, 1990; Samant, 2011). Kristl and Krainer (1999) proposed and investigated three innovative light wells (individual, semi-individual, and joint), as shown in Fig. 12. All the cases had better daylight performance (using daylight factor (DF) index) than reference ones and the best results were achieved using semi-individual light wells.

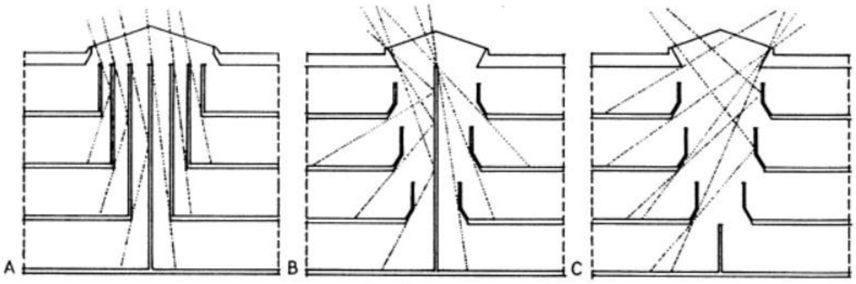

Fig.12. The individual light well (a), the semi-individual light well (b) and the joint light well (c). Broken lines mark the expected range of direct and reflected light (Kristl and Krainer, 1999)

4.2.2. Surface reflectance

Reflectivity of interior spaces also has a significant effect on lighting. High reflectance flooring results in high levels of daylight only at lower floors of the atrium (Boubekri, 1995; Iyer-Raniga, 1994; Lau and Duan, 2008; Cole, 1990; Du and Sharples, 2012). Increasing surface reflectance of the atrium walls increases daylight factor (DF), but its effect is greater at higher levels than lower or middle levels (Du and Sharples, 2011b; Du and Sharples, 2012). Besides, some studies have investigated different vertical or horizontal reflectance distributions of the atrium walls. For atriums with high well indexes, the effect of different reflectance distributions tends to increase (Du and Sharples, 2010a; Du and Sharples, 2011c). Wide horizontal bands of different reflectance distribution patterns influence daylight levels more at base of the atrium. However, narrow bands have a marginal effect on daylight levels (Samant and Yang, 2007; Sharples and Mahambrey, 1999; Samant and Sharples, 2004). The highest illumination is achieved in cases that upper half of the atrium is brighter (Samant and Yang, 2007; Sharples and Lash, 2004). However, vertical bands do not significantly influence daylight potential in the atriums (Du and Sharples, 2010a; Du and Sharples, 2011c).

5. Discussion

Several studies have been conducted on toplighting so far. Survey on the rooflights in scientific studies started to develop since 1984. Substantial studies in the literature are summarized in Table 2 based on year, case study, objectives, study type, the issue of analysis, variable parameters, used simulation program, used measurement tool, sky condition, and studied indices. The graphics, presented in Figs. 13–18, are developed according to summary of reviewed studies (Table 2).

Based on the reviewed studies, the major design parameters of an atrium are physical characteristics of atrium such as its configurations, reflectance of walls, roof configuration and glazing. Furthermore, it should be noted that external and internal shading devices assembled in order to adjust the receiving sunlight can be also impressive in daylight performance of rooflights. These design parameters should be investigated due to the function and the specific climatic conditions of the building.

Rooflights are used in a variety of types and configurations. The suitable rooflight should be chosen due to the location, function, and requirements of the building. Although sunlight transmittance is high through a skylight, it has the most heat gain in summer. And a south-facing rooflight which collect low-altitude light is very efficient in cold climate, while a rooflight which can obstruct high-altitude light and receive significant quantities of reflected light is preferable in warm climate. The rooflight material should allow as much diffuse light as possible whilst controlling direct sunlight. Direct sunlight should be considered in terms of overheating and glare. Therefore, various materials should be investigated and shading devices should be installed in order to increase the amount of diffuse light while decreasing the amount of direct light.

The amount of daylight level within the atrium walls is dependent on the interior configurations and the reflectivity of the surfaces. Previous studies have focused on how these parameters influence light level, using mostly the daylight factor index. Among atriums with equal plan area and depth, the rectangular atriums act better than square and circular ones, as the higher surface area to volume ratio of the rectangular atriums results in more reflections. For any section, increasing the the PAR (width/length of the atrium) which means wider atrium will increase light level, and increasing the SAR (height/length of the atrium) which means narrower atrium will decrease light level. High reflectivity of the surfaces generally has a significant effect on illumination. High floor reflectance has more influence in increasing light level at lower floors of the atrium, and high wall reflectance has more influence in increasing light level at higher floors of the atrium.

It should be noted that assessing the daylight performance of an atrium needs thorough and comprehensive investigation of various design parameters with consideration to the location of the building, solar altitude and micro-climatic conditions. In design process of the optimal atrium, there are other important issues that should be taken into account such as ventilation and occupants' thermal comfort.

Table 2
Previous studies on toplighting in buildings from 1984 to 2021.

Year	Author(s)	Paper Name	Case Study	Analytical Method	Issue of Analysis	Variable Parameters	Simulation Tool	Measurement Tool	Analytical Indices	Sky Condition
1984	S. TREADO, G. GILLETTE and T. KUSUDA	Daylighting with windows, skylights, and clerestories	A 1-storey commercial building in Washington, DC, USA	Computer Simulation	- daylight performance - energy performance - thermal performance	fenestration options (Windows, Skylights, and Clerestories)	NBSLD-2	_	Lighting, Heating and Cooling Consumption	all types of sky conditions
1984	M. FONTOYNONT, W. PLACE and F. BAUMAN	Impact of Electric Lighting Efficiency on the Energy Saving Potential of Daylighting from Roof Monitors	A 1-storey office building in the United States	Computer Simulation	energy performance	- two electric lighting designs - with or without roof monitors	BLAST	_	Lighting, Heating and Cooling Consumption	No sky condition is mentioned.
1989	M. D. Parent and J. B. Murdoch	Skylight dome-well system analysis from intensity distribution data	A 1-storey university building in D`urham, USA	Experimental	daylight performance	- skylight well angle - skylight dome depth (flat, shallow, deep) - skylight material (clear and/or translucent plastic)	_	- silicon light cells - illuminance sensor	- illuminance	clear and overcast sky conditions
1990	R. J. COLE	The Effect of the Surfaces Enclosing Atria on the Daylight in Adjacent Spaces	A 5-storey building	Experimental	daylight performance	- the proportion of openings in the atrium walls - atrium floor reflectance	_	Not mentioned.	- daylight factor (DF)	overcast sky conditions
1993	I. R. Edmonds	Performance of laser cut light deflecting panels in daylighting applications	A 1-storey building	Experimental and Analytical Formulae	daylight performance	- the splay angle of the skylight -tilt angle of the laser cut panels	_	Lux meter	- illuminance - daylight factor (DF)	clear and overcast sky conditions
1994	U. Iyer-Raniga	Daylighting in atrium spaces	A 5-storey office building in Vancouver, Canada	Experimental	daylight performance	- opening size of the atrium wall - reflectance of the atrium wall - atrium Floor reflectance - well index	_	- Photocell - lux meter	- daylight factor (DF) - illuminance	overcast sky conditions
1995	M. Boubekri	The effect of the cover and reflective properties of a four-sided atrium on the behavior of light	A 7-storey building	Experimental	daylight performance	- roof configuration (horizontal glass cover, Roof monitor, Sawtooth system) - the ratio between the glass to the mass portion (G/M) within the walls - reflectance of the atrium wall - atrium Floor reflectance	_	photosensor	- daylight factor (DF)	overcast sky conditions
1995	M. Boubekri and W. Anninos	Skylight wells: A finite-element approach to analysis of efficiency	Any building	Analytical Formulae	daylight performance	- Splay angle of the skylight wells - Height-to-width ratio of the skylight wells - skylight-wall reflectance - Effective reflectance of the glazed cover	_	_	- skylight well efficiency (WE)	all types of sky conditions
1996	I. R. Edmonds, P. A. Jardine, G. Rutledge	Daylighting with angular-selective skylights: Predicted performance	A 1-storey classroom in the Subtropical and tropical climate of Queensland, Australia	Experimental and Analytical Formulae	daylight performance	- slope angle of the skylight wells	_	Not mentioned.	- illuminance	clear and overcast sky conditions
1997	I. AL-TURKI and M. SCHILER	Predicting natural light in atria and adjacent spaces using physical models	A 4-storey building in hot arid climate of Los Angeles, California, USA	Experimental	daylight performance	_	_	illuminance meter	- daylight factor (DF)	clear sky conditions
1998	A. Laouadi and M. R. Atif	Transparent domed skylights: Optical model for predicting transmittance, absorptance and reflectance	Any building	Analytical Formulae	- daylight performance - thermal performance	_	_	_	- illuminance	clear and overcast sky conditions
1998	E. J. Dewey and P. J. Littlefair	Rooflight spacing and uniformity	A 1-storey building	Experimental	daylight performance	- different spacing of the rooflights - roof configuration: flat, northlight, shed, sawtooth, monitor and dome	_	- luminance meter - photometer	- daylight factor (DF) - illuminance	overcast sky conditions
1999	Z. Kristel and A. Krainer	Light wells in residential buildings as a complementary daylight source	A 4-storey residential building in Budapest, Hungary	Experimental	daylight performance	- well Width - types of light wells (individual, semi-individual, joint) - the shape of the clerestory Sills - the slope of the reflecting walls	_	Photocell	- daylight factor (DF)	overcast sky conditions
1999	B. Matusiak, Ø. Aschehoug and P. Littlefair	Daylighting strategies for an infinitely long atrium: An experimental evaluation	A 4-storey typical office or classroom in Norway	Experimental	daylight performance	- Glazing area of atrium wall - Glazing type of atrium wall - opening configuration	_	illuminance meter	- daylight factor (DF) - illuminance	overcast sky conditions

						- room length and width - reflectance values				
1999	S. Sharples and S. Mahambrey	Reflectance distributions and atrium daylight levels: a model study	An 8-storey building	Experimental and Analytical Formulae	daylight performance	- atrium wall surfaces color (black, white, bands of white and black horizontal stripes) - width and arrangement of stripes on well surfaces	_	- Photocell - lux meter	- daylight factor (DF)	overcast sky conditions
1999	S. Sharples and A. D. Shea	Roof obstructions and daylight levels in atria: a model study under real skies	A 5-storey building	Experimental	daylight performance	- atrium roof form (flat, East-west sloping A-frame, and south-sloping monopitch)	_	Photocell	- illuminance	No sky condition is mentioned.
2000	S. Sharples and A. D. Shea	Daylight transmission of atrium roofs under overcast and partly cloudy skies	A 5-storey building	Experimental	daylight performance	- atrium roof form (frame glazed roof with white structural Elements, flat glass roof with no obstructions)	_	Photocell	- illuminance	overcast and partly cloudy sky conditions
2000	A. Tsangrassoulis , M. Santamouris	A method to estimate the daylight efficiency of round skylights	Any building	Analytical Formulae	daylight performance	- height-to-radius ratio of round skylight - round skylight-wall reflectance - transmittance of the glazed cover	_	_	- average illuminance - skylight well efficiency	No sky condition is mentioned.
2002	V. Garcia-Hansen , A. Esteves , A. Pattini	Passive solar systems for heating, daylighting and ventilation for rooms without an equator facing facade	A 1-storey building in cold climate of Malargue City, in the central-western region of Argentina	Experimental and Analytical Formulae	- daylight performance - thermal performance - ventilation performance	- toplight configuration (Skylights, roof monitors and clerestories) - arrangement of each toplight (dimension and size) across a roof area	_	photometer	- illuminance - daylight factor (DF)	Clear and overcast sky conditions
2002	A. Laouadi , M.R. Atif, A. Galasiu	Towards developing skylight design tools for thermal and energy performance of atriums in cold climates	A 4-storey building in cold climate of Ottawa, Canada	Computer Simulation and Analytical Formulae	- thermal performance - energy performance	- fenestration Glazing type (double and triple clear=tinted glazing withor without low-e coatings.) - fenestration surface area - atrium shape (enclosed, three-sided, linear) - interaction of the atrium with its adjacent spaces (closed to the adjacent spaces, communicated with its adjacent spaces via doors) - skylight shape (flat, square-pyramidal and pitched)	- ESP-r - ADELINE	_	energy consumption	No sky condition is mentioned.
2004	S. Sharples and D. Lash	Reflectance distributions and vertical daylight illuminances in atria	An 8-storey building	Experimental	daylight performance	- atrium wall surfaces color (black, white, bands of white and black stripes) - width and arrangement of stripes on well surfaces	_	- luminance meter	daylight factor (DF)	overcast sky conditions
2004	B. Calcagni and M. Paroncini	Daylight factor prediction in atria building designs	A 6-storey building in Lausanne, switzerland	Experimental and Computer Simulation	daylight performance	- well Index	Radiance	- photometer - reflectometer	daylight factor (DF)	overcast sky conditions
2004	T. A. Alraddadi	The effect of the stepped section atrium on daylighting performance	A 4-storey building in Saudi Arabia	Experimental	daylight performance	- two types of atrium (conventional equal section atrium and the stepped section atrium.)	_	dataloger	daylight factor (DF)	clear sky conditions
2004	S. Samant and S. Sharples	Surface reflectance distributions and their effect on average daylight factor values in atrium buildings	An 8-storey building	Experimental	daylight performance	- atrium wall surfaces color (black, white, bands of white and black horizontal stripes) - width and arrangement of stripes on well surfaces	_	- luminance meter - lux meter	daylight factor (DF)	overcast sky conditions
2005	A. Laouadi	Models of optical characteristics of barrel-vault skylights: development, validation and application	Any building in Ottawa, Canada	Experimental and Analytical Formulae	- daylight performance - optical characteristics	- dimensions (radius and length) - orientation (skylight truncation angle ($\sigma_{\circ}$) - azimuth angle ($\Psi_{\circ}$) with respect to the south direction - glazing type (clear, fully translucent or partially diffusing glazing) - surface area - position of the sun with respect to the skylight position	_	- radiometer - illuminance sensor	transmittance, absorptance and reflectance	clear, overcast, and partly cloudy sky conditions
2007	S. Samant and F. Yang	Daylighting in atria: The effect of atrium geometry and reflectance distribution	Any building	Experimental and Computer Simulation	daylight performance	- uniform or horizontally differentiated reflectance distribution of well surfaces - widths of horizontal bands of white and Black on well surfaces - well index	- Ecotect - Radiance	- luminance meter - lux meter	- illuminance - daylight factor (DF)	overcast sky conditions
2008	B. Lau and Z. Duan	The daylight benefit conferred upon adjoining rooms by specular surfaces in top-lit atria	Any building	Experimental	daylight performance	- height to width to length ratio of atrium - section aspect ratio (SAR) - well index (WI) - specular surfaces arrangement on atrium walls - reflectance of specular Surfaces of atrium walls - atrium floor reflectance	_	- luminance meter - photometer	- daylight factor (DF) - illuminance	overcast sky conditions
2008	Y. J. Yoon, M. Moeck, R. G. Mistrick, and W. P. Bahnfleth	How much energy do different toplighting strategies save?	A 1-storey office building in the five regions in the U.S.	Experimental and Computer Simulation	- daylight performance - energy	- different climate locations (hot and humid to temperate/cold and dry climates with different levels of cloudiness)	- Radiance - DOE-2.1E	- illuminance sensor	- illuminance - energy consumption	No sky condition is mentioned.

			(Phoenix, Houston, Philadelphia, Seattle, and Minneapolis)		performance - thermal performance	- different toplight configurations (flat (vertical or splayed wells), roof monitor (with or without diffusing baffles)) - glazing type (clear and diffuse) - glazing area of toplight				
2009	R. Yi, L. Shao, Y. Su and S. Riffat	Daylighting performance of atriums in subtropical climate	Any building in the subtropical climate of Hong Kong and Guangdong, China	Experimental and Computer Simulation	daylight performance	- atrium types (enclosed, semi-enclosed, attached and Linear) - plane aspect ratio (PAR) - section aspect ratio (SAR) - well index (WI)	Radiance	Lux meter	daylight factor (DF)	clear and overcast sky conditions
2010	G. Kim, J. T. Kim	Luminous impact of balcony floor at atrium spaces with different well geometries	Any building in Texas, USA	Computer Simulation	daylight performance	- atrium Well index - balcony Well index	Not mentioned.	_	daylight factor (DF)	overcast sky conditions
2010	J. Du and S. Sharples	Daylight in atrium buildings: Geometric shape and vertical sky components	Any building	Experimental, Computer Simulation and Analytical Formulae	daylight performance	- Well index - atrium height - atrium Length - SAR - PAR	Radiance	photocell	daylight factor (DF)	overcast sky conditions
2010	J. Du, S. Sharples	Analyzing the impact of reflectance distributions and well geometries on vertical surface daylight levels in atria for overcast skies	Any building	Computer Simulation	daylight performance	- well index (WI) - atrium height - atrium wall surfaces color (black, white, gray, bands of white and black stripes) - well wall reflectance distribution patterns (horizontal or vertical bands) - width and arrangement of stripes on well surfaces	Radiance	_	daylight factors (DF)	overcast sky conditions
2011	J. Du, S. Sharples	The variation of daylight levels across atrium walls: Reflectance distribution and well geometry effects under overcast sky conditions	Any building	Experimental and Computer Simulation	daylight performance	- well index (WI) - atrium height - atrium wall surfaces color (black, white, gray, bands of white and black stripes) - well wall reflectance distribution patterns (horizontal or vertical bands) - width and arrangement of stripes on well surfaces	Radiance	- luminance meter - lux meter	daylight factors (DF)	overcast sky conditions
2011	Ch. S. Kim, S. J. Chung	Daylighting simulation as an architectural design process in museums installed with toplights	A 3-storey Museum in Seoul, South Korea	Experimental and Computer Simulation	daylight performance	- rooflight type (pyramid, monitor and sawtooth) - light transmission efficiency of the toplight - opening size of the toplight	Radiance	- illuminance meter	illuminance	clear sky conditions
2011	J. Du , S. Sharples	Assessing and predicting average daylight factors of adjoining spaces in atrium buildings under overcast sky	Any building	Experimental and Computer Simulation	daylight performance	- type of the atrium models according to the plan of the well and adjoining spaces (one-side, two-side and four-side) - type of the well plans (square and rectangular) - PAR (plan aspect ratio: well width/well length) - atrium height - well index - window area on atrium walls - well surface reflectance	Radiance	Lux meter	daylight factor (DF)	overcast sky conditions
2011	S. Samant	Atrium and its adjoining spaces: a study of the influence of atrium facade design	A 5-storey building	Computer Simulation	daylight performance	- glazing ratio of well walls - two opening configuration on well walls (One continuous horizontal strip window, Three vertical windows)	- Ecotect - Radiance	_	daylight factor (DF)	overcast sky conditions
2012	J. Du, S. Sharples	The assessment of vertical daylight factors across the walls of atrium buildings, Part 1: Square atria	Any building	Experimental and Computer Simulation	daylight performance	- atrium height - WID - wall surface reflectances - floor reflectances	Radiance	luminance meter	daylight factors (DF)	overcast sky conditions
2012	J. Du, S. Sharples	The assessment of vertical daylight factors across the walls of atrium buildings, Part 2: Rectangular atria	Any building	Experimental and Computer Simulation	daylight performance	- Height - SAR - Length - PAR - wall surface reflectances - floor reflectances	Radiance	luminance meter	daylight factors (DF)	overcast sky conditions
2012	G. C. Henriques , J. P. Duarte , V. Leal	Strategies to control daylight in a responsive skylight system	A 1-storey pavilion	Computer Simulation	visual comfort	- skylight control heuristic - the degree of aperture of the skylight panel	- Radiance	_	- illuminance	clear and overcast sky conditions
2012	Ch. S. Kim, K. W. Seo	Integrated daylighting simulation into the architectural design process for	A 3-storey Museum in Seoul, South Korea	Experimental and Computer	daylight performance	- toplight type - opening size of the toplight	Radiance	illuminance meter	illuminance	intermediate sky

		museums		Simulation						conditions
2012	I. Acosta, J. Navarro, J. J. Sendra, P. Esquivias	Daylighting design with lightscoop skylights: Towards an optimization of proportion and spacing under overcast sky conditions	A 1-storey typical museum or library room	Computer Simulation	daylight performance	- lightscoop height - lightscoop width - room dimensions - spacing between the lightscoops	- Lightscape 3.2 - DaySim 3.1	_	- daylight factor (DF) - illuminance	overcast sky conditions
2013	I. Acosta, J. Navarro, J. J. Sendra	Daylighting design with lightscoop skylights: Towards an optimization of shape under overcast sky conditions	A 1-storey typical museum or library room	Computer Simulation	daylight performance	- room size - shapes of lightscoop skylight reflector (rectangular, slanted or curved) - proportions for each shape of reflector	Lightscape 3.2	_	daylight factor (DF)	overcast sky conditions
2013	I. Acosta, J. Navarro, J. J. Sendra	Towards an analysis of the performance of lightwell skylights under overcast sky conditions	A 1-storey typical museum or library room	Computer Simulation	daylight performance	- size and height/width ratio of the lightwell skylight - reflection index of the lightwell skylight - height, width and length of the room - spacing of the lightwell skylights	Lightscape 3.2	_	daylight factor (DF)	overcast sky conditions
2013	T. C.Y. Leung, P. Rajagopalan, R. Fuller	Performance of a daylight guiding system in an office building	A 3-storey office building in temperate climate of Melbourne, Victoria, Australia	Experimental and Computer Simulation	- daylight performance - energy performance	- investigation scenarios (the reference case, a semi-silvered reflective Elero louvre system installed, laser cut panels installed)	- Energy-10	Lux meter	- illuminance - luminance	clear and overcast sky conditions
2014	Miguel Ángel Campano Laborda, Ignacio Acosta García, Jessica Fernández-Agüera Escudero & Juan J. Sendra	Towards finding the optimal location of a ventilation inlet in a roof monitor skylight, using visual and thermal performance criteria, for dwellings in a Mediterranean climate	A 1-storey residential building in the Mediterranean climate Of Seville, Spain	Experimental and Computer Simulation	- daylight performance - thermal performance	- location of the ventilation inlet in a roof monitor skylight - air changes per hour (ACH) - work plane height - two positions for the door in the room	- Velux Daylight Visualizer - Design Builder	thermocouple sensors	- daylight factor (DF) - illuminance	clear and overcast sky conditions
2015	I. Acosta, J. Navarro, J. J. Sendra	Towards an analysis of the performance of monitor skylights under overcast sky conditions	A 1-storey typical museum or library room	Computer Simulation	daylight performance	- reflector shape (rectangular, slanted, sawtooth or curved) - proportions for each shape of reflector - room length and width	- Lightscape 3.2 - DaySim	_	- daylight factor (DF) - daylight autonomy (DA)	overcast sky conditions
2015	M. Mohsenin , J. Hu	Assessing daylight performance in atrium buildings by using Climate Based Daylight Modeling	An office building in the warm climate of Raleigh, North Carolina, USA	Experimental and Computer Simulation	daylight performance	- well index - atrium type (central, attached and semi-enclosed) - roof aperture type (monitor and skylight) - monitor roof glazing height	DIVA	- data logger	- spatial daylight autonomy (sDA) - annual solar exposure (ASE)	No sky condition is mentioned.
2015	M. Ghasemi , M. Noroozi , M. Kazemzadeh , M. Roshan	The influence of well geometry on the daylight performance of atrium adjoining spaces: A parametric study	A 4-storey office building in Malaysia	Experimental and Computer Simulation	daylight performance	- atrium width - clerestory height	Radiance	- radiometer - photometer - lux meter	daylight factor (DF)	overcast sky conditions
2015	Y. Huang, L. Borong , N. Yao , and Z. Yingxin	Functional Relationship Between Lighting Energy Consumption And The Main Parameters For Double Atrium Offices	A 10-storey office building in Beijing, China	Computer Simulation	- daylighting performance - energy performance	- spacing of atriums - shape of atriums - position of atriums - area distribution of atriums	- Ecotect - DaySim	_	- daylight autonomy (DA) - useful daylight illuminance (UDI)	No sky condition is mentioned.
2017	S. Motamedi, P. Liedl	Integrative algorithm to optimize skylights considering fully impacts of daylight on energy	A 1-storey office building in the Mediterranean climate of San Francisco, USA	Computer Simulation	- daylight performance - energy performance	- different ratios of skylight to floor area	- Ladybug - Honeybee - Python	_	- special daylight autonomy (sDA) - useful daylight illuminance (UDI)	No sky condition is mentioned.
2017	M. Sudana, R. G. Mistrick, G.N. Tiwari	Climate-Based Daylight Modeling (CBDM) for an atrium: An experimentally validated novel daylight performance	Any building in New Delhi, India	Experimental and Analytical Formulae	daylight performance	_	_	illuminance sensor	illuminance	clear sky conditions
2017	K. M. Al-Obaidi , M. Arkam, C. Munaaim , M. A. Ismail , A. M. Abdul Rahman	Designing an integrated daylighting system for deep-plan spaces in Malaysian low-rise buildings	A 1-storey typical museum or library room in Malaysia	Experimental and Computer Simulation	daylight performance	_	LightToolsTM	pyranometer	illuminance	intermediate sky conditions
2017	A. M. Ardakan, E. Sok, J. Niemasz	Electrochromic glass vs. fritted glass: an analysis of glare control performance	An Airport and a pavilion in the USA	Computer Simulation	- daylight performance	- different controlling strategies for glare (fritted glass and electrochromic (EC) glass) - two different case studies (one with skylight and one with vertical glass) - visible light transmission range	- DaySim - DIVA - Ladybug	_	- Daylight glare probability (DGP)	clear and overcast sky conditions
2017	M. Fält, F. Pettersson, R. Zevenhoven	Modified predator-prey algorithm approach to designing a cooling or insulating skylight	Any building	Computer Simulation	- thermal performance	- the height and the width of the skylight	- COMSOL Multiphysics 4.3a	_	energy consumption	No sky condition is mentioned.
2018	W. El-Abd, B. Kamel, M.	Assessment of skylight design	A 6-storey shopping	Computer	- daylight	- opening ratio of skylight panels	DIVA	_	- daylight	clear sky

	Afify, M. Dorra	configurations on daylighting performance in shopping malls: A case study	mall in the hot arid climate of Cairo, Egypt	Simulation	performance - energy performance	- visual transmittance			availability	conditions
2018	A. Ahadi, M. R. Saghafi, M. Tahbaz	The optimization of light-wells with integrating daylight and stack natural ventilation systems in deep-plan residential buildings: A case study of Tehran	residential buildings in Tehran, Iran	Experimental and Computer Simulation	- thermal performance - daylight performance	- height, length, width of light-well - size and positions of vertical and horizontal inlet and outlet ventilation openings	- Design Builder - Daysim	Lux meter	- daylight autonomy (DA)	No sky condition is mentioned.
2019	M. Tian, L. Zhang, Y. Su, Q. Xuan, G. Li, H. Lv	An evaluation study of miniature dielectric crossed compound parabolic concentrator (dCCPC) panel as skylights in building energy simulation	A single-storey office building	Computer Simulation	- daylight performance - energy performance	- 14 different cities (Asia, Europe and America) - glazing type (standard double glazing (DB), double glazing with a dCCPC layer (dCCPC–DB) and double glazing with low-E coating and a dCCPC layer (dCCPC–LowE)) (dCCPC is the abbreviation for dielectric crossed compound parabolic Concentrator)	Daysim	_	lighting, cooling and heating energy consumption	Clear, intermediate and overcast sky conditions
2019	J. Cabeza-Lainez, J. M. Almodovar-Melendo, I. Dominguez	Daylight and architectural simulation of the Egebjerg school (Denmark): Sustainable features of a new type of skylight	single-storey classrooms of Egebjerg School in Denmark	Experimental and Computer Simulation	- daylight performance	_	Diana X	Lux meter	illuminance	clear, intermediate, and overcast sky conditions
2019	Y. Fang, S. Cho	Design optimization of building geometry and fenestration for daylighting and energy performance	A single-storey office building in USA	Computer Simulation	- daylight performance - energy performance	- three different cities (Miami, Atlanta, and Chicago) - skylight width - skylight length - skylight location - Skylight orientation - roof ridge location	- Ladybug - Honeybee	_	- lighting, cooling and heating energy consumption - useful daylight illuminance (UDI)	No sky condition is mentioned.
2019	K. S. Galal	The impact of atrium top materials on daylight distribution and heat gain in the Lebanese coastal zone	A 4-storey campus in the Lebanese coastal climatic zone	Experimental and Computer Simulation	- daylight performance - energy performance	- atrium top material (Low-E, Reflective, Tinted and Photovoltaics)	Design Builder	Data logger	- useful daylight illuminance (UDI) - special daylight autonomy (sDA) - annual solar exposure (ASE)	No sky condition is mentioned.
2019	F. Sher, A. Kawai, F. Güleç, H. Sadiq	Sustainable energy saving alternatives in small buildings	A 2-storey house in Osaka, Japan	Computer Simulation	- daylight performance - energy performance	with or without skylight	Ecotect	_	- lighting, cooling and heating energy consumption - daylight factor (DF)	overcast sky conditions
2020	A. Bugeat, B. Beckers, E. Fernandez	Improving the daylighting performance of residential light wells by reflecting and redirecting approaches	A 4-storey residential building in the five regions with different latitudes (Barcelona (41◦), Stockholm (60◦), Bilbao (43◦), Mexico City (19◦), and Quito (0◦))	Computer Simulation	- daylight performance	- wall surface reflectances - with or without installed mirrors on the light well top	Radiance	_	- daylight autonomy (DA)	No sky condition is mentioned.
2020	M. Rastegari, S. Pournaseri, H. Sanaieian,	Daylight optimization through architectural aspects in an office building atrium in Tehran	A 9-storey office building in Tehran	Experimental and Computer Simulation	- daylight performance	- well index - well width/well height	- Ladybug - Honeybee	Lux meter	- illuminance - daylight autonomy (DA) - useful daylight illuminance (UDI)	No sky condition is mentioned.
2020	Zh. Fan, Z. Yang, L. Yang	Daylight performance assessment of atrium skylight with integrated semi-transparent photovoltaic for different climate zones in China	A 4-storey public building in six cities of china	Computer Simulation	- daylight performance	- the area ratio of photovoltaic materials over the skylight glass	Daysim	_	- daylight autonomy (DA) - useful daylight illuminance (UDI)	No sky condition is mentioned.

As depicted in Fig. 13, the USA is the most popular selected location among the others. Most of these countries are located at higher latitudes (between 30-60 degrees), where the sun has a lower altitude angle than the regions at low latitudes (under 30 degrees). Therefore, results of these studies are more reliable in regions at latitudes of 30-60 degrees. Furthermore, in more than half of the studies, location has not been considered. And the lack of the attention toward the effect of micro-climate on daylighting is mostly observed. Atrium in cold climates can reduce energy use by decreasing heating load in summer; however, this may result in increasing cooling load in winter due to the heat leakage through the atrium walls. In addition, atrium in warm climates can increase energy use, since the uncontrolled and high-altitude sunrays can bring the risk of overheating especially in summer. This highlights the importance of climate to be considered in further investigations.

As demonstrated in Fig. 14, most of analytical methods have been both experimental and computer simulation with 29% rate. Secondly, computer simulation and experimental methods have been used with a rate of 27 and 25%, respectively. Rest of the methods (19%) include both formulae and experimental, analytical formulae, all three methods, and both simulation and formulae. In recent years, tendency to use computer simulation has increased because of emersion of different types of simulation and illuminance analysis tools, upgrading their capabilities, validating their results, and ease of use.

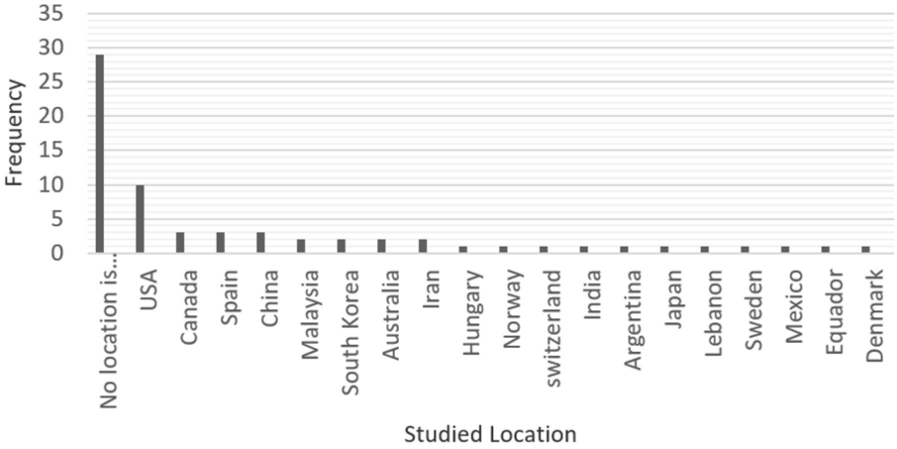

Fig. 13. Distribution of studies into locations

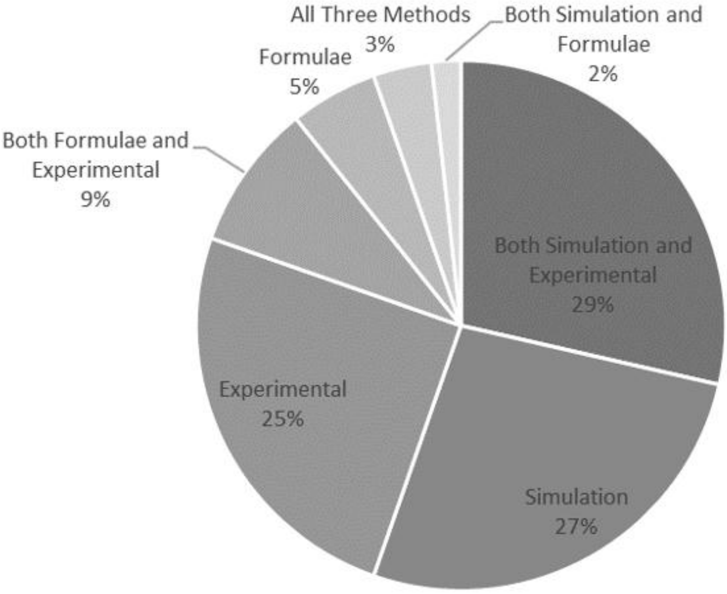

Fig. 14. Analytical methods used in the studies

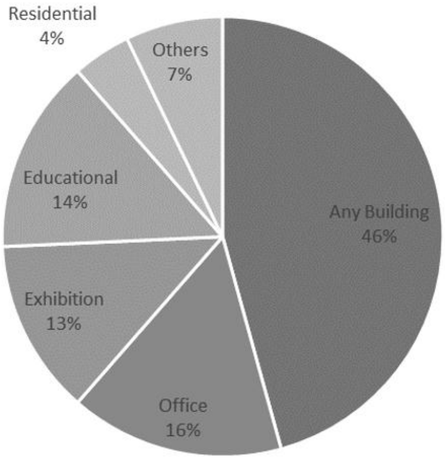

Fig. 15. Building types used in the studies

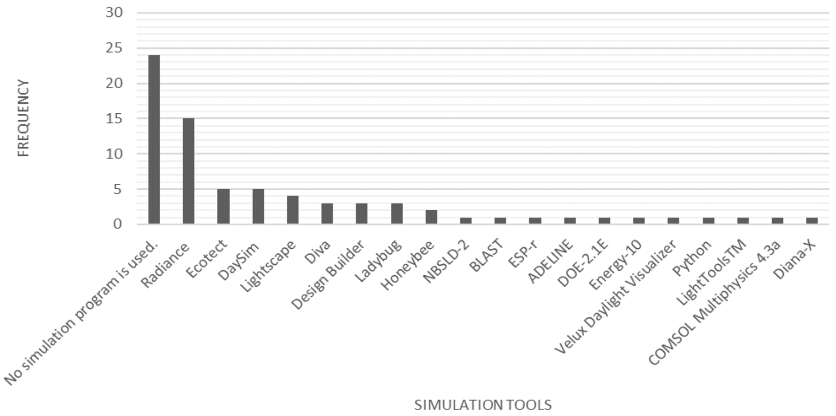

Fig. 16. Simulation tools used in the studies

As seen in Fig. 15, various types of building have been selected as case studies. Building type has not been mentioned in more than half of the studies. Furthermore, most of selected types of building are office buildings with a rate of 16%. Educational buildings such as schools, libraries, and universities have been studied with a rate of 14%. Most of selected buildings have public functions, which operate during the daytime, and have special lighting requirements. In these buildings, integrated space or a single space whose conditions and requirements were similar to those of other spaces have been usually analysed. In the meantime, residential buildings have been less analysed because they have various spaces with different functions that differ greatly in terms of the time of use and lighting needs. Due to land constraints in many residential buildings, some areas are inevitably illuminated by light wells, usually not providing adequate illuminance. Therefore, it is also necessary to analyse toplighting in residential buildings.

As indicated in Fig. 16, Radiance is the most extensively used simulation tool with 35% rate since 2004. Secondly, Ecotect, Lightscape 3.2, DaySim 3.1, DIVA, Design builder, Honeybee, and Ladybug have been used mostly after Radiance. It is worth mentioning that Honeybee and Ladybug are new programs with high accuracy and capability.

As seen in Fig. 17, among indices used for assessing the quantity of light, DF and illuminance are the most used indices for daylight analysis of toplighting. Secondly, skylight Well Efficiency (WE), Daylight Autonomy (DA), Useful Daylight Illuminance (UDI) and Spatial Daylight Autonomy (sDA) have been investigated mostly after DF and illuminance. According to Table 2, just three studies used seperately luminance, daylight glare probability (DGP) and Annual Sunlight Exposure (ASE) indices for assessing glare. It should be noted that, the use of DF and illuminance has decreased in recent years. DF and illuminance have some noticeable limitations. They cannot properly represent non-overcast sky conditions; maximizing them means to receive daylight as much as possible, which can result in overheating (Cantin and Dubois, 2011); and orientation of a building is not considered in DF calculation (Mardaljevic et al., 2009). Therefore, newer indices providing closer results with visual comfort levels are recommended. To achieve an acceptable daylight performance, UDI is suggested to be more than 50%. According to LEED assessment, to provide visual comfort, and reduce overheating and glare problem, sDA must be higher than 50% and ASE must be lower than 10% (USGBC, 2017).

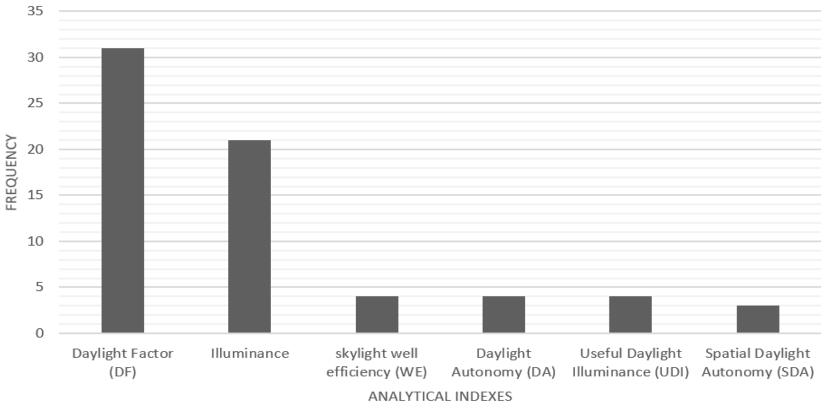

Fig. 17. Analytical indices used for assessing the quantity of light

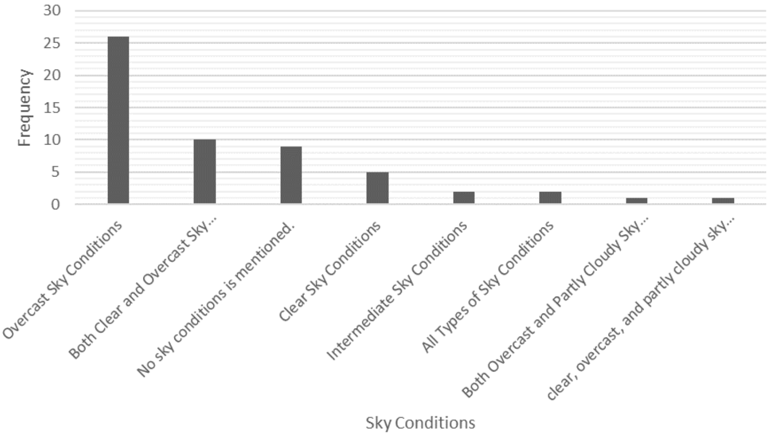

Fig. 18. Sky conditions used in the studies

As seen in Fig. 18, studied sky conditions are clear, intermediate, overcast, and partly cloudy. In some studies, more than one sky condition has been investigated. Overcast sky condition has been mostly used in order to provide the worst situation of daylighting. Secondly, both clear and overcast sky conditions have been used in order to compare the worst and the best situations.

5. Conclusion

In In this paper, a review of the studies on daylighting from the rooflights, influential design parameters of rooflights (type, configuration, and material), and interior spaces (configuration and surface reflectance) was presented. In this review study, an explanation was provided on how these parameters can be utilized and improved to provide a better daylight performance from toplighting. In addition, the methodology of reviewed studies was demonstrated.

Review of 64 papers about toplighting identified from ISI journals presented substantial conclusions that are useful for researchers and designers. Major findings are as follows: In case of types of the rooflight, the monitor roof had the best result, and the skylight provided the highest illuminance levels but had overheating problem. Few studies investigated ratio of rooflights to interior dimensions, so comprehensive investigations are needed. In these studies, few types of materials have been investigated for rooflights, while there are various advanced transparent materials such as prismatic glass, daylight redirecting glass, solar control glazing, and so on. It should be noted that, most of these studies have been carried out in the countries at higher latitudes (30-60 degrees), so these results are not reliable for low -latitude regions. Therefore, it is necessary to evaluate design parameters and daylight performance of toplighting at low latitudes in future researches.

According to the literature, unequal illumination of interiors is a significant problem in the field of toplighting. Therefore, upper levels of the atrium may be overlit, and lower levels may be underlit. Limited use of rooflights at low latitudes because of high solar gains is another problem. Therefore, it is important to propose and investigate innovative approaches such as reflectors, materials, and dynamic strategies in order to transmit, redirect, and prevent daylight into the spaces. Furthermore, the most used indices like DF and illuminance only determine daylight levels while excessive daylight is unpleasant and may cause glare problems. Thus, more cohesive researches on rooflights are also required to consider other factors such as thermal loads, ventilation and glare with consideration to the location of the building, solar altitude and micro-climatic conditions.

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