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Daylight Transport Systems for Buildings at High Latitudes

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Abstract

This paper is a literature study of daylight transport systems aiming at selecting the most appropriate ones for application at high latitudes. It is limited to the systems that transport light at a long distance from the façade and distribute it either in the building core or at a rear place in a room adjacent to the façade. The literature is spanning from the 80s' to the present. It covers the theoretical background and development of the systems from their infancy, through technical development of the design elements and to the adaptation of the systems to different climatic conditions. Since the most literature comes from equatorial and tropical climate, a short contextualization with high latitudes climate is included. Findings are systematized and presented in tables for easier comparison of efficiency, visual comfort, design efficacy, maintenance need, cost and/or availability on the market, and energy-saving potential in different climates. Conclusions confirm that the daylight condition at the location is the main prerequisite when deciding on the type of collector while the building structure and room functionality are the basis for choosing the type of the transport element. Finally, the distribution element showed to be the key factor when discussing applicability in a functional space where the final success depends on human acceptance. This paper can be useful to get an overview of performance characteristics and application preferences of different daylight transport systems or just their components in daylight conditions at high latitudes.

1. Introduction

The demands for energy saving in newly constructed buildings, set by authorities, are systematically increasing. Nowadays there is a passive-house level for all the new buildings, but there have been many political signs about the demands for Zero-energy buildings (ZEB) starting from the year 2020, for residential and commercial buildings. This means that the building (or its site) must provide itself with energy.

Lighting can use just electrical energy while all the other technical systems can use some of the alternative sources that could be renewable or energy-efficient. Electrical energy demands for lighting in buildings could be solved with PV panels usually placed on the roof of the building. However, according to the Norwegian research project "Klima 2050", higher precipitation is expected in Scandinavia soon, because of climate changes. This implicates recommendations for the design of "green roofs". Green roofs help damper floodwater in cities and help reduce the load on the sewage system, thus allowing the design of lower capacity. This further means that it will no longer be possible for solar panels to be placed on roofs in the quantity that could solve all energy requirements. Moreover, it is also widely considered that PV panels are a ''renewable source of power to lighting, but this is wrong as they are just a convertor of the energy with extremely high CO2 footprint [1]. That is why it is important to focus attention on finding a renewable alternative for lighting, for example by providing possibilities to the increased use of daylight. More daylight provided indoors could reduce energy demands for lighting.

High latitude locations are characterized by low sun angles, and the necessity for sun-shading devices for visual and thermal comfort is strong [2-4]. Several studies addressing visual comfort in office buildings at high latitudes show the need for special attention when designing sun-shading devices, not only for low solar angles to balance daylighting and thermal load, but also for the unyielding need of users for manual control of sun-shading devices [5-8]. The practice and research have shown that user-controlled sun-shading devices are often the cause of radical reduction of daylight availability during the day, where daylight contribution through the window is, then, very much dependent on the weather conditions and a single-user personal judgment [9,10]. Daylight transport systems give the possibility to deliver daylight

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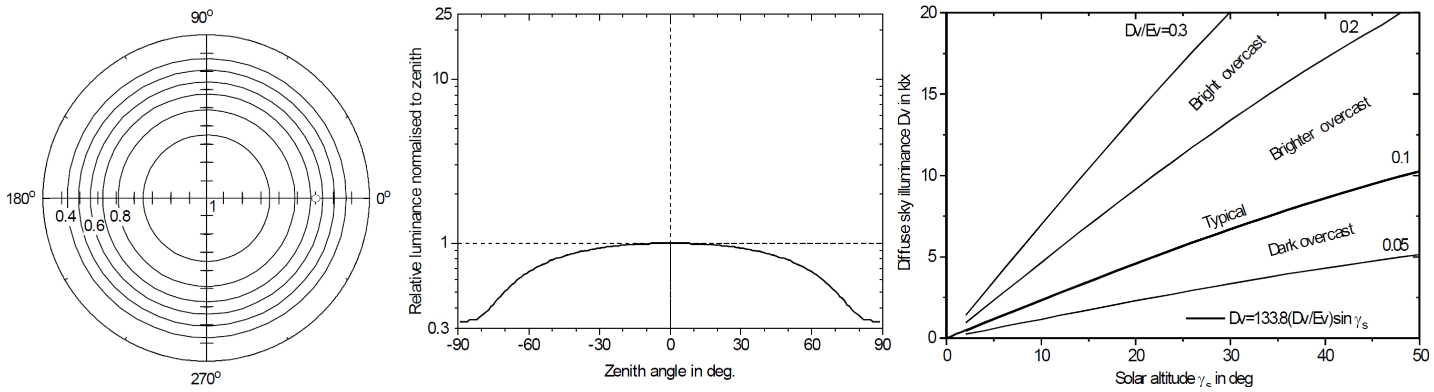
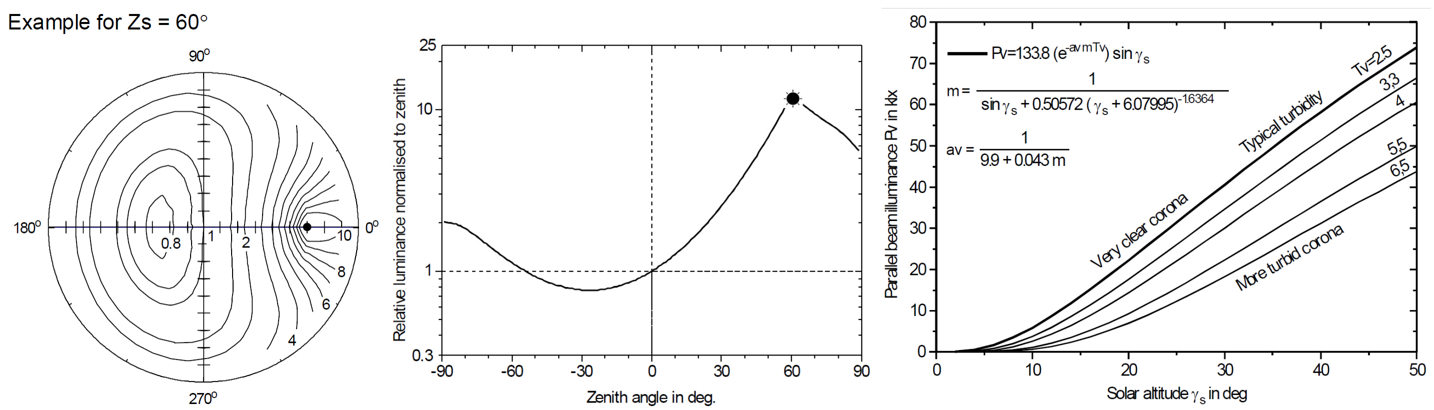


(a) (b) (c)

Fig. 1. Sky model I.1. Overcast sky with steep gradation and azimuthal uniformity, (**a**) Isoline graph e.g. Zs=60°, (**b**) Sky profile in solar meridian, (**c**) Probable diffuse horizontal illuminance Dv under this sky model [14].



(a) (b) (c)

Fig. 2. Sky model V4, very clear/unturbid sky with a clear solar corona, (**a**) Isoline graph for e.g. Zs=60°, (**b**) Sky profile in solar meridian, (**c**) Probable direct solar horizontal illuminance Pv under this sky model [14].

into the room independently on solar radiation control and could make daylight presence indoors more reliable. Any contribution to the daylighting in the deeper space is advantageous. In building cores and rooms without windows as low as 50 lux is a satisfactory level that makes significance for a feeling of daylight presence [11]. Prolonged daylight availability indoor could decrease energy demands for artificial lighting and increase the benefits to the human circadian system.

The primary goal of this literature review was to select daylighting systems suitable for buildings at high latitudes. In the context of this study, it means latitudes higher than 55 degrees. This is important since e.g. the office buildings use almost 40% of energy for lighting, other building types, as commercial or industry even more. The diurnal function for office buildings (9h-17h) corresponds very well with daylight hours. For winter months (the case of Oslo 59N) daylighting hours are from 09 h to 15 h, while for summer months, the daylighting hours are from 04 h to 23 h. This gives notice on systems' applicability for many other functions (e.g. industry, healthcare, sports and recreational buildings, and educational and cultural facilities). The last chapter brings a discussion about the results of the literature review and conclusions about applicability for high latitudes.

There are many benefits of using advanced daylighting systems. "*It increases usable daylight for climates with predominantly overcast skies, increases usable daylight for very sunny climates where control of direct sun is required, increases usable daylight for windows that are blocked by exterior obstructions and therefore have a restricted view of the sky, and Transport usable daylight to windowless spaces*" [12]. Specifically, deep plan offices, corridors, staircases and other core rooms that require lighting during the day can, without a doubt, benefit from advanced daylighting systems. The potential of many of the daylight transport systems was scientifically proven, and they are mentioned in the overview of the daylighting technologies reviewed in the IEA task 21 [12,13].

2. Sun and sky conditions

Literature review reveals that the majority of studies were done in tropical and European maritime climate. The climate in tropical countries is characterized by high sunshine, high humidity, and very frequent cloudiness and rainfall. The exterior illuminance can rapidly decrease from 100000 lux to 20000 lux. High humidity brings light scattering in the atmosphere so even the clear sky has a considerable amount of diffuse light, about 20%. The average yearly sun hours are 2350, which is 55% of the maximum (4476 hours), according to Weather-and Climate site. Nevertheless, the percentage of sunny skies just passed 50%, the research on daylight transport systems in tropical areas mostly dealt with clear and sunny skies, while the studies in the European maritime region

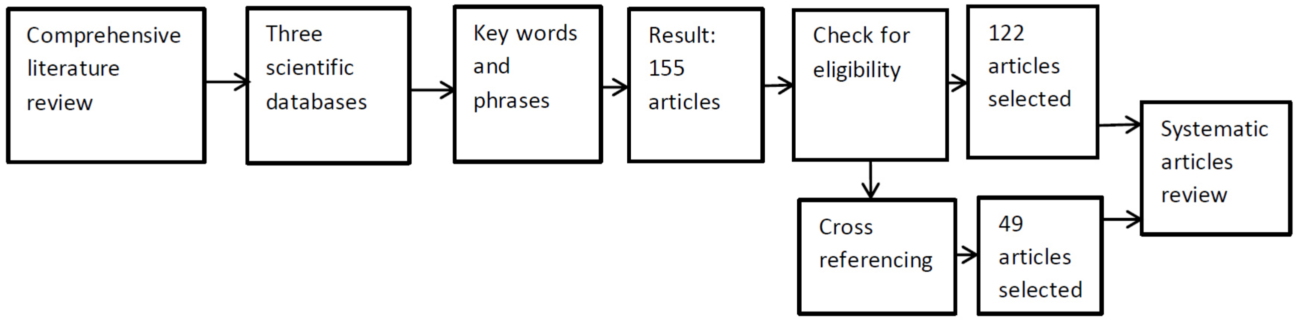


Fig. 3. The review methodology in stages.

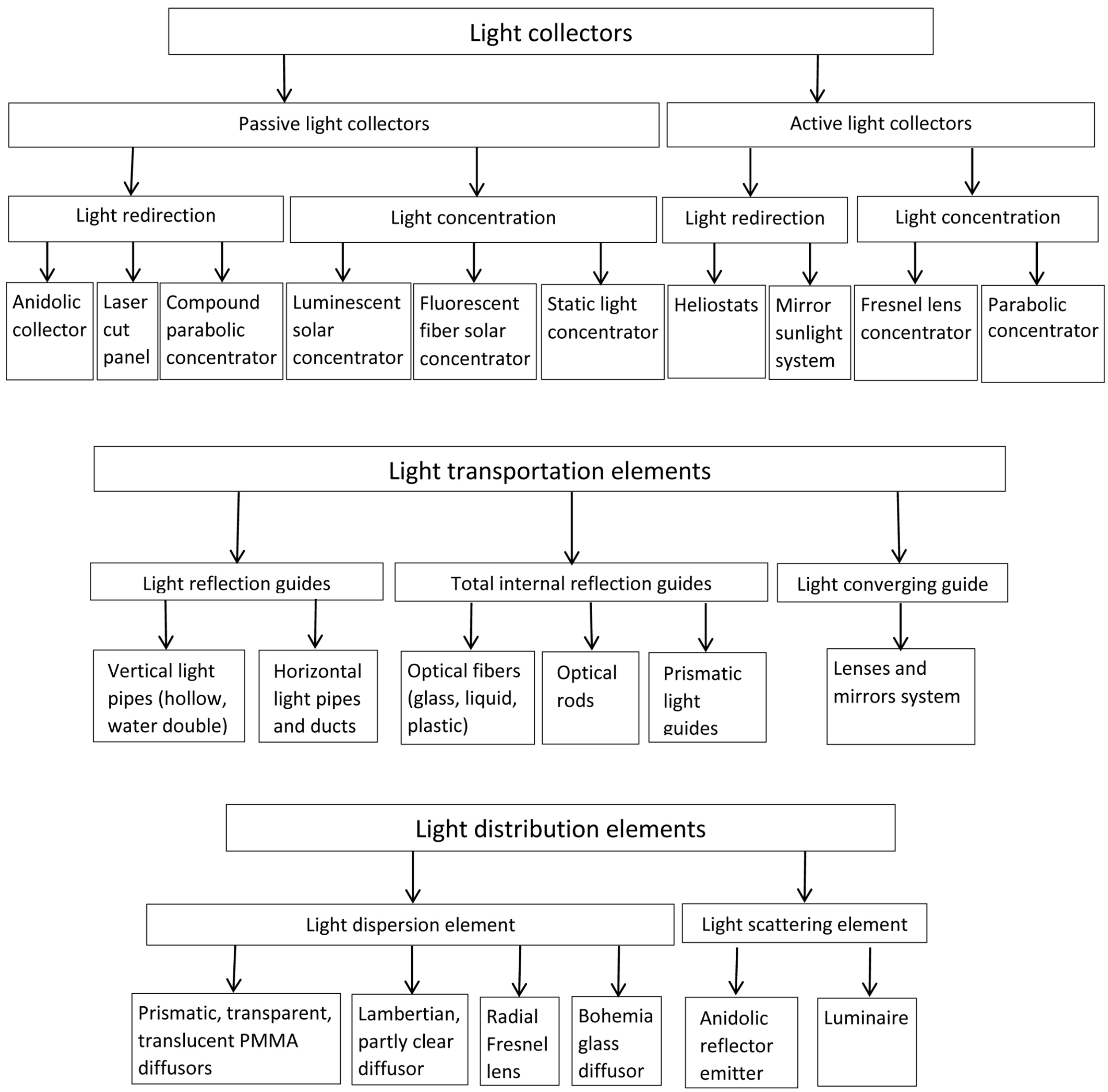


Fig. 4. Overview of the elements in the daylight transport system; blue and pink indicate often combined components.

solely addressed the overcast sky. The conclusions given in the papers about the potential of application for different components in the high latitude regions, based on the research, are too general and more detailed ones need to be drawn based on realistic daylight conditions for almost every region.

Interestingly, in the rather low populated Northern Europe, three capitals (Oslo, Stockholm, and Helsinki) and other large towns (Bergen, Orebro) are located close to 60° N; giving motivation to study the potential for daylight harvesting at high latitudes, at least higher than 55°N (Copenhagen). The climate of the south part of Norway (58° – 62°) is classified as a humid continental climate. There are 1632 hours of sunlight per year (37.2% of day hours), which means on average 4:28h of sunlight per day. The remaining 62.8% of daylight hours are likely cloudy or with shade, haze or low sun intensity, according to the Norwegian Meteorological Institute. At midday, the sun is on average 30.5° above the horizon at Oslo (the lowest 7° in December and the highest 53° in June).

According to Satel Light data and Geophysical Institute, University of Bergen, Norway, predominantly overcast sky type, in the targeted area of 60° N, corresponds to the sky standard type I.1, while clear sunny sky conditions correspond to the sky standard V.4 [14]. When solar altitude is 10° for bright overcast sky (type I.1.), the exterior diffuse horizontal illuminance is 4650 lux, while for solar altitude 50° is 20500 lux, calculated from Dv=133,8×Dv/Ev sinα, Fig. 1 [14]. This result indicates the possible expected illuminance intensity and it helps to choose the right collector type and its design properties. When the solar altitude is 10° for clear sunny sky with very clear corona (type V.4; Tv 2,5), parallel normal illuminance Pv is 9468 lux, while for the solar altitude 30° it is 42000 lux, calculated from the Pv=133.8 (e^{-avmTv}) sinα, Fig. 2 [14].

3. Daylight transport systems

The literature review covered scientifically studied components and available market systems. The review started with a repeated search in the following online data bases: Google Scholar, ScienceDirect and Scopus. The following keywords were used: daylight, light, pipe, fiber, rod, system, and phrases: lighting rod, fiber optical system, mirror light pipes, daylight shading system, daylight guiding system and daylight transport system. The literature search resulted in 144 articles, 22 of which were excluded and 122 were selected as eligible. Those articles gave the second set of articles via cross-referencing. The majority of second articles were older than two decades, but they were selected as eligible since they covered the innovation issues - patents or theoretical background of the main topic. Included patents also show that the first ideas of daylight transport in buildings were not solely initiated by the energy crisis but were triggered by the need for cheap and quick rebuild in the after-war period. The search was done in September 2018 and the updated search was done in September 2019. The review methodology is presented in Fig. 3.

A systematic review of the selected scientific articles showed that all light transport systems consist of three elements: a) a light collector, that collects diffuse and/or direct sunlight; b) a light transporting element, which allows light propagation inside itself; and c) a light distributor that extracts the light, and delivers it into the space [15]. An overview of the elements in the daylight transport system is presented in Fig. 4.

3.1. Light collectors

A light collector aims to collect light and convey it to a specific point or direction. Light can be concentrated or redirected through passive or active light collectors. Passive light collectors are fixed in one position, usually the best-suited place according to design prerequisites, and they rely on predominantly light-incident conditions. Active light collectors rely on the highest light intensity source and its beam directionality. Active collectors have a fixed position in the place, but their light concentrator moves through a single or double axis and follows the direct normal component of the light source to efficiently convey the light.

3.1.1. Passive light collectors

Passive light collectors are fixed elements placed in a certain position outdoors to enhance light collection. Since their position is fixed, they mostly rely on the permanent light conditions, such as sky illuminance, and occasional direct sunlight incident on a collector's entrance. With the exception of flat glass [16] or dome [17,18] that (1) transmits light almost without changing its

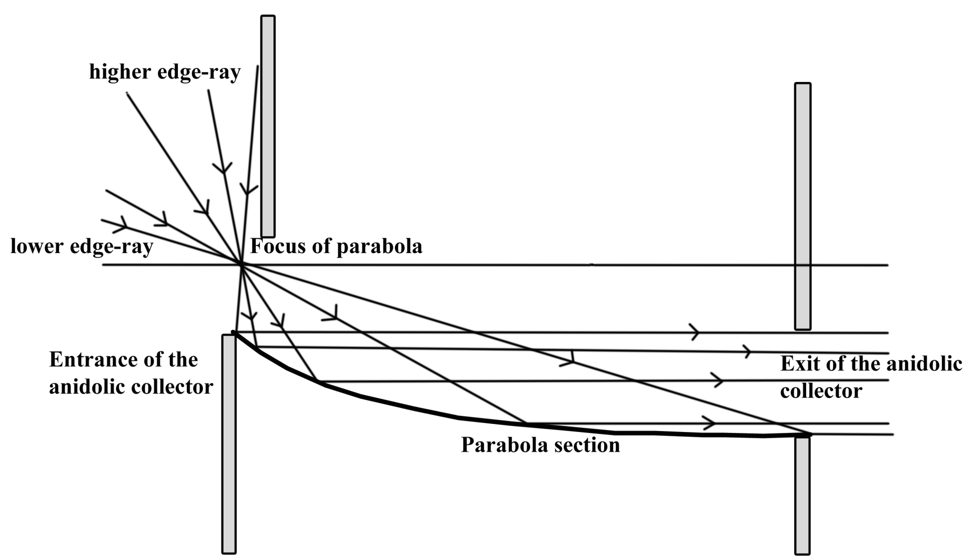


Fig. 5. Schematic view of an anidolic concentrator based on the edge-ray principle [27].

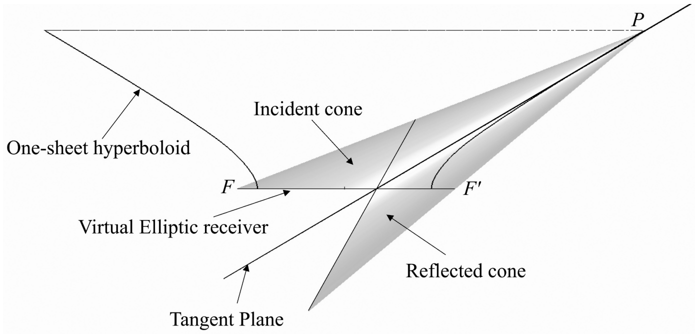


Fig. 6. Hyperbolic concentrator, incident cone, reflected cone and tangent plane [19].

direction, the light is (2) reflected on an anidolic concentrator or hyperbolic concentrator [19], (3) refracted by the prismatic film in CPC [20], (4) deflected by laser cut panels (LCP), or (5) absorbed by a fluorescent fiber solar concentrator (FFSC) or a luminescent solar collector (LSC). Some active solar collectors were also studied with a fixed position (passive collection) [21,21].

3.1.1.1. Anidolic concentrator

This is a highly reflective element, composed as a compound parabolic concentrator (CPC), where the edge light rays' principle of acceptance sector is used [23]. It can be constructed as a 2D element, or as a 3D element rotating around its symmetry axis. Anidolic concentrator works on a non-imaging principle of light reflection, where all the incident light on an aperture entry (in the edge rays span as minimal-low to maximal high) is reflected and redirected towards the aperture's exit, Fig. 5 [24]. The concentrator was simulated for the CIE overcast sky and experimentally tested in winter weather conditions in Switzerland, where authors concluded that the admission sector of anidolic collector should match the visible part of the sky [25-27]. Experimental results show energy-saving potential of up to 31% compared to the reference room and additionally better visual comfort, improved uniformity and less contrast, as well as better results in human performance tests (string reading test according to Hygge and Löfberg, [28]) [29-31]. An asymmetric hyperbolic concentrator was developed based on non-imaging optics to contribute to the non-tracking solar applications. This design shows almost 100% of ray transmittivity for incident angles of up to 60°, and it could be used for collecting visible radiation too, Fig. 6 [19].

3.1.1.2. Laser-cut panel

Laser-cut panel (LCP) is a transparent acrylic panel with laser cuts which act as a reflection surfaces for light rays refracted inside the panel. The incident light on a panel is redirected as output light in the desired direction, according to the specific D/W (distance to width) configuration of the LCP [32-34]. It was proven that 90% of light is deflected, 8% of light is reflected from the panel, while 2% of light is passed through (undeflected), Fig. 7. For non-inclined cuts, there is a unique incident light angle and D/W configurations that result in the highest light deflecting ratio Fig. 7(b), while for inclined cuts there is a span of incident angles for the same D/W configuration which results in the highest light deflecting ratio, Fig. 7 (c). Inclined cuts are thus more appropriate for variation in incident light angle, such as altitude variation during the day, because the output light-angles span will be more narrowed and suited to the aimed propagation in a desired angle. LCP is very effective in redirecting both direct and diffuse light if placed as a collector for the daylight transport system [35-37]. Simulated and proven studies were conducted for LCPs placed on the east and west side for horizontal light pipes in tropics [38,39]. It was also suggested that LCP can track the Sun's azimuthal movement to enhance light collection [35,40], still, the greatest usage for LCP is as a passive shading and daylight enhancer for windows since it provides the outside view [12,41,142].

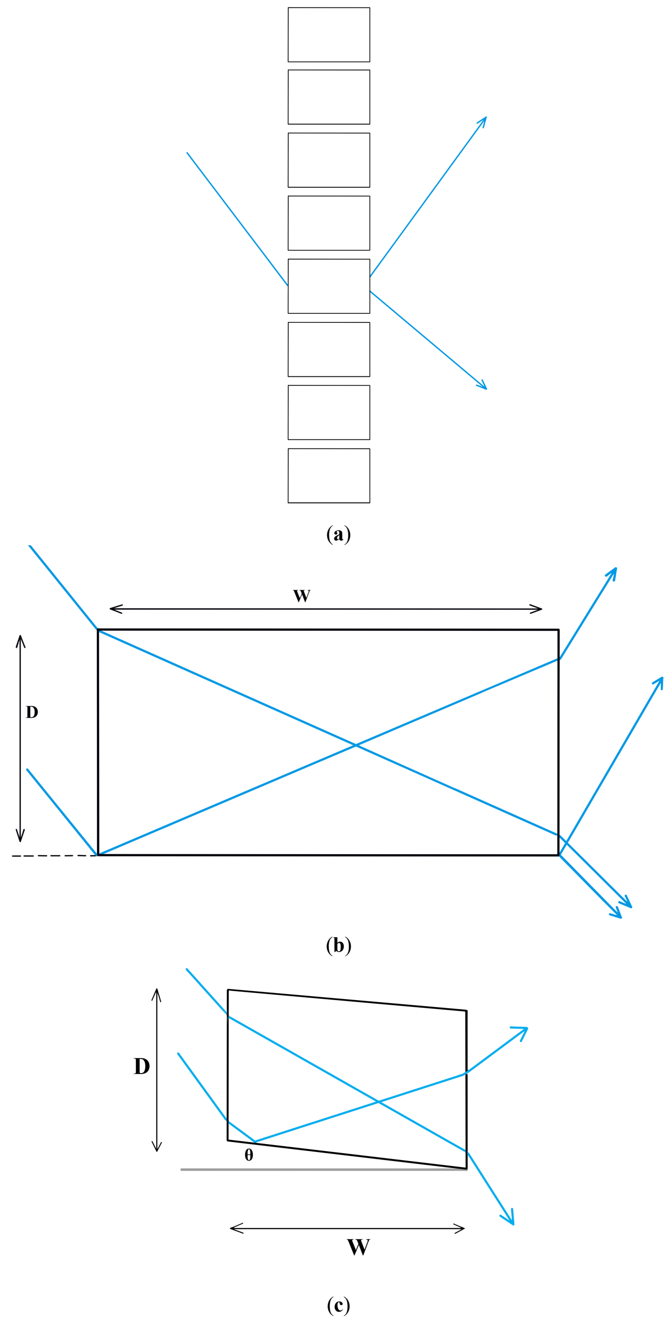


Fig. 7. (**a**) A laser-cut panel produced by dividing a clear acrylic sheet into rectangular elements with a laser cutter, (**b**) a fraction of light incident on an element is deflected by refraction and total internal reflection, and (**c**) light deflection through an inclined cut [32].

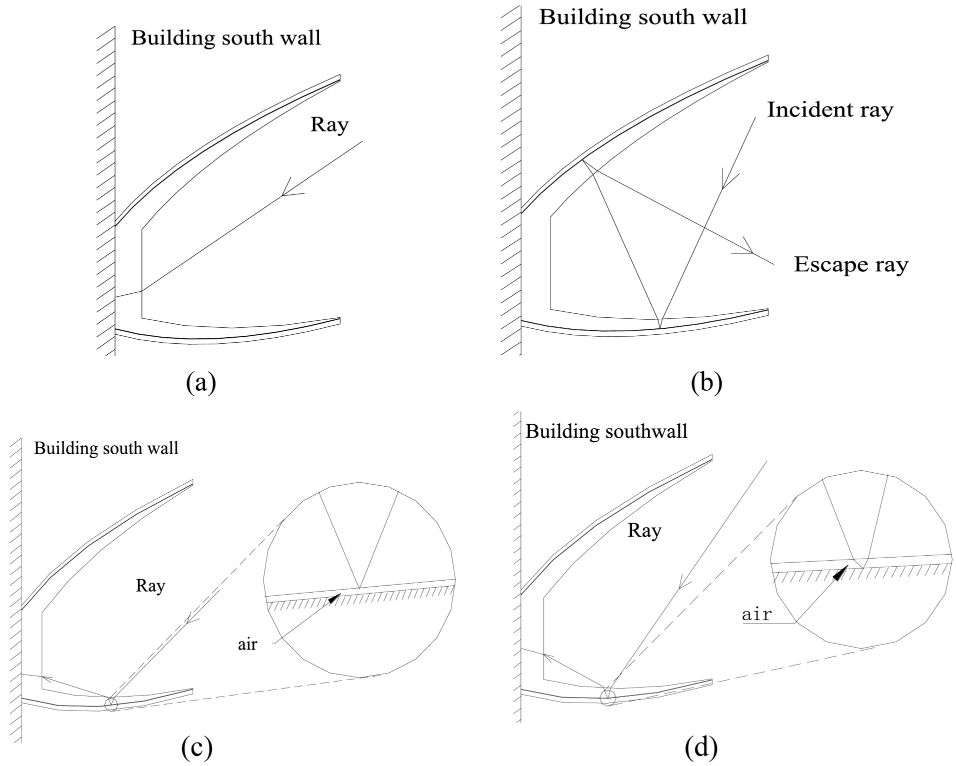


Fig. 8. (**a-d**) diagram of four kinds of ray paths in asymmetric lens-walled CPC [45].

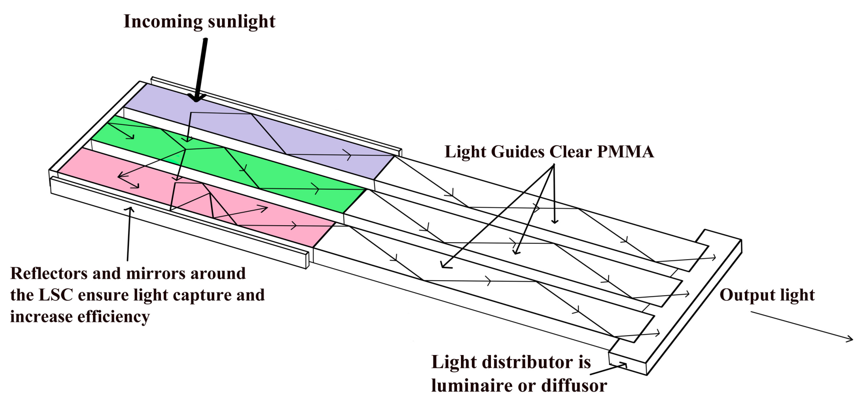


Fig. 9. Schematic of three-color LSC stack connected to light guides and luminaire [48].

3.1.1.3. Compound parabolic concentrator

Modified compound parabolic concentrators were also studied to be integrated into the building south façade and to primarily collect direct sunlight. Compound parabolic concentrator lined with prismatic film has the potential for light collection about 6 times higher than the Aluminum lined one, because of the light incident possibility also through the body of the concentrator [20]. Truncated CPC was developed as a rectangular array CPC collector in the ADASY daylighting system for the offices [43,44] Asymmetric lens-walled CPC was developed to concentrate solar radiation to increase incident energy on BiPV placed on the south façade Fig. 8 [45].

3.1.1.4. Luminescent solar concentrator (LSC)

It was developed as a three color PMMA stack dyed in pink, green and violet luminescent dye. Luminescent quantum species absorb solar photons entering the stack and reemit them in random directions, where light propagation is secured by a total internal reflection inside the stack [46,47]. An experimental study, with prototype stack, 13.5 cm thick and 1.2 long, recorded 1000 lumen delivered output light from 100 000 lux of the exterior illumination. Since the system needs UV blocking to lengthen the lifetime of the violet dye, the luminous efficiency was increased up to 311 Lum/W, consequently, the output light color was white greenish [48]. This collector does not concentrate light to convey it to the transport element, but it is a collector and transporter in one, Fig. 9.

3.1.1.5. Fluorescent fiber solar concentrator (FFSC)

As LSC did not provide a solution for light concentration, an experimental study aiming at getting point-on-light concentration for fiber optics was conducted [49]. This collector consisted of 150

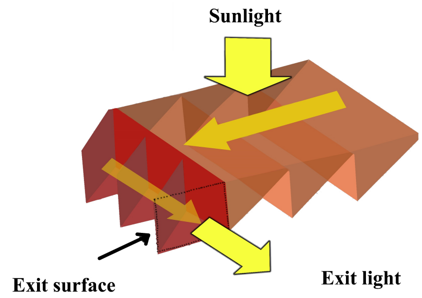


Fig. 10. Sunlight path in a static light concentrator [50].

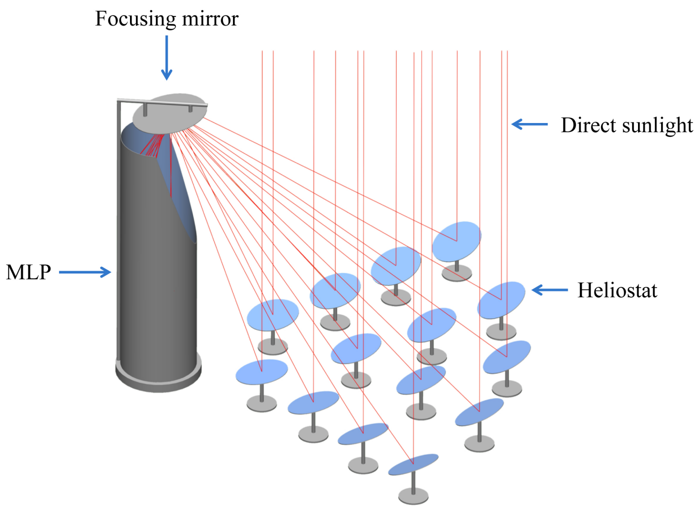


Fig. 11. Heliostats capturing and focusing sunlight into the mirror light pipe [51].

fibers of three luminescent colors (yellow, red and green), placed on a PMMA plate with a reflecting underlay to increase light absorption. Every fiber had quantum dots seeded in them to absorb solar photons and re-emit them with light propagation according to the total internal reflection inside the fibers. Point-on-light concentration was achieved at the end of the fibers where light transport fibers were connected by UV glue.

3.1.1.6. Static light concentrator

Static light concentrator was developed by a group of scientists in Taiwan, to collect, focus and direct light [50]. It is a combination of different prisms in array to create cascading units, Fig. 10. It was reported that, as a passive collector, it improved the total collected sunlight energy and that it could create a uniform light distribution.

3.1.2. Active light collector

Collectors that work on collecting the direct light beam are called active, based on a fact that they constantly track the source of direct light beam – the sun, for their best performance. Light is (1) collected and conveyed further to the transport element by light redirection, for heliostats, and mirror sunlight systems, and by (2) light concentration for Fresnel lens and parabolic concentrator. The tracking system for active light collector is the most important part, which works on a high degree of tracking accuracy to ensure system efficiency. The tracking computer adjusts the position using open or closed-loop algorithms and the sun tracking photo-sensors or satellite data for solar altitude and azimuth for a specific location [52]. Tracking systems are power-operated mechanical devices, which is why they easily wear off and they are expensive [22]. A single-axis passive tracker, which used solar thermal power to operate, was developed and studied [53].

3.1.2.1. Heliostats

Heliostats are single or multiple planar mirrors that track the sun's position by computer and reflect sunlight to redirect it into another optical element, lenses, mirrors or directly in the light tube. They have been used with the Fresnel lens in the Artelio project [54], and in a multistory office building in South Korea with the vertical mirror light pipe [51,55], Fig. 11. This collector type was used as a proposal for the staircase of the Semperlux building in Berlin to collect daylight and to guide it along with the prismatic hollow light guides [56]. Heliostat mirror is suggested for fiber optical systems for high latitudes location as sunlight redirecting and concentrating device placed on a south facade [57].

3.1.2.2. Mirror sunlight systems

Mirror sunlight systems usually consist of a single or several mirrors and are available from many different manufacturers. They are used to reflect and redirect sunlight into the spaces that sunlight never reaches, or where daylight level is very low because of too high obstacles. Kim and Kim reported an applied usage of those systems, known as Heliobus, Natulite, T-Soleil, Kuzelka, usually in dense city centers [58,59]. There were reported results on testing the different mirror sunlight systems to conclude on energy saving potential [58,60,61].

3.1.2.3. Fresnel lens concentrator

Fresnel lens, first developed in the 17th century, has been used in many forms with different optical principles for the concentration of solar energy [62]. In the form of a thin and lightweight lens it was developed by the Japanese inventor Dr. Mori, to be used as a light-concentrating lens for Himawari fiber optical system [63,64]. Fresnel lenses of different dimensions and shapes (square and circular) have been used mostly for concentrating direct sunlight into fiber bundles [65] or in a combination with funnel-like concentrators [66,153]; as a multi-lenses system [67,68] or to concentrate solar radiation into PV cells [69], Fig. 12.

The issue of uniform acceptance of concentrated light into the fiber bundle was treated using the secondary convex, biconvex, concavo-convex or plane-concave lens, to spread bundles of fiber and use them into separate locations [70,71]. Fresnel lens as a light concentrator generates the need to filter out heat from the concentrated radiation.

3.1.2.4. Parabolic concentrators

Parabolic concentrator for collection and focusing of light was first used in Fries's invention of the fiber-optical solar lighting system [72], but the origin of the parabolic collector dates from the antique where it was called ''burning mirror'', and was used to collect solar heat [73]. Parabolic concentrator is mostly used for fiber-optical systems as a primary optical element (POE) that focuses light into the secondary optical element (SOE) that is supposed to redirect the focused light into fiber and filter out UV

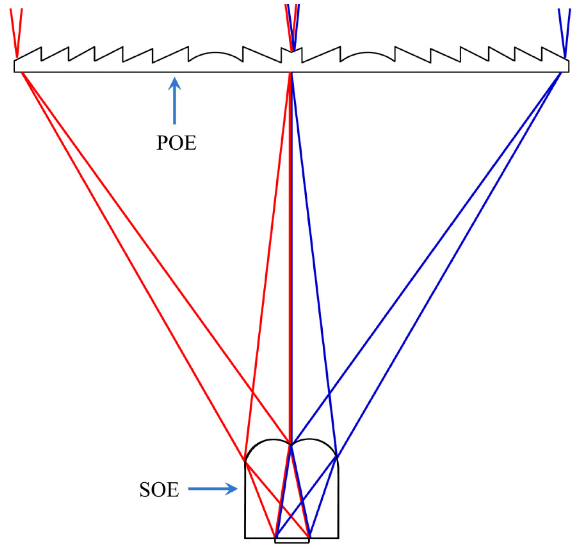


Fig. 12. Schematic showing the edge-ray mapping in an ideal Fresnel concentrator [69].

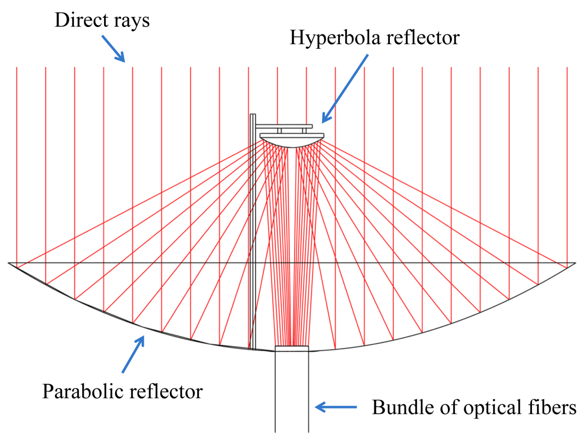


Fig. 13. Light concentrating principle in an ideal parabolic collector [71].

and IR radiation, Fig. 13. The primary parabolic collector can be circular with a focus point [70,74], or rectangular, called parabolic trough, with a focus line [75,57,68]. Secondary optical element was a topic for many studies, where a convex ''cold'' or ''warm'' mirror was used [72,70]. Sapia studied special made cold mirror made of SiO_2 and TiO_2 [76].

3.2. Light transport element

The light transporting element guides light to a remote place where it is to be exported. Light propagates in the guide by (1) multiple specular reflection (mirror light pipe), (2) total internal reflection (solid guides made of PMMA, glass or liquid in form of optical fibers, rods, and hollow pipes), or (3) light convergence (system of lenses and mirrors).

3.2.1. Light reflection guide-pipes

They are defined as transporting devices used to distribute natural or artificial light into a remote space. In daylighting applications, they can also be called sun pipes, solar pipes, light or daylight pipes depending on their position in the building [77], Fig. 14 and 15. Those elements have a role to provide effective internal light reflection and are coated with highly reflective materials like silver, aluminum or 3M [78] and dielectric [79] films, which approach reflection of 99%. Light transmittance (efficiency) of the pipe depends on its Diameter to Length ratio called aspect ratio. It was reported that the optimal aspect ratio is up to 1/10, while its maximal value should be up to 1/20 [80]. The low aspect ratio increases the number of internal reflections and affects output light. It was recorded that silver coatings, after many interreflections, change light to reddish and more reminiscent to halogen light, while aluminum coating changes it to bluish and reminiscent to a fluorescent light source, while Ra- color rendering index was much higher for silver coating. Efficacy was in order 81% and 66% respectively [81]. To address designing and decision-making issues for usage of light pipes daylight penetration, factor (DPF) was developed and introduced to supplement to well-adopted daylight factor (DF) [82-84]. Recent experimental studies conducted worldwide, addressing the comparison of different light pipe configuration, lead to a conclusion on energy saving potential in many specific local solar climates [85-95].

3.2.1.1. Vertical sun pipes

Vertical sun pipes are highly reflective hollow pipes and have been used to transport primary direct sunlight [77]. They are mostly tubular, i.e. with circular section [96-98], but other shapes have been studied as well; e.g. triangular [99] and rectangular [47,26]. Bended light pipes have been studied for both direct and diffuse light concluding that for the angled entrance part, accumulated yearly light output was higher than for the straight pipes due to the larger sun-facing area [100], but bends in pipes body inside the building should be avoided due to the increasing number of interreflections and decreasing efficiency [83,101,102]. Many theoretical and experimental studies addressed different pipe configurations aiming to find calculation models [103,95,104-111], resulting in more information on weather and design parameter dependence. Vertical light pipes give high and excessive luminous output when Sun's altitude and azimuth are nearly axillary and beam light propagates with minimal interreflections, while diffuse skylight gives uniform luminance with homogenous output during the daylight hours. It was recorded that daylight penetration factor for cloudy and clear sky was: 0,14% - 0,16% and 0,08 - 0,22% respectively [89]. This gives indications about the uniformity of the delivered light in the room and homogeneity of the light illuminances during the whole daylight period. Studies for overcast sky during winter, with 10 000 - 40 000 exterior lux, show up to 30% energy saving potential in a room with 350-500lux lighting demand [112-115].

Water filled light pipes were reported as efficient light guides with 20% light transmittance after 10m length. Due to the water's spectrally selective absorption of IR and the red part of the visible spectrum, the color of the light is bluish, and the luminous efficacy is 296lm/W because of IR and UV filtration [116].

Double light pipes were used for a building preservation case in architectural heritage. The double pipe consisted of an internal mirror pipe and the external transparent acryl tube for light deflection and transmission [117,118]. The authors studied luminance output for overcast and intermediate sky conditions concluding similar distribution of light in both cases, thanks to

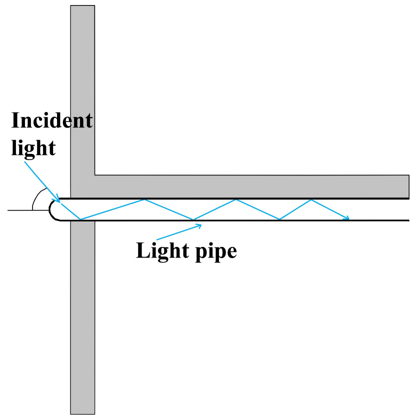


Fig. 14. Light guiding principle in horizontal light pipe.

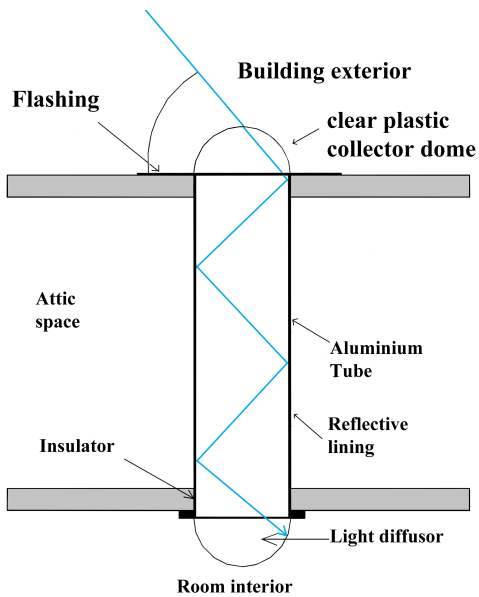


Fig. 15. Light guiding principle in vertical light pipe.

optical luminous film (OLF) used on the acryl tube, but drastically decreasing uniformity for increasing external illuminance.

Light pipe coated inside with dichroic material, which reflects 95% of visible light and transmits IR to the heat-generating component, was also studied [119]. This design showed the potential for the zenithal sun-pipes in hot climates in compound technology for natural ventilation since the extracted heat can help natural ventilation force.

3.2.1.2. Horizontal light pipes

Horizontal light pipes were first used to provide direct sunlight from the east and west in the tropics, because of the heat gain issues with vertical pipes [38,120-123,92]. They were also used to provide diffuse skylight in high latitude areas with predominantly overcast sky [124]. Horizontal light duct, with a rectangle section, was used as a custom-made solution in studies addressing anidolic collector and laser cut panels [37,38], or in studies dealing with light extraction elements [125,16,38]. Evaluations of analytical models for straight and bent horizontal light pipes were done to compare the results with experimental measurements [126,127]. The result was that the luminous efficiency of the horizontal pipes is dependent on its orientation to solar azimuth variation during the day or the year [120] and for solar altitude [39]. The study on energy savings for anidolic collector and horizontal light duct, for Singapore and UK, shows higher daylight autonomy and energy saving for overcast sky conditions (21% and 26%, respectively) then for the clear sky [128]. Similar studies showed up to 20% of energy-saving potential for direct light beams in Los Angeles [123,122].

3.2.2. Total internal reflection guides

Total internal reflection light guides convey the light that had an incident within a certain acceptance angle and that are reflected inside the guide on the boundary with the lower refractive medium. Transparent polycarbonate, acryl, glass, and different liquids were used as solid-state guides. A solid-state guide can be produced in different forms as fibers, rods, or it can take the form of a hollow pipe with walls of prismatic polycarbonate.

3.2.2.1. Optical fibers

Optical fibers rely on concentrated incident light, within acceptance angle (point-on-lite), to convey light with total internal reflection principle (TIR). Optical fiber consists of a core and cladding, where the higher refractive index of core comparing to cladding ensures total internal reflection of light in the fiber. The outer layer of cladding ensures the efficiency of the TIR by capturing the eventually scattered light. Each fiber has a flexible jacket, which has a reflective inner surface to protect fiber and ensure that light stays in it. Core is mostly produced of silica-based glass (SOF) or can be a mixture of highly purified liquids typically water and methanol and/or ethanol, but the most used is a synthetic polymer called polymethylmethacrylate or PMMA (POF) [129].

UV and IR radiation need to be filtered out because they can harm the optical fibers due to the low maximum operating temperature as 92.7 °C for POF and 120°C for liquid fibers. SOF has a much higher tolerance of 277°- 400°C, but this material has a great production cost and fragility, which makes it unpractical to use [57,130,131].

The incident light at the optical fiber cannot be completely transmitted, due to the material's density, imperfection, and light absorption by core and cladding, and there is a light transmittance loss called attenuation (db/km or %/m). POF has the attenuation of 64, 73, and 130 dB/km for 520, 570, and 650 nm light respectively, which means that POF has lower transmittance for particularly orange light color (this is approximately 3% loss of luminous flux per 1-meter length of POF). SOF has very low attenuation for all wavelengths, and just as low as 0.2-dB/km at a wavelength of 1550-nanometers (nm). This makes the SOF the most efficient transmitter of the light and it can be used in the applications where light needs to be transported at a great distance [129]. It was recorded that light output using SOF was 4200K, Ra 98, while POF had 7000K, and Ra75 light output. Light transmittance on exterior 100 000lux after 20m fiber was 500lux for SOF and 400lux for POF [132]. Liquid core fibers have attenuation coefficients below 2-dB/m across for the visible spectrum, and very low for IR [133].

The coupling of fibers in branching showed significant light loss for which there were attempts to be solved by using a stepped coupler [50]. It was recorded that the index matching gel on the input fiber helps with light acceptance and uniformity [70,134].

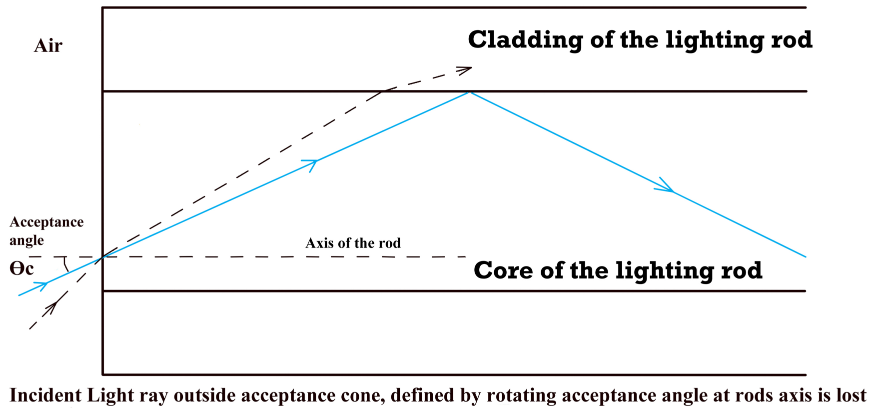


Fig. 16. Optical rod and light acceptance principle [76].

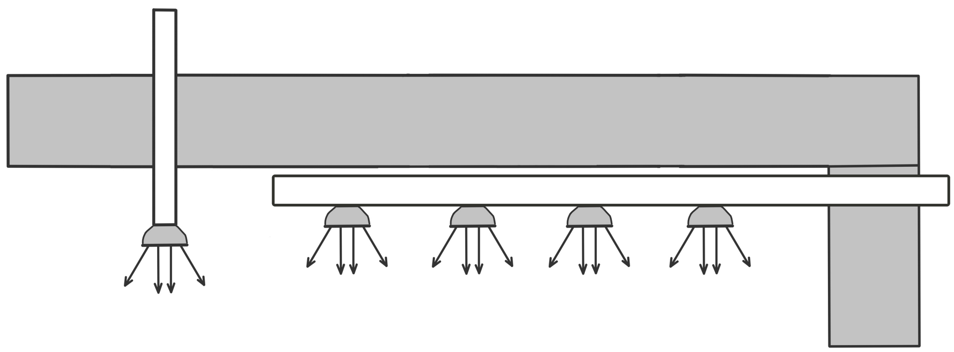


Fig. 17. Optical rods and possibilities for light emission [140].

Light acceptance into the fiber and its output were studied within the idea of stepped-thickness waveguide, which is an optical component, which redirects focused sunlight from the vertical direction to the horizontal direction, and it guides light to the attached optical fiber [135,136]. Modified optical fiber daylighting system (M-OFDS) for indoor lighting, with a collimated parabolic concentrator (CPC), attached to fiber and collimated end-part of the fiber, which emits a 5cm concentrated beam of light which propagates 30m in free space after leaving a fiber optical end [137,138] was also studied. This result could be used further to develop low diameter light pipes.

3.2.2.2. Optical rods

Optical rods were developed to be efficient in light transport and robust in form. They are made of transparent PMMA with different refractive index for core and cladding, Fig. 16. Light rods are sensitive to IR radiation, but they resist, and efficiently convey UV radiation. Similar to optical fibers, rods have its certain light incident acceptance angle for light to be transported by TIR, but comparing to fibers rods have a slightly manageable output issue, Fig. 17 [139]. Callow and Shao studied straight and bent light rods of 5mm diameter and 1000mm length, under the sunny and overcast sky, concluding that the luminous transmittance was between 47% and 64%, while the bend of 90° reduced rods transmittance by 20% [140,139].

3.2.2.3. Prismatic light guides

Prismatic light guides consist of one inner prismatic surface, coated with reflective coating on certain parts where the light reflects and propagates, and, one prismatic side where the light deflects and emits out of the guide, as in Conductalite prismatic emitter. If a prismatic guide is formed as a closed shape, as a hollow pipe, the emitted light is accepted again on the other side of the pipe and the light-guiding is continuous [141]. Light can be emitted along the guide, if the prismatic side is oriented outside [142,55]. High efficiency of the prismatic light guide used in the building core to convey and distribute daylight was reported in Heliobus and Artelio projects [56,143]. A recent study confirmed that the prismatic light pipes have higher light transmittance efficacy than mirror light pipes and that color rendering index and light color is constant CRI 99,7 and CCT6500 for the prismatic pipe comparing to the CRI 80-90 and CCT 3400-4400 for mirror light pipes which decrease with the distance [20].

3.2.2.4. Light converging guide

Light converging guidance relies on a light convergence between the precise arrangement of lenses and mirrors. System configuration depends on the lenses' focal distance. The physical construction around the lenses is not necessary but it is preferable because of the physical protection and dust maintenance, which can decrease system efficiency [141]. It is reported that the convergence system needs too much space and precise mounting, which makes it complicated to use [120]. The reported efficacy of one case application was 28%, due to the 13 lenses involved where each had a light transmittance of 92%, Fig. 18 [144].

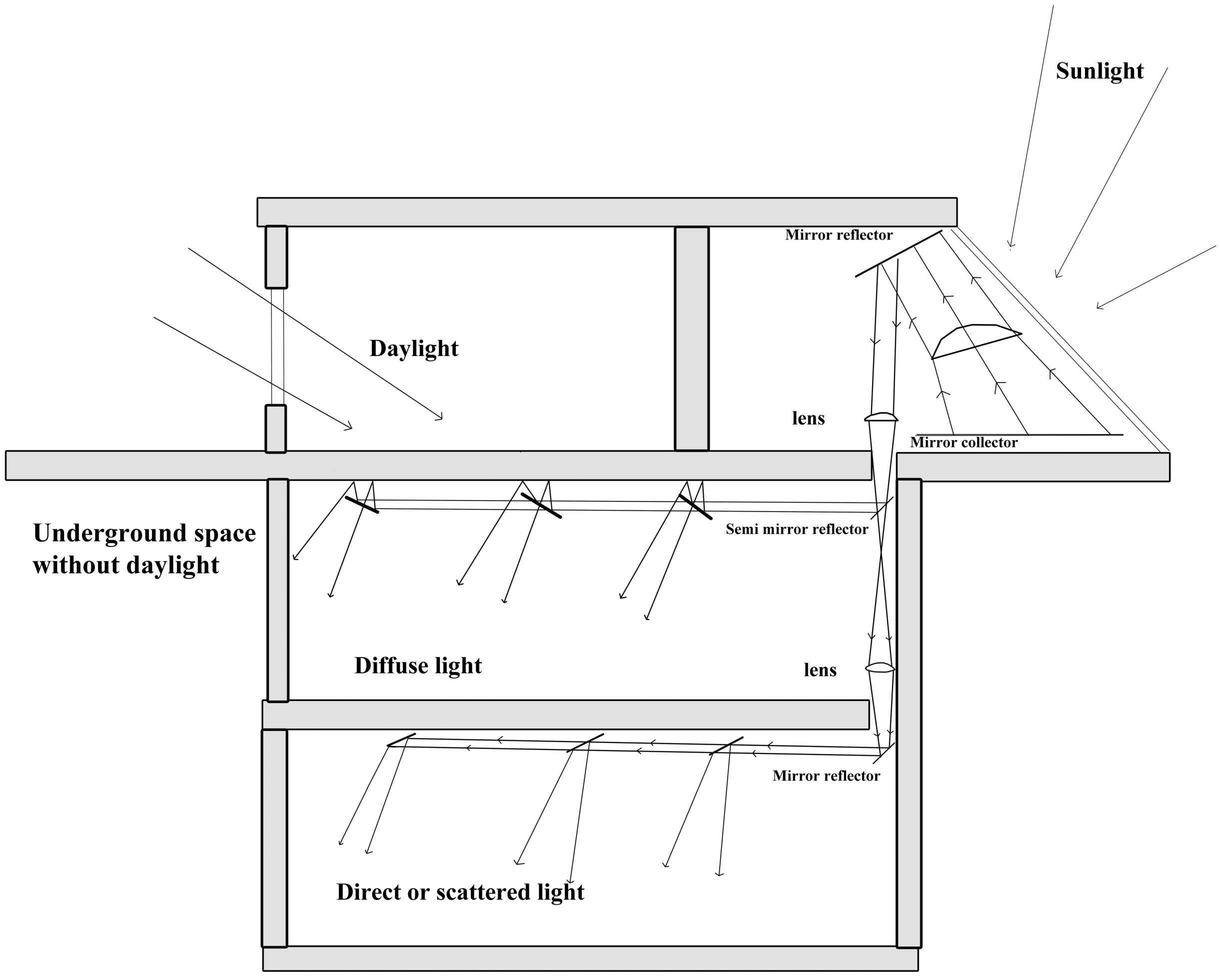


Fig. 18. The principle of light-converging guide in engineering building at the University of Minnesota [144].

3.3. Light distribution elements

Light distribution from the daylighting transport system is done by the light transmission and scattering through the emitters. Depending on the system's design idea there can be just one distribution point at the end [104,16], many distribution points along the light guide [142,155,43], or the distribution can happen continuously along the guide [145,146]. Light emitters are produced as circular or square (prismatic or transparent) PMMA diffusers, or as radial lenses (Fresnel) in a luminaire form. If light is transported by a wider guide, as light pipes or duct, diffusers are bigger, while for highly concentrated light from fibers, emitters are smaller, and in a spots or downlights form. Some studies were carried out to improve light uniformity [147].

Kocifaj worked to develop highly efficient, glare control diffuser, especially for the low solar altitude light, based on a fact that low incident light undergoes many interreflections in the tube with a low reflection angle. It consisted of a transparent glass on the outer part and a circular Lambertian diffuser in the center [104,105]. The same authors used continuous emitters as 6m thick transparent glazing and 5mm thick translucent glazing, with transmission factor 0.84 and 0.69 respectively. The issue of the output diffuser, as it is not a 100% transmissive and reflects light back into the pipe, was discussed in calculation models issue [125].

Emitters can be in form of a flat or an anidolic mirror element, placed at the end or along the light guide, to redirect light into the ceiling, walls or the working area [27,39], or to absorb light on a luminous gel and convey it further [39]. If a reflecting emitter is used, the glare issue needs to be handled carefully.

The emitters for concentrated light were often constructed as luminaires, which affect the beneficial feeling of transported daylight. Prismatic emitter with dot pattern screen was used to distribute light transported through fiber [65,50]. Luminaire-like emitters, made of crystal glass, were used as a light distributor for the LightWay light pipes, with producers promise for higher visual comfort.

Patterned or prismatic surface of the diffuser must be placed on the outside of the pipe, not inside the pipe, even though it is a preferable position due to the easier maintenance. Light is deflected and transmitted if it incidents on the flat side, while it mostly reflects back if it incidents on the prismatic side [80,18].

Light distributors are an understudied area, which needs special attention. As the last element in the daylight transport system and the only visible element in the indoor space, it has a responsibility and possibility to distribute light in the room and it affects the visual perception of light and the user's experience.

Table 1. Most usual combination of light collectors and light distributors for a light transport element.

	Possibilities of finished configuration of daylight transport systems					
Light Collector possibility	• Anidolic collector • LCP • CPC • Heliostats • Mirror sunlight system	• Anidolic • CPC	• CPC • Static light concentrator	• Heliostats • Mirror sunlight system	• Static light concentrator • Fresnell lense concentrator • Parabolic concentrator	• Fluorescent/ Luminescent solar concentrator • Fresnell lense concentrator • Parabolic concentrat
Light transport element	Vertical light pipes (hollow, water, double)	Horizontal light pipes and ducts	Prismatic light guides	Lenses and mirrors system	Optical rods	Optical fibers (glass, liquid, plastic)
Light Distributor possibility	• Prismatic, transparent, translucent PMMA diffusors • Lambertian, partly clear diffusor • Bohemia glass diffusors	• Prismatic, transparent, translucent PMMA diffusors • Bohemia glass diffusors	• Prismatic, transparent, translucent PMMA diffusors	• Anidolic reflector emitter	• Radial Fresnel lens • Luminaire	• Radial Fresnel lens • Luminaire

Table 2. Review of elements in daylight transport systems.

Daylight transport system	Mode of operation	Optical light principle	Light to light Efficiency (light transmittance)	Ease of physical integration in the building	Maintenance	Cost	Availability
Collector							
Anidolic collector [124,24,26,27,30,29, 31,153]	Passive	Light reflection	72% [124]	Robust need space	none	medium	Specially constructed and produced
Laser-cut panel [32,33,35,41,42]	Passive	Light deflection	Max 90% for custom (incident angles) LCP [32]	Light and compact, do not need additional space	none	low	Specially developed and produced
Compound parabolic concentrator [45] (dielectric prismatic film) [20]	Passive	Light reflection (total internal reflection)	Almost 1000% for edge ray light incident angles (up to 600%)	Light and compact, can be placed on sun-exposed façade	none	Not specified	Specially developed and produced
Luminescent solar concentrator [46-48]	Passive	Light absorption, reemission and Total Internal reflection	6 – 10% for 1.2m concentrator length [49]	Need a small space	Need special care	medium	Research study
Fluorescent fiber solar concentrator [49]	Passive	Light absorption, reemission and Total Internal reflection	Very low [49]	Need a small space	Need special care	medium	Research study
Static light concentrator [50]	Passive	Light absorption and refraction on a prism	Up to 35% [50]	Concept phase	Need special care	medium	Research study
Heliostats [51,54,55]	Active	Light reflection	High, not defined	Need a lot of space	Need maintenance	high	Available, many producers
Mirror sunlight system [58-61]	Active	Light reflection	High, not defined [61]	Need space	Need maintenance	high	Available, many producers
Fresnel lens concentrator [63,64,68,69,154,74, 70,134]	Active	Light refraction on a prism	90 – 92% [144,64]	Robust or Compact but need space	Need maintenance	high	Available, many producers
Parabolic concentrator [70,72-75,68,76,22]	Active	Light reflection	Depending on many parameters	Robust Need space	Need maintenance	high	Available, many producers
Light transport element	**Light transport distance**						
Vertical pipes [77,82-84,96,101,78,102]	D/L max 1/20	Light interreflection	Decreasing with length	Need vertical space	none	low	Available, many producers
Water-filled pipes [116]	6-8 m	Light absorption and scattering	20% after 10m [116]	Need vertical space	Special care	high	Research study
Double pipes [117,118]	3m	Light reflection and deflection	200lux delivered indoor for exterior 40Klux	Robust, Need space	cleaning	low	Case and Research study
Horizontal pipes [38,120-123,92]	7-8 m	Light interreflection	Decreasing with length, 300lux after 8m	Need space in the ceiling plenum	cleaning	low	Available a few producers, case concept

Horizontal ducts [37,38,124]	4-6m,up to 10m	Light interreflection	Decreasing with length	Need space in the ceiling plenum	cleaning	low	Specially constructed and produced
Optical fiber [68,75,76,130,155,132,156,157,129,57]	Up to 200m	Total internal reflection	Attenuation dependent	Compact, totally integrable	none	medium	Available, many producers
Optical rods [139]	1.2m studied	Total internal reflection	46-66% for 1.2m [139]	Compact and semi-flexible	none	high	Research study
Prismatic light guides [141-143]	3-4 floors	Total internal reflection and light diffraction	20%	Need space		medium	Specially constructed and produced
Lenses and mirrors system [144]	3-4 floors	Light convergence and reflection	92% on each lens, 28% in total [144]	Robust, need place	Need special care	high	Specially constructed and produced
Light distributors	**Suitable for**						
Prismatic, translucent diffuser [125]	Light Pipe	Light diffraction	84% prismatic 69% translucent [125]	Compact, fit into ceiling	Dust cleaning	low	Available, many producers
Lambertian, partly clear diffuser [104,105]	Light pipe	Light diffraction and transmission	65% - 300% more than transparent glass	Compact, fit into ceiling	Dust cleaning	low	Research study
Crystal glass diffuser [158]	Light pipe	Light diffraction	94-95% light transmission	Usually formed as luminaire in different designs	None,self-cleaning	medium	Available
Radial Fresnel lens	Fiber	Diffraction of focused-concentrated light	90-92% light transmission	Compact, fit into ceiling	Dust cleaning	medium	Research study
Anidolic emitter [39]	Horizontal pipe and duct	Light reflection and scattering	70 - 99% depending on a finish reflectance	Robust, need space	Dust cleaning	medium	Research study
Luminaire (spot /downlight) [65,50]	Fiber	Light scattering	Depending on Luminaire Output Ratio (LOR)	Compact, fit into ceiling	Dust cleaning	medium	Available, many producers

All reviewed components are systematized in Table 1, where columns present finished daylight transport systems and possible combination of light collectors and light distributors. Table 2 shows the overview of each component and their important characteristics to be widespread in the building industry.

4. Analytical models and design adjusting for light transport systems

Research studies addressing Light pipes aimed also to solve the issue of performance prediction for straight and bent light pipes. Design parameters as diameter, length, and optical properties of material and daylight directionality (sky types) were used to re-develop many different analytical methods and models [99,81,33,148]. To ease the design and decision-making process for light pipes, the concept of daylight penetration factor (DPF) was developed and experimentally validated [82-84]. DPF models predict the transmission of daylight (sky diffuse light + sunlight) through the light pipe system. A modified method for just overcast sky was introduced to be used for a simple design [78,102]. Carter also developed a simple method to determine the number of light pipes in the room [112]. Later he argued that in order to value DPF together with DF both methods should be considered for just overcast sky, as it is for DF [91,90]. HOLIGLIM analytical method, which uses ray tracing, backward ray-tracing and asymmetry parameters was developed for predicting light transmittance for straight and bent pipes [107,106,109,110]. HOLIGLIM was evaluated in light pipe studies for overcast and clear sky conditions [105,103]. A new analytical method, which analyzes the contribution of the direct and diffuse light separately was recently introduced [108].

Many computer-based simulation methods were developed and validated in building simulation tools [149]. Literature mentions the DOE-2 building energy simulation program, the SUPERLITE daylight analysis program, RADIANCE ray-tracing program, and recently Energy plus and CODYRUN [123,37,11,150,151].

Active collectors need solar tracking for the best working performance. The tracking system consists of two axes (or one axis) tracking, where the first actuator should align azimuth and the second one should align altitude/zenith angle. The tracking system needs an engine for the rotation that aligns the position using either a sensor for the highest solar radiation or the astronomical positioning system. Alignment tolerances are very tight (1 st. rad) and errors bring significant reductions in collection efficiency and system efficiency [129]. In order to minimize the alignment errors, tracking algorithms of open and closed-loop are used. Closed-loop algorithms are based on the feedback control principles, where parameters in the sensor are compared to give the info of the eventual fine-tuning the tracking position, while open-loop types of algorithms do not have this feedback information possibility and can result in 40-70% lower solar tracking efficiency [52,152]. It was recorded that azimuth axis tracker is more important than altitude because of the wider variating angle.

Table 3. Certified daylight transport systems as market available products, available to buy and install (not custom-made products for one case project).

Daylight transport system	Type of collector	Type of transport element	Type of distributer	Efficiency, light transmittance according to the producer
Solatube [169,170]	Polycarbonate dome, clear or Reybender technology, and LightTracker™ Reflector	Straight and elbowed pipes Spectralight® Infinity tubing material	Prismatic and Fresnel lenses	81.3% for the dome; 99.7% Rf for tube
Solarspot [98]	Acrylic clear dome, RIR® Fresnel lens light funnel	Straight and elbowed pipes Vegalux® – anodized aluminum laminated with 3m Daylighting DF2000MA film	Lambertian diffuser, prismatic, pearled	86% for the dome; 99.7% Rf for tube
Monodraught [100]	Acrylic Diamond Dome with prismatic vertical on the circumference	Straight and elbowed pipes SUPER- SILVER mirror finished aluminum tube	Satin diffusers	84.3% for the dome; 98% Rf for tube.
Velux [169,170]	Dome like Skylight	Rigid and flexible Sun tunnels	EdgeGlow diffuser	Not available
LightWay [158]	Acryl and bohemian crystal domes, parabolic like mirror concentrator	Straight and elbowed, horizontal and vertical light pipes	Satin acryl diffuser and bohemian crystal diffusers	92% Tf for acryl dome 94% Tf for Crystal dome 98-99.8% Rf for tube
ADASY [158]	Facade mounted array of truncated compound parabolic concentrators (T-CPC)	Horizontal mirrored chamber	Prismatic diffusers	
Heliobus daylight shaft [171,58]	Laminated safety glass cover	Highly reflective shaft for basement	Laminated glass	Not available
Heliobus® Light Guide [58,171]	Mirror	Prismatic light pipe	Prismatic light emitter	420lux for overcast sky 10000 lux [171]
Parans [155]	Multiply Fresnel lenses collector	Optical fiber plastic	Spot luminaire, satin panel	100m length, 30 floors. 80% transmittance [165], energy-saving 20% north 46% south [155]
Himawari [142,64,63]	Fresnel lens honey-combed system	large diameter quartz glass fibers	Spot luminaire	Up to 200m, but 23% transmittance, after 2m length 500lux indoor
Sundolier [58,158]	Mirror sunlight system	24'' hole – light pipe	Light distribution fixtures	Up to 3 floors [59]
Solux by Bomin Solar Research [58,158]	Big single Fresnel lens	Liquid light guide	Luminaire	80-90% after 10m length [58]

5. Development of market products

Since the first researches and scientific results, many finished and patented products have appeared on the market, coupling the over-reviewed components by their optical properties. Sun-pipes and light-pipes were patented [159-162,98,97,163], manufactured and implemented widely. Fiber-optical daylight systems with the active [64,21,72] or passive [62,53] solar tracking, were patented and produced by different manufacturers [164,66]. Many studies were conducted addressing the light efficiency of those finished products [165,155,65]. An overview of daylighting systems on the market is presented in Table 3.

Some daylight transport systems were combined with electrical light sources to become hybrid daylight systems. The idea of combining natural and artificial light sources, and just one transport and emitter part was made mainly to have a better energy-saving control and to reduce the material and costs [166-168,65]. Studies showed that coupling losses can be up to 50% when a hybrid system is enabled for dual light source operation.

6. Discussion

This comprehensive literature survey of daylight transport systems and their light conveying components show performance characteristics of each component, their limitations, and options for utilization.

Light collectors are designed to collect and redirect or concentrate direct or diffuse light depending on a light transport guide. Passive collectors cost less in production, running and maintenance than active collectors which also wear off easily, and need perpetual service. Passive collectors collect much less of exterior daylight flux than active collectors, which means that one active collector can serve a larger area than a passive collector. Because of the different light emission on the diffuser part, it is not possible to compare them to make investing or profitability comparison.

Anidolic collectors showed reliable applications for zenithal diffuse light collection for overcast conditions and could be customized to ensure direct sunlight redirection for every location (unique solar altitude variation). According to recorded energy-saving potential, of ca. 25% for different locations, it can be concluded that an anidolic collector can be universally used to improve daylighting conditions in deep plan buildings. Specially designed Laser-cut panels can deflect a span of incident angles of direct light beams and transmit diffuse light from the sky, which qualifies them for usage in both clear and overcast sky conditions. Luminescent and fluorescent concentrators have shown low collecting efficacy, but their advantages are in physical adaptability in the aesthetical façade concept. Static light concentrators are in the concept phase but could be compared to the PV panels as they are flat, and if placed on a roof, do not violate building aesthetical concept.

Active light collectors are bigger elements, they are often placed on a roof in hot climates but could also need façade placement in temperate climates to collect direct sunlight. Heliostats and mirrors redirect direct light beam but only in little extend diffuse light. Fresnel lens and parabolic collector almost exclusively concentrate direct light. Tracking elements are mechanical components that use electrical energy, which needs to be considered in a total energy calculation. Active collectors are in general not suggested for predominantly overcast skies. However, literature suggests that heliostats on the south façade, for multistory buildings at high latitudes, could be more efficient for occasionally clear sky than horizontal light pipes for predominantly overcast skies.

Light transport guides as a mirror or prismatic pipes, water or double pipes need vertical or horizontal physical space, which dictates other technical systems and, to a smaller extent, building construction concepts. Mirror light pipes, supplied with customized collectors, have shown potential for daylight supplement in temperate and hot climates. Vertical light pipes could be used in single or double story buildings, while horizontal pipes could be used in multistory buildings. Light pipes convey direct and diffuse light, where daylight output from the pipe is more uniform, homogeneous, and discreet during the day when exterior light conditions are overcast than when they are clear sunny. Predominantly clear sky and direct light made high variations in the output light in terms of intensity and uniformity, while overcast sky and diffuse light did not show this problem, mainly because the light flux was lower and uniform by nature.

Fiber-optical light guides are flexible and of small diameter and could be protracted deeper in the buildings without the need for space. Silica-based fibers have higher light transmittance than plastic and liquid ones, but higher cost, too. Daylight output from the fiber can be problematic to spread since it comes from a very small section and it can variate as much as exterior light illuminance change, which makes it them difficult to design and problematic for user acceptance. Optical rods showed considerable light transmittance for diffuse and direct light, but the production cost and inflexibility labeled them as not attractive for use.

Light converging systems with lenses and mirrors remained on a few case solutions, as they showed high cost, and demand for space and maintenance, while light transmittance was low compared to other systems.

Light distribution elements, as the last component, are responsible for light spreading in the space, but also have high potential to manage the visual effect of light. However, this component is understudied and there have been just a few attempts to improve efficacy and control excessive light. Prismatic, translucent, and transparent plastic diffusers are used for light pipes, while spots and downlights are used for fiber optics. They are produced in a luminaire like form which affects the user's acceptance and opinion about the delivered daylight.

Research on tubular DTS gave several more components that can be combined than the research on fiber optical systems did, Table 1. The research in fiber optical DTS went into the direction of improving sun-tracking algorithm devices, and not much in the direction of the development of new component. Tubular DTS are also more applied and used in buildings than fiber optical DTS in spite of the implementation ease and flexibility of fibers [158]. This can indicate that the need for more building space for Tubular DTS was not such a great issue as the need for passive systems versus mechanical active systems.

Several daylight transport system reviews tried to define methodology on how to choose the best system for a specific building type, a room function or daylight conditions at the location. Cost and profitability analyses were also provided to ease the process of implementation by decision-makers. However, none of the researches so far has considered that if we aim at good integration between the daylighting system and artificial lighting, the artificial lighting, and control system should be redesigned as well. Additionally, to distribute daylight better in the space, space design, form and finishes could be adjusted and customized to reassure the expected daylighting effect. Only one single paper discusses ceiling form as curved, sloped, or chamfered for better daylight distribution from the anidolic ceiling [41] and another one discusses the mode of lighting controls for artificial lighting for better integration with daylighting systems under direct or diffuse daylight [93].

Daylight transport systems, as technical products, showed an increasing application tendency, but as they are designed to suit predominantly sky and sun conditions for a specific location, application in other locations brings decreasing transmittance efficacy and energy-saving potential is not certain. All systems are available in many configurations to suit new buildings or redevelopment. Solatube is efficient for both high and low solar altitudes because of its Reybender optics in dome. Monodraught provides light redirection on a diamond dome with prismatic optics, while LightWay promises higher light transmittance though Bohemia crystal glass dome. Solarspot has a clear acryl dome and relies on its Fresnel lens RIR deflector for low direct light, while Velux relies mostly on diffuse zenithal light collected through skylight dome. Horizontal Adasy system showed high potential for use in ceiling plenum. Heliobus's daylighting shaft is simple and has a high potential for applications, while Heliobus's light guide is more a special product. Parans and Himawari systems show high efficacy in clear sky conditions, while for non-clear sky conditions, they affect the profitability of the application. Solux and Sundolier systems had a few applications, but big dimensions and design shapes of the collector and guide components make them unattractive to use on the building exterior. For high latitudes locations with predominantly overcast sky, Solatube could be used as a vertical system, and Solarspot, LightWay and Adasy could be used as a vertical and horizontal system. For non-costal locations, between 55-65°N Parans system could be used if placed on the roof.

7. Conclusions

According to the daylight conditions for the high latitude locations, and the aim of this study (to address energy-saving potential for multistoried buildings), it could be concluded that the systems that can efficiently collect zenithal daylight and variable position of direct sunlight should be used. Table 4 shows conclusions on suitability for each element in predominantly overcast sky and direct sunlight at low solar altitude. Anidolic collector showed the

Table 4. Review of suitability for elements of daylight transport systems in predominantly overcast sky and direct sunlight at a low solar altitude.

Daylight transport system	Directionality of transported light	Suitability for direct light and predominantly low solar altitude	Suitability for predominantly overcast sky
Collector			
Anidolic collector [27,153]	Predominantly overcast and clear in temperate climates	Partly, if constructed according to edge rays for low solar altitude	Excellent
Laser-cut panel [40,38,39,35]	Predominantly clear in hot and temperate climates	Excellent	Partly, depending on a configuration and the tilt of the panel
Compound parabolic concentrator [43-45]	Predominantly overcast and clear in temperate climates	Excellent	Partly, depending on a form of the concentrator
Luminescent solar concentrator [48]	Predominantly clear	Excellent, can be placed to align the incident angle	Bad
Fluorescent fiber solar concentrator [49]	Predominantly clear	Excellent, can be placed to align the incident angle	Bad
Static light concentrator [50]	Predominantly clear	Excellent, can be placed to align the incident angle	Bad
Heliostats [54,51,55]	Predominantly clear	Excellent	Bad
Mirror sunlight system [58-61]	Predominantly clear	Excellent	Bad
Fresnel lens concentrator [63,64,68,69,150,74,70,134]	Predominantly clear	Excellent	Bad
Parabolic concentrator [72-74,70,68,76,22]	Predominantly clear	Good, but positioning is problematic for building facade	Bad
Light transport element			
Vertical pipes [77,83,101,102,40]	Diffuse and direct	bad	Excellent
Water-filled pipes [116]	Direct	bad	Excellent
Double pipes [117,118]	Diffuse and direct	Bad if vertical, but relatively good if horizontal	Excellent if vertical, bad if horizontal
Horizontal pipes [38,121,125,92]	Diffuse and direct	good	Yes, if suited with anidolic collector
Horizontal ducts [124,37,38]	Diffuse and direct	good	Yes, if suited with anidolic collector
Optical fiber [68,75,76,130,155,132,156,157,129,57]	Direct	good	Bad
Optical rods [139]	Direct and diffuse	Relatively good for short distance	Bad
Prismatic light guides [141-143,20]	Direct	Relatively good	Bad
Lenses and mirrors system [144]	Direct	Relatively good for short distance	Bad
Light distributors			
Prismatic, translucent diffuser [125]	Diffuse	Yes, it reduces eventual excessive light	Partly, it decreases the efficacy of predominantly diffuse light
Lambertian, partly clear diffuser [104,105]	Diffuse	Yes, it reduces eventual excessive light and increases transmission	Suitable, it partly decreases efficacy of diffuse light
Crystal glass diffuser [according to producer LightWay]	Diffuse and direct	Partly, it and can introduce excessive light and light diffraction	Suitable, it increases light transmission
Radial Fresnel lens	Direct	Partly, it can disperse the excessive light	Partly, light dispersion can be uncontrollable
Anidolic emitter [39]	Diffuse and direct	Partly, light emission depends on a surface finish	Excellent
Luminaire (spot or downlight) [65,50]	Direct	Bad, it can introduce excessive light	Bad

potential to collect diffuse light from the zenithal part of the sky dome, but it could be also custom-designed to suit other directions of light beams, according to the edge-ray principles. Laser-cut acryl panel with sloped cuts showed a possibility to redirect a span of light beam directions, which could be used for variating sun altitude and azimuth. Both vertical and horizontal light tubes, depending on the functionality and architecture of the building, could be used for daylight conditions in high latitude locations with specially tailored collectors.

Systems reviewed in this paper deliver daylight deeper in the space than a usual window does and increase daylighting level and uniformity in total. More extensive use of daylight in buildings obtained through the application of the systems has many benefits. The daylight luminance uniformity across the room could be improved, comparing to the daylighting through the side windows only. Visual comfort would be better since the luminance condition will change glare conditions for a user. Seasonal and diurnal variation of exterior daylight will imply in light color and intensity dynamics inside. These two were qualified as beneficial characteristics of daylight that comes through the window, which, in case of deeper delivery spot, could extend the same positive feeling deeper in the space and far away from the window.

The literature survey showed light efficacy of the different components and light transmittance for the entire systems, which is summarized in Table 3. The accumulated supplement in daylight flux, during different weather conditions, season, or the entire year, was covered in many studies, resulting in energy-saving potential for artificial lighting, too. The supplementary flux has been studied according to light demands in test rooms (very often offices) as 500lux in general, and conclusions were taken on this basis. Since studies were done mostly by architects, building engineers, or physicists, the lighting demands were only approximated. The real lighting demand according to standard and best lighting design practice is 500lux on a horizontal working area of 60×30cm, 300lux on a working desk and 200lux in the wider surroundings. If those prerequisites had been taken in the assumption the energy-saving potential would have been higher. Besides, the light controlling system for daylight supplement should be suitable for the predominantly daylight conditions as it was recorded that there are highest energy savings if the direct light is combined with on-off control, while diffuse light is combined with dimming.

The answer to the objective of this paper "which system is the most suitable for the buildings in high latitudes?" is more complex if we seek for the answer taken for typical office building and a general presumed predominantly daylight condition. There are very many types of building floor solutions, and room functions, orientation, settlement in the neighborhood. In addition, every location has its specific solar microclimate. It is, therefore, not surprising that decision could not be easily made by following the methodology, but it should rather be designed in detail through consideration of all prerequisites. It is not possible to generalize the good method for the choice of this '’technical component'' and leave it to the architects to pick out. It is necessary to design a daylighting system together with the artificial lighting system and building spaces themselves. There should be an integrative design of building spaces and daylighting from the concept stage. One single building could have two or several system configurations depending on the orientation. Spaces oriented north could be designed with diffuse zenithal daylight transport systems, and spaces on the south could rely on a facade mounted direct sunlight daylighting systems, which either actively track suns altitude or passively rely on sunlight reflection. East and west façade could similarly actively track sunlight azimuthal movement or rely on passive light deflection.

The building industry nowadays aims to produce environment-friendly materials, components, and equipment, so that they could have primacy on the market in more and more strict building standards. Daylight transport systems need to follow this vision in using environmentally friendly materials and to strive for low a CO_2 footprint.

Perception of, opinion about and satisfaction of daylight delivered through the daylighting systems depends on the nature of the distributed light inside. All the reviewed systems were constructed with diffusers that imitate a luminaire. This is probably because the producers of the systems wanted to have a finished product that they can put on a market as technical equipment while disregarding the primary aim of this application and that is to provide all the daylight beneficial features, and not just the light flux. This is probably the reason why user acceptance, and, in general, application breakthrough of those technologies has never happened.

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Contributions

B. O. conceived and wrote the study, B.M. helped define the scope of the study, gave feedback on the contents of the paper and contributed by performing quality assurance and proofreading.

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