Guidelines for Daylight Guidance Systems Application

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ABSTRACT: Daylight guidance systems (DGS) are used to transport daylight into windowless or remote spaces in buildings; beyond the traditional daylighting systems limits. The wide variation in the DGS components and techniques makes it very difficult for building and lighting designers to know which system is the best to meet their specific needs. This work describes the main components and techniques used in the majority of the developed DGS over the last two decades. Guidelines have been established to provide a full understanding of the DGS abilities, applicability and limitations. It is found that concentrating sunlight by the DGS is the most influential aspect in both performance and application. The work sets out under what circumstances light delivered by DGS is perceived as daylight.

Keywords: Daylight guidance system, collector, guide, output device.

INTRODUCTION

Traditional daylighting systems, such as side windows and skylights, are limited to distribution of daylight into the parameter zones of buildings. Daylight guidance systems (DGS) have been developed to channel daylight into remote spaces from building envelop. Light guidance technology captures daylight using collector devices, transports it into core areas via some form of linear guidance system, and distributes it using different types of output devices. Two main types of DGS have been developed. The first delivers daylight solely, such as the commercially successful tubular daylight guidance systems (TDGS) (Fig. 1) [1]. The second type is the hybrid lighting system (HLS) that combines electric light and daylight prior to delivery; such as Parans daylighting system (Fig. 2) [2]. Many techniques and a wide variation of devices and materials have been used to enhance the DGS ability to channel daylight; whether in the daylight collector, daylight guide or output device.

The wide variation in the DGS components and techniques occurs as a result of attempts to improve DGS performance and efficiency. Some systems are commercially available, notably TDGS, Parans, Himawari and Sundolier systems [1-4]. Others are custom-designed and produced, and thus not widely spread, such as Heliobus system and Solar Light Pipe (SLP) [5-6]. Some are still under development, such as Hybrid Solar Lighting (HSL) and Solar Canopy Illuminance System (SCIS) [7-8]. Many systems are conceptually successful, but efficiently, practically or economically unsuccessful, such as Arthelio, Solux and the Universal Fibre Optics (UFO) systems [9-11], and some didn’t progress beyond the theoretical or physical model stage [12-13].

The commercially available systems exhibit a big variety in components types in terms of material, size, mounting method, and movement. They use a variety of techniques for light collection, transport and distribution, and deliver light that varies in quality and quantity depending on sky conditions and building geometry. This variety makes the inclusion of DGS in building design a difficult process. This study suggests guidelines which enable the capabilities of DGS to be realised. This will be of assistant to architects and lighting designers to decide which DGS meet their needs, and will help them to utilize DGS in their buildings.

Figure 1 (left): TDGS, Figure 2 (right): Parans collector.
DAYLIGHT COLLECTOR FEATURES
All DGS have a light collector located at the outside end of the light guide. The light collector characteristics determine the amount of daylight collected, utilization times, which daylight component (direct, global or diffused) is collected, and characteristics of daylight (e.g. spectrum, intensity and colour) due to the optical process.

Collector optical elements
The collector’s optical elements might be as simple as a clear glass dome, and might be a combination of mirrors and lenses. The more optical process the light goes through, the greater he losses of quality and quantity in the delivered daylight.

TDGS normally use a clear dome [1]. Solux and UFO systems are based on a 1m diameter Fresnel lens (Fig. 3) [10-11], whilst Parans and Himawari systems use arrays of small Fresnel lenses (Fig. 1, 4) [2-3]. The HSL system uses a set of two mirrors, while the SCIS uses a set of around 74 mirrors (Fig. 5,6) [7-8]. A combination of mirrors and lenses are used in Heliobus and Arthelio systems [5, 9]. A laser cut panel of glass or acrylic are used in a newly developed light pipe [12].

Glass and plastic domes or flat mirrors do not concentrate sunlight. Lenses and concave mirrors on the other hand concentrate direct sunlight up to 1000 times [3], and collect minimal diffused daylight. Concentration of daylight results in greater amount of collected daylight and smaller light guide size, but at the expenses of light quality. De-concentration of daylight to produce a uniformly distributed daylighting requires further optical processes, and thus more losses. Concentrating systems do not work under overcast skies, and suffer rapid and repeated changes in light delivery under partially cloudy skies.

Collector movement
The TDGS and some Heliobus installations have static collectors, whether fixed horizontally on the roof, vertically on the façade, or inclined to face the sun. Most of the other systems mentioned above have tracking systems that follow the sun path to keep the collector perpendicular to the sunrays to maximize the collected daylight. The collector might stand free and has the potential to track the sun path all daytime round as in the HSL (Fig. 5), and might be assembled in enclosures that limit their tracking coverage angle such as SCIS (Fig. 6).

Collector mounting and orientation
Static collectors, such as the TDGS domes, may be horizontal or inclined. Arthelio system and some Heliobus installations have vertical collectors. Roof mounted collectors are more likely to collect daylight for longer time than the façade mounted. The roof mounted collectors mostly require ceiling holes; vary from few centimetre-diameters to more than one meter, to connect to the light guide. They are more applicable in upper stories and deep-plan buildings. Meanwhile, façade mounted collectors, such as SCIS and some types of sun pipes and Parans systems, are applicable in multi-storey buildings. They also require holes vary in size in the external walls to connect to the light guide. For more efficiency, façade mounted collector are preferably being south oriented in the Northern hemisphere.

In many cases special requirements are needed for collector mounting. They might need a structural support due to the weight or wind resistance. For instance, the large size of Himawari system is 628kg weight and 1.63 x 2.5 m size [3]. Some systems require a protection shed or enclosure, such as Arthelio for the former and SCIS for the later. Very precise systems, such as HSL, need skilled technicians for installation to minimize the probable fire hazard due to incorrectly focused sunrays.

Collector size and shape
The collector size and shape influences building appearance, especially if it is a façade mounted.
Additionally, it determines the type and amount of the collected daylight. Collector sizes range from around 0.06m² to 4m². They have a wide variety of shapes, e.g. domes, cones, boxes, dish-shape and banana-shape. The TDGS have relatively small collectors with diameters ranges from 250 to 630 mm, the 3rd generation of Parans system is 1.1 x 0.45 m, and the small type of Himawari system is 0.52 x 0.81 m [1-3]. The medium size collectors are such as the HSL, Solux, UFO and some types of Himawari and Heliobus systems that come with collectors of around 1m diameter. The largest collector can be seen in the SCIS with approximate dimensions of 3 x 1.3 x 1 m [8].

DAYLIGHT GUIDE FEATURES
The light guide is what identifies the DGS. It channels the collected daylight into the building core. Mostly there is an output device at the internal end of the guide, however sometimes it has a dual function; transporting and emitting daylight along its route. The light guide characteristics determine transport distance, and have a significant impact on maintaining daylight characteristics.

**Guide optical material**
There are two main types of guides; light pipes and optical fibres. Both transfer light by total internal reflection. The inner surface of the light pipes has to be of highly reflective materials such as polished aluminium of reflection as high as 99.8%, or lined with mirrors or optical films. Light pipes or ducts made of prismatic materials may contain diffusing extractors to create dual function guides; as can found in the SCIS, Heliobus, Arthelo and SLP systems (Fig. 7). Glass or plastic optical fibres have been used to guide concentrated light. Glass fibres tend to provide better quality, but with more cost and less flexibility. Liquid light guides, which are a flexible pipe filled with an optical clear liquid, have been used in Solux system. The transmission through the liquid results in poor light quality.

**Guide mounting and routing**
For routing purposes optical fibre guides can be treated like electric cables, meanwhile, light pipes and ducts can be treated like ventilation ducts. They can be mounted horizontally, vertically, or any angle in between, bends as applicable. The horizontal guides can be mounted in the ceiling cavity, or left exposed, and may need wall holes to reach building core. They are mostly used with the façade mounted collectors such as the SCIS. The vertical guides, which are mostly used with the roof mounted collectors, might go through the building vertical voids such as lift shafts, otherwise floor holes are required. The vertical guides might penetrate fire compartment, occupy a valuable area, and conflict with the interior design. Horizontal guides might conflict with the building beams and HVAC ducts. The guides might need structural support in accordance to their weight. In some cases these represent a negligible load, but in others the system weighs as high as 8 tonnes [5].

**Guide size and shape**
The light pipes diameters range from around 0.25m in the small TDGS up to 1.75m in the SLP [1, 6]. Rectangular cross section light ducts are used in the SCIS and some Heliobus installations. The typical SCIS duct is 0.25 x 0.60 m [8]. Guide length widely varies according to the light loss ratio, and its potential to route throughout the building. The length of the light pipes and ducts start from less than 1m to connect a roof mounted collector with the building last story; up to the 36m light pipe used in the SLP [6]. The optical fibres are more easily routed, but the light loss ratio limits their effective distance to some 20m [2, 7].

**DAYLIGHT OUTPUT FEATURES**
The transported daylight either emitted via output devices at the internal end of the light guides, or along the entire or parts of the guide side(s), which include in these cases extractor devices to allow emittance of proportions of daylight where it is needed. The output devices determine where the DGS can be employed properly; in terms of building type and space function.

The DGS output devices are available as point or linear luminaires, or a luminous surface. They might be custom-designed such as Parans and Sundolier systems, or conventional-like luminaires as in the HSL and SCIS systems (Fig. 8). Non-concentrating systems are more likely to provide a uniformly distributed illuminance.
Meanwhile, concentrating systems require a proper de-concentrating process to achieve a similar result; otherwise a narrow light beam will be obtained resulting in separate light batches using the average distance-to-height ratio.

All DGS output devices provide daylight without connection with the outside view, which means there is a danger that light will not be perceived as daylight, especially if delivered by a conventional-like luminaires. HLS provide in addition top-up electric lighting to offset any shortage of daylighting. That leads to more difficulties in the perception of daylight since it mostly changes daylight colour and intensity.

DGS GUIDELINES
From the above, it can be seen that a lot of factors interact to determine DGS performance and applicability. The awareness of these relationships may be used by system developers to find out how to improve systems performance; or by the building designer to know which system is optimally applicable in a particular case. For both, a full understanding of system potential and limitations is fundamental. The following sections will firstly examine performance and applications aspects related to each component of the DGS to reveal its potential and limitations. A summary at the end will discuss the most important issues raised from a comprehensive perspective.

LIGHT COLLECTOR GUIDELINES
The main aspects that stipulate the light collector performance and applicability are its light concentration ratio, the area size of the effective collecting part, the mounting location, and the sunrays tracking system.

Concentration ratio
Both none- and high-concentrating systems are more efficient between 10°N and 15°N in the Northern hemisphere [14]. Other aspects related to systems with high concentrating ratio are set out below. In general terms, for non-concentrating systems opposite characteristics apply.

High concentrating ratio leads to:
- Collecting direct illuminance only, and thus it is more applicable under sunny conditions.
- More optical processes are required for concentration.
- Smaller size for the collector than comparable none or low concentrating collectors.
- Smaller guide is required to channel concentrated light.
- More accuracy is required to focus the concentrated sunlight on the guide mean.
- Technically more complicated and thus more expensive.
- More possibility of fire hazard.
- High skilled labour may be required for installation and adjustment.
- Potential need for more technical maintenance.

Size
Small size collectors have opposite characteristics to what are mentioned below for the big size collector.

Big size leads to:
- Potential ability to collect more light than smaller collector with similar concentrating ratio.
- More influence on building appearance.
- More difficulty in mounting, and structural support may be required.

Mounting
Roof mounting leads to:
- Potential ability to collect daylight across the entire daytime.
- Less influence on building appearance than facade mounted systems.
- Occupation of the roof, especially systems that need protection constructions.
- Roof opening may be required to connect with the guide.
- More applicable in deep-plan buildings.

Facade mounting leads to:
- Preferably being south oriented.
- ‘See’ the sun or the bright sky less time during the day.

Figure 8: Sundolier custom-designed luminaire (top), and HSL conventional-like luminaire (bottom).
than the roof mounted system.
- More influence on building appearance than roof mounted system.
- Facade openings are likely required to connect with the guide.
- More applicable in high-rise buildings.
- Almost inapplicable in spaces reachable form the North facade only.

**Tracking system**
No tracking option leads to:
- Less collected daylight, since the system will benefit from the horizontal illuminance rather than the normal illuminance. This assumes that the collector is horizontally installed, but if tilted it will benefit from the normal illuminance for short time.
- Less complicated systems, which is likely cheaper and need less maintenance.

Limited tracking coverage leads to:
- Less operation time, and thus less collected daylight.
- More efficient between 15˚N and 40˚N in the Northern hemisphere, where the available illuminance and the tracking limits are balanced to achieve the most benefit [14].

**LIGHT GUIDANCE GUIDELINES**
The main aspects that stipulate the light guidance performance and applicability are their size, route, and transmittance.

**Size**
Big cross-section guide (i.e. light duct) leads to:
- High potential for conflict with other building services networks and structural system elements.
- Likely to require extra spaces or cause loses of usable spaces.
- Less flexible routing.
- A considerable attenuation in transported light is likely to happen with every bending.
- The bigger the light duct, the more efficient.

Small cross-section guide (i.e. optical fibres) leads to:
- High possibility of colour shifts.
- More applicable and more potentiality to reach further distance.
- Less modification in building is required for installation, and consequently more saving in the installation cost.

**Route**
Horizontal routing leads to:
- Floor to floor height bigger than the minimum is required for big light guides.
- Openings in the external and internal walls are required.

Vertical routing leads to:
- Openings in the building roof and floors are required.
- They can be routed through any suitable vertical ducts.
- The big ducts penetration of usable spaces is possible, which causes potential loss of rentable areas.

**Transmittance**
The better the light guidance transmittance, the further the distance that light can reach. Highly reflective materials of transmittance exceeding 99% per light bounce have recently become cost-effectively available, which are used to increase light ducts efficiency. Assuming light duct with 0.25m height, 99% transmittance, and light incidence angles range between 30˚ and 60˚, the number of bounces per meter are between ~7 and ~2.5. That means the remaining light after 5m is about 70-88%, and after 10m is 49–78%.

The transmittance of the plastic fibre optics used currently in the daylighting applications ranges from 90% to 97% per meter. Assuming fibre optic with transmittance of 96% used to channel light 5m and 10m, the remaining light are 81.5% and 66.5% respectively.

The above examples that are derived from real applications and prove that the light ducts are not less efficient than the fibre optics, and may under some circumstances be more efficient if the duct size is increased. The main drawback of ducts is their sizes, although they have the potential to deliver better quality.

**OUTPUT DEVICE GUIDELINES**
The main aspects that stipulate the output device performance and applicability are its size and shape, in addition to the number of luminaires, the mounting method and their layout.

**Size**
Systems that transport light via fibre optics more usually provide spot luminaires due to the nature of the narrow beams emitted from the end of the optical fibres. These can be used for many purposes such as task lights or wall washers. Side emitting optical fibres provide linear luminaires. Light ducts use circular and rectangular luminaires, which can also be provided by the optical fibres if proper diffuser is used to de-concentrate the emitting light. Luminous surfaces can be provided by dual-function light ducts that transport light, but at the
same times contains extractors to force proportions of light to emit along certain parts of the duct route.

**Shape**

Some systems distribute light via custom-designed luminaires. These may be functionally required for better distribution of light, but as well may be wanted to enhance the perception of daylight. Conventional-like luminaires may increase the system applicability, but on the expense of the perception of daylight.

**SUMMARY**

From the above, it can be noted that the concentrating ratio can be considered the most influential aspect in both performance and application for the following reasons:

- **It determines which daylight component can be collected**, therefore what the favourable sky condition is, and thus in which geographical location the system can be more efficiently used.

- **It determines the collector size**, which has a major influence on building appearance.

- **It determines guide size to a great extent.** That in turn is likely to affect the delivery distance, and more likely to affect the degree of ease of integration with other building systems and elements. Ultimately this determines the system applicability in buildings; where from this concern only, high concentrating systems is far more applicable.

- **It influences light quality.** Low light quality is a greater possibility with high concentrating systems. The optical fibres used in them are likely to notably change the light spectrum. Collecting direct illuminance only results in non-uniform distribution over the time under partially cloudy condition. De-concentrating the transported light if not effectively carried out, badly affects the uniform planar distribution.

- **It influences system cost.** High concentrating systems are more complicated and have more precise engineering, which raise the system cost in comparison with none or low concentrating systems.

In brief, high concentrating systems are generally more applicable but at the expense of the cost and light quality. In terms of light delivery and energy saving, a fair comparison between the two types is inapplicable, since it depends on how many systems are used to illuminate the required space. Any increase in systems number leads to increase in the delivered illuminance. So how many systems of each alternative have to be considered for a fair comparison? The number of systems may be assumed equal to the number required to achieve the recommended illuminance level, but systems’ ability to deliver daylight vary with daylight availability. So under which circumstances will the systems be designed? This argument shows the difficulty to select the best DGS, which has to be based on the balance between system performance and applicability on one side, and the lighting design requirements on the other side. In addition to the integration with building systems and elements that is subject to investigations in a separate study [15].

Knowing the DGS features, a very important question arises: is the delivered light still perceived as daylight? The daylighting effect is based mainly on three aspects, the visual connection with outside world, the unique spectrum of daylight, and the seasonal and diurnal changes in daylight colour and intensity. The first impact is completely unavailable via the DGS. The second one is subject to changes throughout the different optical processes, particularly in the high concentrating systems. The mixed light in cases of hybrid operation is likely to change the original spectrum. In addition, it makes the third aspect very questionable because the continuous and instant top up fades the intensity changes and risks the awareness of colour variations.

**REFERENCES**