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# Hybrid lighting systems: Performance and design

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Hybrid lighting systems simultaneously deliver daylight and electric light into the core of a building where they are combined and distributed via luminaires. The systems have only been developed in the last few years and accordingly there is little accumulated experience of light delivery or design methods. This paper presents measured data for a commercially available hybrid system located in the United Kingdom. The performance of the hybrid system is compared with that of a tubular daylight guidance system. The results are discussed in the context of use of the systems for a range of sky conditions. Design recommendations and limitations to address knowledge shortfalls for hybrid systems are put forward.

## 1. Introduction

Daylight guidance has been an interesting area of interior lighting innovation in recent years. The technology, based on highly efficient optical materials, has made possible the redirection of daylight into areas of buildings that cannot be lit using conventional glazing. The use of guided daylight, it is argued, fulfils the human desire for daylit interiors, with consequent beneficial effects on human well-being and performance, and permits energy conservation by the use of daylight as an electric lighting substitute.

The most commercially successful type of daylight guidance, passive tubular daylight guidance systems (TDGS), has been used worldwide during the last decade for a range of applications. There have been a number of studies of light delivery, design criteria and integration of TDGS with electric lighting, and design methods to provide comfortable and economic interior conditions using the systems have been promulgated.[1]

Hybrid lighting systems (HLS) are a more recent attempt to better combine the delivery of daylight and electric light to the same space. They channel daylight into the core of a building where it is combined with electric light within luminaires that are equipped with controls to maximise use of available daylight.[1] Although a number of systems have been developed, the technology is so new that no post-installation or post-occupancy studies of actual installations have been published.[2–4] Also, little information exists on design methods or criteria or performance of the systems in use.

This work presents measured data for a commercially available HLS located in a temperate latitude. These are compared with parallel measurements for a TDGS in a similar location. The implications in terms of light delivery from HLS for other geographic locations and for HLS design methods are set out.

## 2. Daylight guidance systems

### 2.1. Hybrid lighting systems

The HLS reviewed in reference 1, with one exception, use concentrated sunlight collected at roof level as their daylight source. The exception uses non-concentrated sunlight collected on the

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building façade. The roof-mounted collectors generally supply daylight to more than one luminaire usually via optical fibre cables.

The hybrid system used in this work is commercially available and manufactured by Parans.[4] It consists of a roof- or facade-mounted solar collector, optical fibre cables to transport collected daylight and a custom-designed luminaire. The Parans collector is an approximately 1 $m^2$ aluminium box with a glass top containing 62 pivot-suspended tracking and concentrating Fresnel lenses that move uniformly around their axis. A control system combines input from sensors with historic data of the solar path during the period of use, and ensures that, even in cloudy conditions, the axes of the Fresnel lenses track the sun path. The lenses move up to 60° from the perpendicular to the panel, forming a 120° measurement cone, which permits tracking of the order of 8 hours per day (Figure 1). Each lens concentrates the sunlight into 0.75 mm-diameter high performance polymethymethacrylate (PMMA) optical fibres, each bundled into four 6-mm-diameter flexible cables. These have a transmission of 95.6% per metre and can transport the collected sunlight up to 20 m. The hybrid luminaires are made of diffusing semi-transparent PMMA sheets. The light sources are the ends of the optical fibres, or tubular or compact fluorescent lamps equipped with automatic dimmers linked to sunlight delivery. The luminaires tested were suspended rectangular 'small' (45 × 45 cm and supplied by one cable) and 'large' (90 × 90 cm and supplied by all four; Figure 2). The luminaires were tested using daylight only.

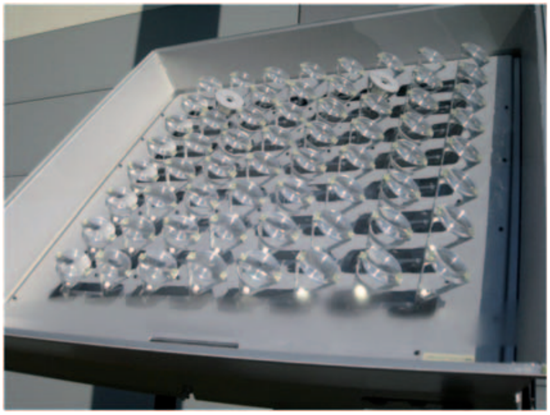

**Figure 1** Parans collector

## 2.2. Tubular daylight guidance systems

TDGS consist of a horizontal or inclined clear polycarbonate dome collector at the upper end, a rigid or flexible light transport tube (typically between 200 and 500 mm diameter) coated with highly reflective material as a transport device and, at the lower end, a light diffuser made of opal or prismatic material. In general terms, overall light transmission is a function of surface reflectance, input angles of the incident light, the proportions of the tube in terms of the ratio of length to diameter (aspect ratio), number and angles of bends and dome and diffuser transmittance ratios.[5,6]

## 3. Experimental investigation

The work investigated luminous flux output, luminous intensity and planar illuminance distribution for the Parans HLS and TDGS. The 'hybrid' system investigated consisted of a daylight-only device, which was the subject

**Figure 2** Parans 'large' luminaire (from Reference 4)

of the measurements, with the assumed addition of electric lamps for purposes of the subsequent energy consumption calculations.

### 3.1. HLS location

The HLS collector was installed on the roof of the University of Liverpool, School of Architecture, Liverpool, UK (53°25'N, 3°0' W). It was installed around 14 m above ground facing due south and tilted at approximately 35° from the horizontal. This enabled it to track the entire vertical path of the sun and a 120° cone of the horizontal path, between 120° and 240° from north. The collector faced Abercromby Square which is approximately 100 m wide and contains no tall buildings, trees or other obstructions. Buildings on the other side of the Square are of a similar height to the School.

The Parans luminaires were ceiling mounted in part of the room adjoining the collector site (approximately 3 m × 1.8 m × 2.2 m). This space had a dark grey carpet with three walls and the ceiling painted matt black. The fourth side was made of dark heavy duty blackout material such that all external sources of light were excluded. The connection from collector panel to luminaire was by four 20-m-long optical fibre cables.

### 3.2. HLS measurements and equipment

A goniophotometer, based on an optical length of 1 m, was installed beneath the luminaire to measure luminous intensity in the vertical plane for the quadrant 0°–90°. Illuminance was measured using calibrated photocells connected to a 16-channel data logger which also recorded simultaneous global horizontal external illuminance. From these measurements, the luminous intensity distribution was plotted and the luminous flux output calculated using the 'zone factor' method for symmetric luminaires described in the CIBSE Technical Memorandum 5.[7] Measurements were made from March 2010 to August 2010 inclusive. Readings of global horizontal external illuminance and nadir internal illuminance 2 m below the centre of the luminaire were taken simultaneously every 10 minutes throughout the whole period.

Separately, luminous flux output was measured using a cubical box that approximated the characteristics of a photometric integrator. The box consisted of a hardboard cube of 0.8 m side, with interior joints sealed and coated on the inside with matt white emulsion paint. Separate lids were constructed for the box with different-sized holes in the centre to accommodate the luminaires or the optical fibre cable. A calibrated photocell, centrally mounted on a 20-cm bracket facing the base of the box was used to measure illuminance whilst acting as its own baffle to direct light from the source. The box had been calibrated in the laboratory of a major lamp manufacturer using lamps of known output with one of the lids.

### 3.3. TDGS measurements

The TDGS was in the roof space of the University of Liverpool Pilkington Building with unobstructed collectors above the roofline. The TDGS diffuser was mounted in the roof space surrounded on all sides with heavy duty blackout material. This system was the subject of an earlier study which had determined the luminous intensity distribution and the relationship of total luminous flux output to nadir illuminance.[5] In summary, the system was a 1.2-m long, 330-mm diameter guide with a dished opal diffuser. Limitations of the building determined the maximum length of guide that could be measured. Accordingly only nadir illuminance was measured 1 m below the diffuser and recorded using data logging equipment similar to that described above, over the measurement period.

### 3.4. Liverpool solar resource

Liverpool has a maritime temperate climate with an annual mean daytime global horizontal illuminance hourly value of 23.8 klux made up of diffuse and direct components of

14.7 klux and 9.1 klux, respectively. Over the measurement period, the corresponding monthly mean values are 29.9 klux, 18.7 klux and 12.1 klux, with peak values of 34.7 klux, 19.6 klux and 15 klux in July.[8]

Typical sky conditions over the measurement period are 28.5% sunny, 40.7% intermediate and 30.8% overcast.[8] Daily sunshine duration ranged between 10:50 and 17:02 hours with mean of 15:00 hours. The earliest local sunrise and sunset time were 04:43 and 17:50, respectively. The latest local sunrise and sunset time are at 07:00 and 21:45, respectively.[9]

## 3.5. Results for HLS

### *3.5.1. Measurements*

Throughout the measurement period, maximum solar elevation angle reached 59.9° with solar azimuth angle between 46° and 312.5°.[10] A total of 26,496 readings were recorded of which 16,481 (62.2%) were during daylight hours. Of the latter, only 6,684 (40.6% of daylight readings) were gathered within the tracking limits – that is within the 120° active cone. However, considerable quantities of sunlight were collected when sun paths were up to 25° past the tracking limits in all directions. Some 4000 more readings of this nature were collected and used in the subsequent analysis.

### *3.5.2. Illuminance*

A summary of the 6,684 illuminance values at 2 m below the centre of the luminaire and within the tracking limits is shown in Table 1. Some 30% of the internal values are above 300 lux and approximately 60% are below 50 lux. The relationship between average external and internal values, shown in Figure 3, is nearly linear between 35 klux to 85 klux external. Below 35 klux, the predominantly cloudy sky generally delivers insignificant values of internal illuminance. A plot of all values in Figure 4, however, suggests that under some conditions, external conditions giving global values of below 35 klux may deliver internal values of the order of 200 lux. The explanation for this is that the system works efficiently under clear skies by delivering concentrated direct sunlight, but less so under overcast conditions where the low luminous intensity source cannot be effectively concentrated. Under partially cloudy conditions, the illuminance delivered depends on the degree to which the sun is obscured. It is apparent that above 85 klux, the rise in internal illuminance tends to slow and levels out around 100 klux, probably due to the external sensors going out of range.

Light delivery variation under partially cloudy conditions is illustrated in Figure 5

**Table 1** Global external horizontal illuminance and corresponding internal illuminance 2 m below the centre of the luminaire

| External illuminance, Y, range (klux) | External illuminance average (klux) | Internal illuminance average (lux) | Number of readings | External illuminance % | External illuminance, cumulative % |
|---|---|---|---|---|---|
| $Y > 100$ | 107.3 | 780 | 300 | 4.5 | 100 |
| $90 < Y \leq 100$ | 94.9 | 764 | 384 | 5.7 | 95.5 |
| $80 < Y \leq 90$ | 84.9 | 714 | 440 | 6.6 | 89.8 |
| $70 < Y \leq 80$ | 75.4 | 627 | 387 | 5.8 | 83.2 |
| $60 < Y \leq 70$ | 65.5 | 490 | 334 | 5.0 | 77.4 |
| $50 < Y \leq 60$ | 55.1 | 353 | 476 | 7.1 | 72.4 |
| $40 < Y \leq 50$ | 45.8 | 165 | 740 | 11.1 | 65.3 |
| $30 < Y \leq 40$ | 36.0 | 63 | 1061 | 15.9 | 54.2 |
| $20 < Y \leq 30$ | 25.6 | 16 | 1178 | 17.6 | 38.3 |
| $10 < Y \leq 20$ | 15.3 | 12 | 1029 | 15.4 | 20.7 |
| $Y \leq 10$ | 7.3 | 14 | 355 | 5.3 | 5.3 |

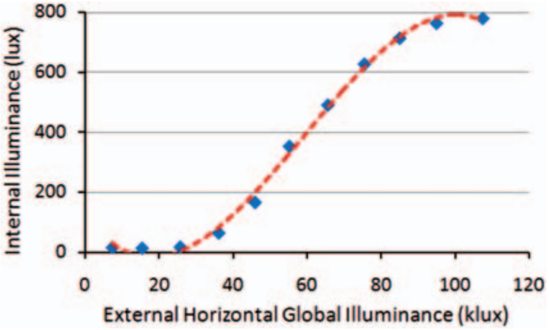

**Figure 3** Relationship of the external global horizontal illuminance to the average value of nadir illuminance delivered by the Parans system

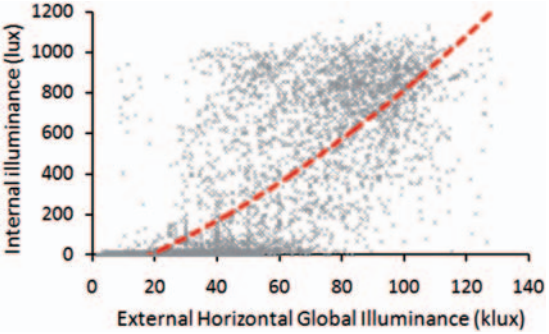

**Figure 4** Relationship of the external global horizontal illuminance to all values of the nadir illuminance delivered by the Parans system

and shows measured internal nadir illuminance and corresponding external illuminance at 10-second intervals during a day in February 2010. This confirms that the internal illuminance becomes negligible when the external illuminance falls below 30 klux. When variation over a 30-minute period is studied (Figure 6), it can be seen that internal illuminance varies between 0 and 700 lux two or three times within 1 minute. These rapid changes have implications for the longevity of lamps within the HLS and for its control system, and for occupier comfort. It can be observed that the internal illuminance is around 700 lux in the periods 12:23 to 12:26 and 12:47 to 12:50, but that the external illuminance was 75 klux and 100 klux, respectively. The explanation for this may be that the measured external illuminance is a global illuminance but the HLS is effectively delivering the direct component only but further measurements of both components separately would be needed to verify this.

### 3.5.3. *Luminous flux output*

The characteristic light delivery of the system described above produces a corresponding variation in delivered luminous flux. The estimated outputs of the luminaires supplied by a 20-m optical fibre cable and

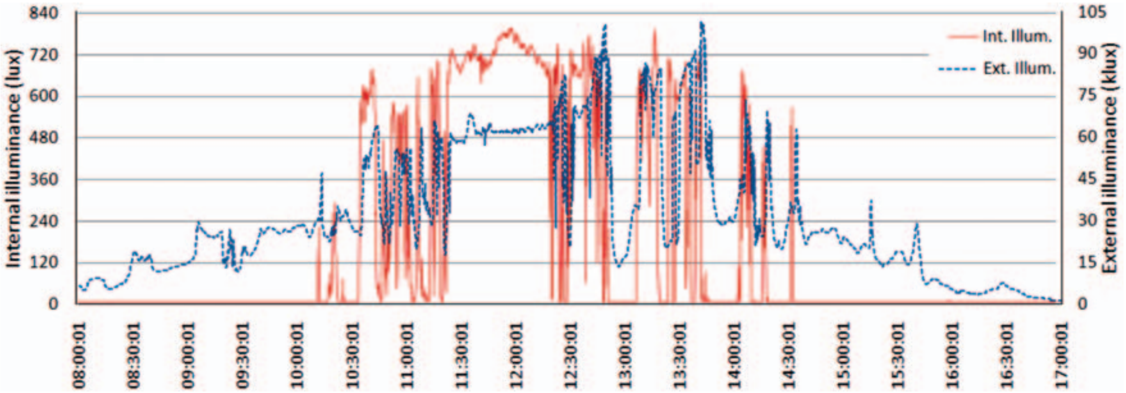

**Figure 5** External illuminance under a partially cloudy sky and corresponding nadir internal illuminance delivered by the Parans system

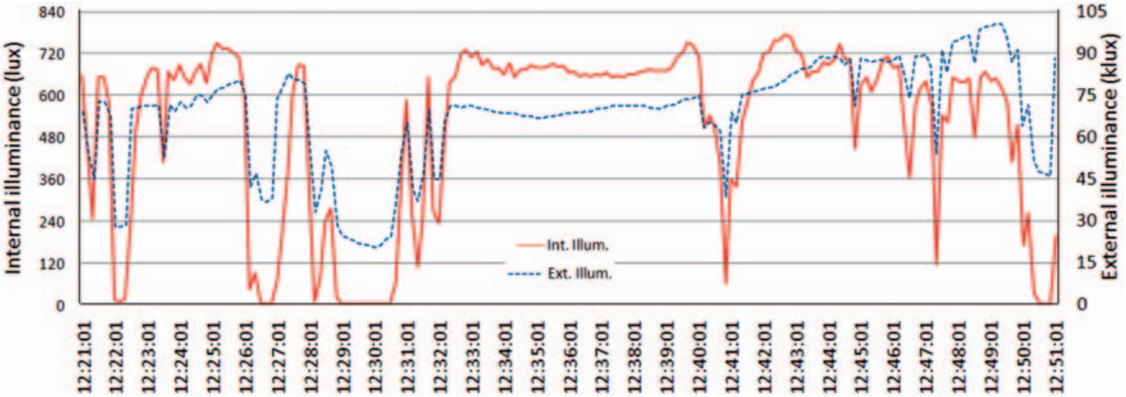

**Figure 6** Variation in internal illuminance delivered by the Parans system over 30 minutes and the corresponding external illuminance

**Table 2** Luminous flux from hybrid lighting systems (HLS) output devices for given external horizontal illuminance (20 m optical fibre cable)

| External illuminance (klux) | 20 | 50 | 100 | 20 | 50 | 100 |
|---|---|---|---|---|---|---|
| Luminous flux output measurement tool | Goniophotometer (lm) | | | Integrator (lm) | | |
| Four optical fibre cable luminaire | Negligible | 1550 | 3100 | Negligible | 1995 | 3990 |
| One optical fibre cable luminaire | Negligible | 380 | 740 | Negligible | 490 | 940 |

measured using the two methods described in Section 3.2 are shown in Table 2. Note that the outputs vary almost linearly with external horizontal illuminance above 30 klux for the reasons described above. The differences between the estimates using the two methods may be attributed to the limitations of the field measurement methods used with the integrator method producing consistently higher values. Whilst every effort was made to ensure that alignment of optical fibre tails, luminaire surfaces and measurement cells were accurate; that the cells were in calibration; and that stable sky conditions applied when measurements were undertaken, small variations in any of these influence the resulting polar curve and the subsequent TM5 calculation procedure. The integrator method would better account for such variations in spatial output from a daylight device.

### *3.5.4. Polar curve*

The goniophotometer was used to measure luminous intensity for both the Parans L1-large and L1-small luminaires as supplied by the manufacturer. Readings were taken with the apparatus aligned axially ($C = 0$) for a range of external horizontal illuminances above 50 klux and the results averaged. Polar curves for the two luminaires are shown in Figure 7. The characteristics of the curves are related to their construction (Figure 2). Luminous flux leaves the output device in three ways; some directly via the holes in the diffuser located directly below the ends of fibre optic cables, the rest scattered by the PMMA sheets or sideways via the gap between the sheets. The influence on the polar curve of the light passing directly through the holes is apparent.

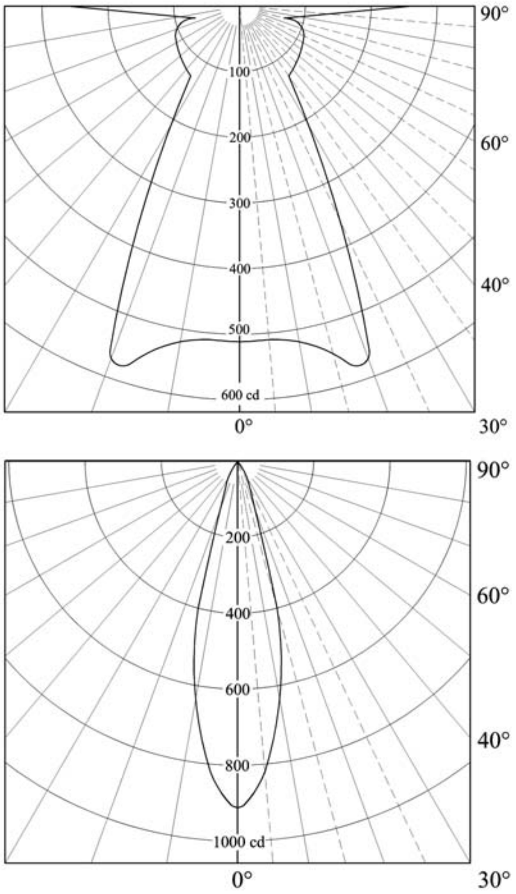

**Figure 7** Top: Parans *L1-large* luminaire (Nadir luminous intensity 273 cd/1000 lumens). Bottom: Parans *L1-small* luminaire, (Nadir luminous intensity 1220 cd/1000 lumens)

Figure 8 illustrates the horizontal illuminance distribution at 2 m below an L1-large luminaire for a global horizontal external illuminance of 45 klux. The peak illuminance of 390 lux is directly under holes in the diffuser with that under the centre of the luminaire being 305 lux. The illuminance decreases sharply at some 50 cm from the centre of the luminaire, dropping to below 50 lux at 1 m and a negligible value at 2 m. This suggests that uneconomically close luminaire spacing would be required to maintain an acceptable average horizontal illuminance and planar uniformity if the devices were to be used in daylight delivery mode only.

### 3.6. Results for TDGS

A plot of all measured nadir and external illuminance values in Figure 9 exhibits considerable scatter. This is due to the quantity of luminous flux delivered by the short guide being heavily influenced by sun position. Using the measured nadir and external illuminance, and the luminous intensity distribution from Reference 5, estimates were made of luminous flux output using the TM5 method for a range of external illuminance values. Row 1 in Table 3 shows the luminous flux output with a 1.2 m transport element and, using data from CIE Publication 173,[6]

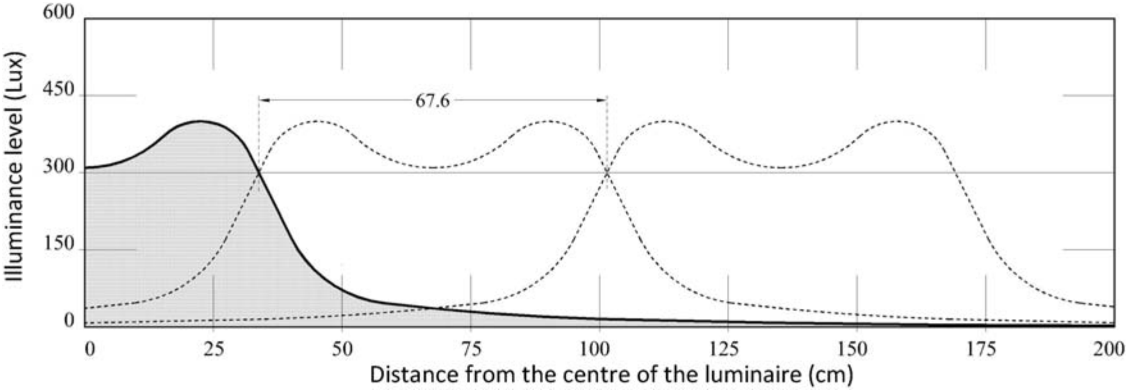

**Figure 8** Horizontal illuminance distribution at 2 m below a repeated *L1-large* luminaire

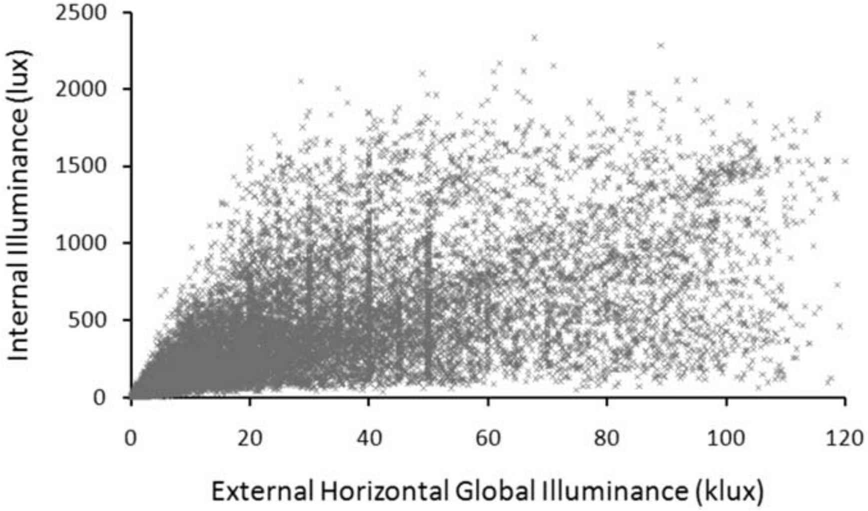

**Figure 9** Relationship of external global horizontal illuminance to all values of nadir internal illuminance delivered by tubular daylight guidance systems (TDGS).

**Table 3** Calculated luminous flux from tubular daylight guidance systems (TDGS) output devices for given external horizontal illuminance

| External illuminance (klux) | 20 | 50 | 100 |
|---|---|---|---|
| Luminous flux output measurement tool | Goniophotometer (lm) | | |
| 330 mm diameter output device, 1.2 m guide | 1355 | 2554 | 3520 |
| 330 mm diameter output device, 5 m guide | 665 | 1255 | 1720 |
| 330 mm diameter output device, 20 m guide | 342 | 643 | 890 |

estimates were made of outputs from similar 5 m and 20 m long guides. It is clear that TDGS can deliver useful quantities of luminous flux when external illuminance is of the order of 20 klux and below, and that the output of the TDGS is comparable to that of the small hybrid luminaire for external values over 50 klux. Figure 10 compares luminous flux outputs delivered over 5 m travel for different external illuminance values using 330 mm diameter TDGS and one 30 mm Parans optical fibre and small luminaire. The measurements, and those quoted in Reference 11, confirm that HLS deliver more flux above 30 klux external, and TDGS vice versa.

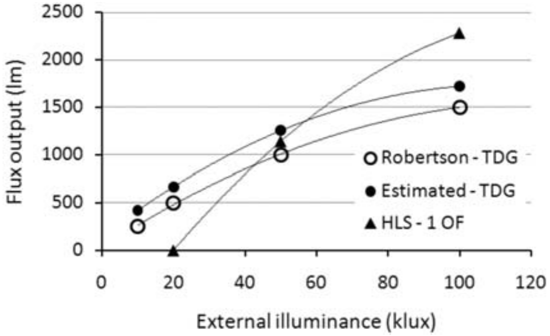

**Figure 10** Comparative luminous flux outputs for different external illuminances delivered over 5 m travel using 330 mm tubular daylight guidance systems (TDGS) and one 30 mm Parans optical fibre and small luminaire

## 4. Design tools

Prediction methods for daylight guidance systems can usually be broken down into two parts; the first being an estimation of the amount of light delivered by the system and the second a method of predicting the likely distribution of this light.

### 4.1. HLS light delivery

Light delivery is influenced by the optical losses that occur, variously, in collector, output device and optical fibre. Using the recorded external horizontal global illuminance and the combined area of the 62 lenses in the collector, the flux collected at a given time was estimated. The simultaneous system output was determined as described in Section 3.2. This enabled the total efficiency to be determined. The average for the system with the 20 m long optical fibre and the large luminaire was 21.7%. The contribution to light loss caused by the optical fibre can be determined using manufacturer's data. Figure 11 shows both total transmittance, and that of the optical fibre only, as a function of cable length. This information was combined with the luminaire outputs for the range of external global illuminance to give Figure 12.

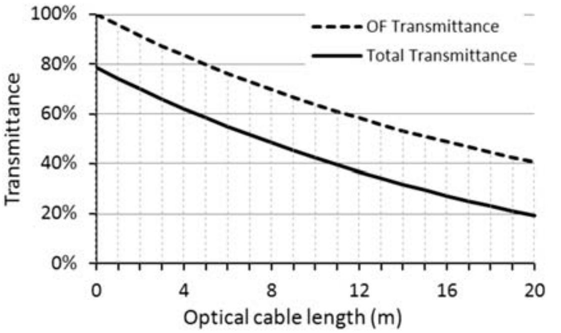

**Figure 11** Parans transmittance of total system and optical fibre only

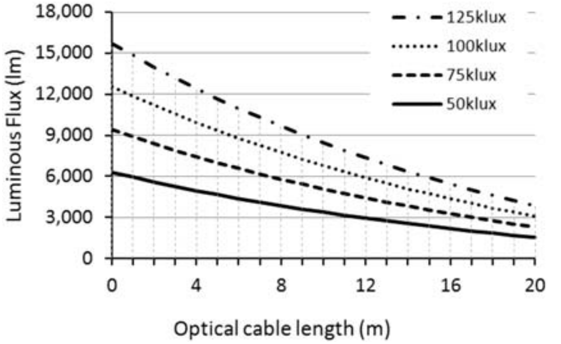

**Figure 12** Parans luminaire outputs for a range of external global illuminance

### 4.2. Distribution of light within the room

The combination of luminaire luminous flux output and polar curve can be used, either directly in point-by-point calculations or as the basis of spacing to height ratio (SHR) and utilisation factor calculations. Selection of an appropriate calculation method for hybrid luminaires is complicated by their dual function as predominantly daylight devices under clear skies and as conventional electric luminaires at other times.

Calculations of the type described above could be made for daylight-only devices similar to those measured in this work. However, it could be argued that there would be little value in these since, firstly, the nature of the polar curve would mean that the SHR necessary to give an acceptable work-plane illuminance uniformity would be uneconomically small (spacing less than 1 m for L1-large) and, secondly, in hybrid use the daylight is automatically 'topped-up' by electric lighting. Notwithstanding this, a daylight only utilisation factor table can be calculated for the luminaires using the TM5 method,[7] and an extract for a Parans large luminaire is shown in Table 4. Similar data exists for daylight-only TDGS output devices but, since these function separately from any electric lighting in the same room that may be used for design purposes.[11]

The luminous flux output in Figure 12 may be used for calculation of the daylight

**Table 4** Extract of utilization factors for Parans *L1-Large* luminaire, spacing to height ratio (SHR) *NOM* = 1.00

| Reflectance | | | Room index | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| C | W | F | 0.75 | 1.00 | 1.25 | 1.50 | 2.00 | 2.50 | 3.00 | 4.00 | 5.00 |
| 0.7 | 0.5 | 0.0 | 0.55 | 0.61 | 0.66 | 0.69 | 0.74 | 0.77 | 0.79 | 0.83 | 0.85 |
| | | 0.1 | 0.57 | 0.63 | 0.68 | 0.72 | 0.77 | 0.81 | 0.84 | 0.87 | 0.90 |
| | | 0.2 | 0.58 | 0.65 | 0.71 | 0.75 | 0.81 | 0.85 | 0.88 | 0.93 | 0.96 |
| | | 0.3 | 0.60 | 0.68 | 0.74 | 0.78 | 0.85 | 0.90 | 0.94 | 0.99 | 1.03 |
| | 0.3 | 0.0 | 0.49 | 0.55 | 0.60 | 0.63 | 0.68 | 0.72 | 0.74 | 0.78 | 0.81 |
| | | 0.1 | 0.50 | 0.56 | 0.61 | 0.65 | 0.71 | 0.75 | 0.78 | 0.82 | 0.86 |
| | | 0.2 | 0.51 | 0.58 | 0.63 | 0.67 | 0.74 | 0.78 | 0.82 | 0.87 | 0.91 |
| | | 0.3 | 0.52 | 0.59 | 0.65 | 0.70 | 0.77 | 0.82 | 0.86 | 0.92 | 0.96 |
| | 0.1 | 0.0 | 0.44 | 0.50 | 0.55 | 0.58 | 0.63 | 0.67 | 0.70 | 0.74 | 0.77 |
| | | 0.1 | 0.45 | 0.51 | 0.56 | 0.60 | 0.65 | 0.70 | 0.73 | 0.78 | 0.81 |
| | | 0.2 | 0.45 | 0.52 | 0.57 | 0.61 | 0.68 | 0.72 | 0.76 | 0.82 | 0.86 |
| | | 0.3 | 0.46 | 0.52 | 0.58 | 0.63 | 0.70 | 0.75 | 0.80 | 0.86 | 0.91 |

penetration factor (DPF), the metric advanced for quantification of daylight delivered by guidance systems. DPF is defined as ‘the ratio of the illuminance at a point due to light received via a light guide from the sky to the illuminance on a horizontal plane due to an unobstructed hemisphere of this sky’.[5] The DPF of the system was calculated using 12 measurement runs of 4–5 h each were made, equating to some 600 readings under as far as is practical a clear sky. The nadir average DPF 1.5 m below the luminaire varied between 0.62% and 1.53% with a mean of 1.07%. Using all measurements within the system tracking limits (6684 readings), the average nadir DPF under all sky conditions was 0.71%. This compares with a DPF varying between 0.15% and 0.47% with mean of 0.29%; measured 1.5 m below a 2.7 m long, 250 mm diameter TDGS lined with 98% specular material, topped with twin domes, and equipped with a frosted diffuser.[12] However, whether the DPF concept is meaningful in the case of hybrid systems where daylight is automatically ‘topped-up’ by the lamps is also open to debate.

For hybrid systems to be effective at all times they must be designed for the ‘worst case’ which is as an electric only system. The function of the daylight element under these circumstances is to provide distinctive temporal and spatial variation of illuminance. Figure 13 shows areas of local high daylight illuminance beneath luminaires, which might be considered an attractive feature. The upshot of this is that hybrids should be designed to electric lighting norms meaning that conventional electric lighting photometry is necessary. This is not currently published for the Parans devices.

## 5. Potential for energy saving

### 5.1. Energy saving calculation procedure

One of the arguments advanced by the advocates of light guidance is that daylight delivered deep into interiors allows energy to be saved by electric light substitution. The proportion of each source used (the usage pattern) and any resulting energy saving varies with daylight conditions. To investigate this, an arbitrary working space was lit, in turn, using an electric lighting system (ELS) with linked TDGS, and Parans output devices with the assumed addition of lamps to form a hybrid luminaire. The specification of the room and its lighting equipment was as follows:

- Single storey windowless room 20 m × 10 m × 3 m-high with a pitched roof necessitating light transport of 5 m. Room surface reflectance of 70%/30%/20%.

**Figure 13** Daylight-only luminaire in use (from Reference 4)

- Lighting systems designed to deliver variously 300 lux, 500 lux and 700 lux average working plane illuminance.
- An ELS of 600 mm$^2$ surface-mounted opal luminaires selected to resemble as closely as possible the Parans luminaires. Twenty-eight luminaires equipped with three 18 W lamps were required to provide an average illuminance of 300 lux, 36 with four 18 W lamps for 500 lux and 36 with four 24 W lamps for 700 lux. These were positioned at close to the recommended spacing to height ratio.
- The TDGS was designed to provide a'well day-lit space' having a DPF of 0.5%.[13] This required twenty-eight 330 mm diameter guides in a spacing grid co-ordinated with that of the ELS.
- In the absence of photometric information for the Parans devices in hybrid mode, these were assumed to have similar optical properties to those of the ELS luminaires, and with daylight delivered using one, two, three or four optical fibres connected to a Parans luminaire.

An identical procedure was followed for both ELS/TDGS and HLS. The measured external/internal illuminance data was used to generate the luminous flux emitted by the output devices for the full range of external illuminances. Average work plane illuminance was estimated by a lumen method calculation assuming utilization factors variously from Reference 3 or the ELS luminaire manufacturer's data. The study assumed working hours extending from 0800 to 1800 hours, 7 days a week for the measurement period. Calculations were performed every 10 minutes and the supplementary illuminance and wattage required by the ELS to reach the design work plane illuminance for each case calculated. The energy saving relative to full electric load was computed.

## 5.2. Energy saving results

Energy savings and lighting usage patterns for the measured external conditions are shown in Table 5. 'Full daylight' was considered to be when the system delivered an average work

**Table 5** Lighting usage patterns and load savings in example room

| | TDGS 330 Ø | | | HLS 1 OF | | | HLS 2 OF | | | HLS 3 OF | | | HLS 4 OF | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Design illuminance (lux) | 300 | 500 | 700 | 300 | 500 | 700 | 300 | 500 | 700 | 300 | 500 | 700 | 300 | 500 | 700 |
| Load saving (%) | 48 | 30.1 | 21.5 | 24.4 | 12.2 | 8.7 | 38.6 | 24.5 | 17.5 | 48.7 | 35.7 | 26.2 | 53.7 | 43.3 | 34.3 |
| Full daylight (%) | 11.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 11.8 | 0.0 | 0.0 | 26.5 | 7.9 | 0.1 | 42.1 | 18.1 | 6.2 |
| Hybrid (%) | 75.4 | 86.7 | 86.7 | 55.5 | 55.5 | 55.5 | 42.3 | 55.4 | 55.5 | 29.0 | 47.6 | 55.4 | 13.4 | 37.4 | 49.3 |
| Full electric (%) | 13.3 | 13.3 | 13.3 | 44.5 | 44.5 | 44.5 | 44.5 | 44.5 | 44.5 | 44.5 | 44.5 | 44.5 | 44.5 | 44.5 | 44.5 |

plane illuminance equal to or greater than 300 lux, 500 lux or 700 lux, and full electric lighting when the daylight illuminance was equal to or less than 50 lux. Otherwise, it is considered hybrid lighting. There is considerable variation in both usage pattern and electric load saving as a function of external illuminance for both types of guidance system.

In general, the load savings are greater at lower design illuminance values where more electric light is substituted. The TDGS produces load savings that are slightly better than the HLS with two optical fibre cables but inferior to that with three optical fibre cables. This is not just because of the varying capacity of the systems to deliver daylight. Inspection of Tables 2 and 3 shows that for external illuminance above 30 klux a single optical fibre cable delivers a comparable output to a TDGS device for similar external conditions and transport lengths. However, Table 1 suggests that some 38% of measured external values were under 30 klux. At these levels, the HLS ceases to deliver useful quantities of daylight but the TDGS continues to do so. Thus, the overall energy performance of the TDGS was enhanced by its ability to work effectively in the lower range of external illuminances.

The major differences in the lighting usage pattern between the two systems are that the TDGS may operate as 'hybrid lighting' for some 80% of time whereas the HLS varies between 30% and 50%. These figures are reflected in the amount of 'full electric lighting' for the respective systems. This further indicates the ability of TDGS to deliver light under cloudy conditions. The HLS managed to achieve 'full daylight' consistently only when equipped with three optical fibre cables, and even under these circumstances for substantially less than half the time. The daylight luminous flux contribution in these cases was substantially above half the total luminaire output. In summary, it appears that the HLS is much better in providing a full daylight condition, but the TDGS is able to provide a more consistent delivery of daylight for a variety of external conditions.

## 6. Discussion

### 6.1. Light delivery

It is clear that the quantity of daylight delivered depends on system type and mode of use, and the solar resource. Using concentrated sunlight as a source enables HLS, under favourable conditions, to deliver to luminaires flux outputs comparable to those of ELS lamps. The major drawback however is that that HLS of this type only work effectively under clear skies but much less so under overcast or partially cloudy conditions. The evidence of this study is that below external illuminances of about 30 klux, the HLS delivers negligible quantities of daylight luminous flux. This is a major drawback for the use of these devices in temperate latitudes. The TDGS were able to transfer both sunlight and skylight over the whole range of external illuminance conditions. This is a compelling argument for their use in temperate latitudes or where cloudy skies predominate, and indeed there is evidence that TDGS has a slightly higher efficiency under cloudy than under clear skies.[12] Under some sky types, notably partially cloudy, there is considerable short-term variation in daylight delivery. These rapid changes have implications for the longevity of lamps within the systems and for the control system.

The different light transport methods in the two types of system have implications for the distance from the building envelope that daylight luminous flux can be delivered. Using highly concentrated sunlight and optical fibre transport, the HLS permits daylight penetration much deeper into a building than is generally possible using TDGS. Indeed, the measurements in this work suggest that under favourable conditions a Parans system can deliver a luminous flux comparable to an electric lamp some 20 m into a building. In practice, TDGS are rarely used with more than about 10 m of guide because of their optical and physical constraints.[13] There is evidence that HLS is a more efficient way of delivery of daylight deep into a building. Based on the measurements, the average work plane DPF for a typical office using the HLS was 0.71%. This is superior to that of 0.29% delivered by a 2.7 m long, 250 mm diameter TDGS lined with 98% specular material and topped with twin domes; lighting the same area. However, the important difference in the two systems is that the TDGS output devices deliver daylight separately from that of the ELS whilst the hybrid luminaires are configured to automatically 'top-up' daylight using their own lamps. Thus, the daylight component in an HLS is simply part of the luminaire output. Whether the DPF concept is meaningful in this case is open to debate.

## 6.2. Perception of daylight

A more fundamental question is whether the HLS output would be recognised as 'daylight' at all. There is evidence from previous studies that building users recognised that a TDGS could be regarded as providing 'daylight' if the amount delivered was sufficient. These studies also suggested that if the daylight output devices resembled luminaires, they were perceived as delivering electric light.[13] The HLS have been shown in this work to be capable of delivering large quantities of concentrated sunlight. However, given that the Parans output devices have all of the characteristics of a luminaire, it is questionable whether users would regard the output as daylight with all its associated benefits. Spatial and diurnal illuminance variation is one of the unique properties of daylight. There is a danger that the automatic illuminance 'top-up' necessary for energy saving that is a feature of HLS will create a uniformly lit space that users will perceive as dominated by electric lighting no matter how much daylight is being delivered. Similarly any user perception of diurnal variation would require a daylight device that is capable of mimicking in some way external illuminance. It is at least arguable that control of 'top up' light on a working plane should include some diurnal and seasonal variation. To answer these questions, studies of user reaction to actual installations are required.

## 6.3. Light distribution

There are a number of concerns relating to the distribution of light delivered via hybrid luminaires. This work assumed an intensity distribution of the hypothetical luminaire as that of a diffusing electric luminaire of similar size and diffuser type. It is clear that the addition of one or more end-emitting optical fibres will change this since the polar curves of the daylight (point sources) and electric lighting (linear sources) components differ markedly. For practical design purposes, this information is required. Although there are published polar curves and recommended spacing to height ratios for TDGS output devices, there are none for HLS luminaires.

This leads to the wider question of sub-optimal optical processes within the luminaires – the optics necessary for electric sources need modification to accommodate the daylight emitters and vice versa. Whilst the use of end-emitting optical fibres may be acceptable for delivering daylight to spotlights, side emission might be more appropriate for a luminaire, similar to that assumed, in which the electric light component is distributed by a diffuser. Although luminaires with the latter configuration have been developed, they are not yet available commercially.[2]

### 6.4. Architectural implications

Daylight guidance systems may affect interior architecture and have implications for other building systems since they require vertical and/or horizontal paths for guides. The main unique concern is fire resistance and the prevention of passage of smoke in both vertical and horizontal transport components, which is usually addressed by provision of fire compartments. HLS and TDGS based on light guides may pass through compartment enclosures and a range of measures including fire-protected ducts, fire dampers and fire-resisting cladding may be required. HLS that deliver daylight via flexible optical fibre cables would require little more space and fire provision than electrical or communications cables. They also have few implications for interior spatial layout, and merely require coordination with other building services. On the other hand, TDGS may require dedicated ducts through several storeys. These are of widths measured in centimetres and lengths in tens of metres and may occupy rentable floor area and restrict internal spatial flexibility. By way of illustration of this point, the measurements indicate that a single 30-mm diameter flexible optical fibre cable can deliver similar quantities of luminous flux to a similar length of 330 mm diameter rigid tube TDGS.

### 6.5. HLS design methods

Standardised methods of design calculation, data production and exchange are universal in the lighting industry. Electric and daylight codes set out recommendations for equipment, illuminances and surface properties and recent work extends this guidance to TDGS.[6] The present study makes it possible to suggest tentative design methods for HLS based on likely luminous flux outputs and luminous intensity distributions. Estimates of luminous flux input to an HLS based on external illuminance conditions are possible. These are more reliable in locations where clear skies predominate. For cloudy conditions, the assumption must be that no useful luminous flux can be gathered. Estimates of light loss can be made for individual elements of the HLS. In the present work, the collector and luminaire appear to account for about 20% of the total, but there is little in the literature about similar losses from other types of HLS. On the other hand, there is extensive published information about losses in the optic fibre transport element. In the absence of published material, the polar curves in this work were produced using short range field measurement photometry. From these, it was shown that it is possible to compile an utilisation factor table for an HLS daylight component. However, because the daylight is subsumed into the output of an electric luminaire, it can be argued that there is little value in this approach. Before designers have confidence in HLS as an alternative to other electric and daylight systems, photometric data to industry standards data for hybrid luminaires, similar to that available for TDGS, are required.

When this is available, the question is ‘How is it used’? In principle knowing the luminous flux output and the polar curve for any source a range of calculations are possible. Hybrid systems must be able to operate at night and thus must be designed for the ‘worst case’ which is as an electric only system. For this, photometric data in the form of an utilization factor for the luminaire and predicted luminous flux outputs for likely external conditions are necessary. The function of the daylight element under these circumstances would be to displace electric load and/or to provide a distinctive 'daylight' temporal and spatial illuminance variation. The trade-off between the two functions requires further work to balance the benefits of user satisfaction against the costs of any increased electrical load.

### 6.6. Limitations of the work

Any work of this nature has a number of limitations. The TDGS used could be considered representative of that technology, but there are currently no commercially available HLS luminaires. The 'hybrid' system luminaire studied in fact consisted of a daylight only device which was the subject of the measurements, with the assumed addition of electric lamps. As noted, these additions will alter the optics and photometric performance of the system. Also in practice there are likely to be efficiency losses in trading a lumen of daylight for a lumen of electric light using dimming hardware given the non-linearity in the lumen output with power reduction. Notwithstanding this, the study could be considered to provide an indication of the performance of the systems. The techniques of field measurement used provide data which, although satisfactory for the estimations used in this work, would have to be replicated using test house standard photometry for design purposes. The measurements were restricted, due to building works, to a summer period when larger amounts of clear sky conditions prevailed than in a winter period of similar length. The typical winter sky condition in northern Europe of overcast conditions suggests that HLS in these areas would operate for long periods as conventional ELS.

The results of this work are in terms of light delivery and electricity savings relative to the electric lighting only case. The savings in absolute terms would be higher with increases in cost of electricity and the systems would become more attractive economically. No account has been taken of capital costs of providing the equipment. The wider question of the long-term economics of the various systems has been addressed in other work.[14]

## 7. Conclusions

Further research and development is necessary before sun-concentrating HLS of the type used in this study can take their place alongside TDGS as a form of daylight guidance used by mainstream lighting designers. The most pressing are the development of luminaires that accommodate both types of source, suitable photometry systems for these luminaires, and of controls that permit the daylight element to be apparent. It is clear that the design process for this type of HLS is akin to that of conventional electric systems. More generally, the systems work best in conditions of direct sunlight and, arguably, for temperate latitudes where cloudy skies predominate, TDGS may be a more suitable method of daylight provision.

The complete integration of daylight and electric lighting has long been an ambition of lighting designers. HLS offer one approach to make this possible but whilst hardware development is proceeding rapidly its practical use is still very much at the exploratory stage. This work demonstrates some of the challenges of using HLS in temperate latitudes using examples of the first 'daylight luminaires' to come onto the market. A second generation, which promise improved light collection and transport, is now being installed in commercial applications. However, these are being constructed before a full understanding of the properties of the systems and their integration into buildings are available. Only when post-occupancy data is available will the full potential of the systems be realised, a sequence of events which occurred in the early years of the development of TDGS.

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