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# Daylight Performance of Elbow Geometry in Light Pipe Models

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**Abstract**

Light pipes are innovative daylight lighting systems often used linearly which transmit light through reflections on carrying surfaces. However, in order for the system to be used in more complex buildings, it should be possible to integrate one or more elbows into the system if needed with the purpose of deliberately change the direction of light transmission. In this study, attention is drawn to the assumption that the light carried in the elbowed light pipes is related to the design of the elbow geometry as well as variables such as pipe length, diameter (aspect ratio), reflectance and transmittance values of the components, sky conditions, solar angles, latitude-longitude data, elbow angle, etc. The purpose of the study is to investigate the daylight performance of elbowed light pipe system and different elbow geometries. In this respect, the models used in scientific studies and commercial products were compared and new elbow models were proposed. Daylight levels (lux) and Daylight Factor (DF) achieved through a numerical simulation software based on a correct method and well-established algorithm were evaluated as performance measures. Whether the light levels reached as a result of the analyses alone are sufficient to illuminate the space varies depending on the dimensions, function and duration of use of the space.

**Keywords**

light pipes, daylight, modelling, elbows, light transmission systems, interior illuminance distribution

## 1 Introduction

The positive effects of daylight on people's psychological well-being and comfort have increased efforts to make it more actively preferred in buildings (Carter, 2014). Additionally, in the last decades the use of daylight instead of electric lighting in buildings is being supported as a strategy for energy saving and environmental protection, in particular to reduce greenhouse gas emissions from the construction sector (Baglivo et al., 2017; Carter, 2014). As a daylight lighting system in buildings, traditional daylighting techniques were used on the façade and roof surface for buildings with high shell and volume ratio. Traditional daylighting techniques used in high-rise and deep plan buildings built in line with new construction forms and changing user needs are insufficient in transmitting daylight to spaces (Mayhoub, 2014). In this context, strategies were developed to improve traditional daylight techniques, develop glazing systems for facades, or invent innovative daylight systems (IDS) to use daylight in new building forms and deep spaces (Mayhoub, 2017).

Light pipes which are believed to be the most suitable innovative daylight system commercially (Al-Marwaee and Carter, 2006; Mayhoub, 2014) are defined in the literature as Tubular Daylight Guide Systems (TDGS) (Carter, 2014), Sun Tunnels (Velux), Tubular Skylights (Solatube), Light Tubes (Darula et al., 2013), Sunpipes (Monodraught) or Light Pipes (Garcia-Hansen and Edmonds, 2015). The system is set up especially in spaces where the contribution of benefiting from daylight is desired such as in windowless spaces, deep volumes (Knoop et al., 2016), underground spaces, basements (Goharian and Mahdavinejad, 2020), the cores that lack of daylight (Mayhoub, 2014), and in large areas such as halls, conference halls, corridors (Kocifaj et al., 2010), sport halls (Velux) etc.

The components of light pipes consist of a collector installed on the outside that collects daylight, a pipe that carries light over long distances, and a diffuser that will distribute light throughout the space (Carter, 2002; Garcia-Hansen and Edmonds, 2015; Goharian and

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Mahdavinejad, 2020). Basically, the research of the light pipe system, which consists of these three components, deals with the performance of the system with some variables. Mayhoub et al. (2021) investigated the transmittance performance of the collector component of the system through daily measurements, Goharian and Mahdavinejad (2020) examined the light pipe systems they designed through variable time data, solar altitude angles and space features. Baglivo et al. (2017) obtained results by using the number and length of pipes as variables in the light pipes they modeled over different lighting factors, whereas Tsang et al. (2018) obtained results based on different lighting factors for the variable latitude, sky conditions, solar elevation angles of the pipes they modeled. Ciugudeanu and Beu (2016), examined the performance of an experimentally installed elbow pipe over four different times of the year, Al-Marwaee and Carter (2006) examined the systems in 13 office spaces with different spatial properties in the UK. When many other studies in the literature like this are investigated, the variables affecting the system are classified as external environment conditions (latitude, solar angles, sky conditions, time data), spatial properties (analysis space properties, surface reflection values, working plane) and properties of system components (reflection / transmittance coefficients, material, form, size and number).

Light pipes that transmit daylight through multi-reflections on highly reflective surfaces (Tsang et al., 2018), are systems that are often used linearly (Al-Marwaee and Carter, 2006). It has been stated that the most effective light pipes are those which are flat, low in aspect ratio, short, large in diameter (Carter, 2002; Oakley et al., 2000) and studies in the literature have focused more on straight pipes in this context. The reason is that more loss of light happens in an elbow light pipe compared to a straight pipe of the same length (Carter, 2002). It is also difficult to accurately predict light transmissions in elbow light pipes because they are affected by more variables (Wang et al., 2022). However, in order to use the system in more complex buildings, one or more elbows must be integrated into the light pipes in order to deliberately change the light transmission direction, and the daylight transmission performance must be evaluated. Light transmission calculations of elbows at different angles (0-5-30-60-70-90°) were made based on a series of analytical calculation methods made on this integrated system (Carter, 2002; CIE, 2006; Ellis et al., 2016; Jenkins et al., 2005; Kocifaj et al., 2010; Wang et al., 2022; Zhang and Muneer, 2000; Zhang et al., 2002). However, in the models used in the calculations, the elbow geometry is considered as the elbow surface formed by joining two straight pipes at variable angles from a single point. In light pipes used in commercial companies producing light pipes, there is no connection from only one point, as in calculations. In the pipe module produced, In the pipe module produced, one or more pipes for different angles are integrated together to obtain an elbowed pipe surface. The elbow geometry in the models used in analytical calculations is not the same as the model produced for the commercial, and there is no method or study comparing the light transmission performance. In addition, evaluating the performance by integrating different elbow geometries into the system will provide the opportunity to increase the usability of the system for designers and producers.

In this study, one of the variables affecting the performance of the light pipe system was determined as the elbow geometry in the transporter pipe component. The daylight performance of different elbow geometries was investigated by accepting the assumption that the system performance in the elbow pipes is also related to the design of the elbow geometry.

## 2 Methodology

### 2.1 Methods used in performance evaluation of light pipes

There are different methods to be used in the performance evaluation of light pipes. In light pipe studies analytical calculations, experimental measurements and simulation software were used as performance analysis methods in order to determine the light transmission of different typologies. The analytical calculation method is based on assumptions regarding the collector, pipe and light transmission efficiency and is inadequate to characterize complicated systems (Lo Verso et al., 2011). On the other hand, in the experimental measurement method where real data is obtained, a series of long-term daylight measurements are required in order to determine the efficiency of various pipe typologies. Since this is a time consuming and expensive research, a more suitable approach seems to be a numerical simulation tool based on an accurate method and well-established algorithm (Darula et al., 2013).

### 2.2 The simulation software

Simulation software which can be used in the evaluation of such as environmental analyses, energy simulations, daylight analysis are based on analytical computation-based, semi-experimental or ray tracing methods. As a result of the research of these software programs, one or more of the problems such as the problem of accessing current versions or plugin, the inability to identify collector and diffuser components, the complex interface, operating only for straight light pipes, and the fact that it does not allow flexible design to limit the availability of simulation tools. That the software series consisting of the 3D modelling software Rhinoceros and its plugin provides parametric modelling unlike other performance analysis software, therefore allowing for flexible design, free access to its versions and plug-in, that the parametric model and the building performance can run on the same interface, brings this software and its plugins as a method tool forward.

This study was conducted using software based on daylight performance simulations, parametric modeling and ray tracing method in order to investigate the daylight performance of the elbow light pipe system and different elbow geometries. In this context, basic software series have been created with 3D-based Rhinoceros, algorithmic graphical editor Grasshopper (*Grasshopper, Algorithmic Modeling for Rhino*) and Ladybug and Honeybee plugins (Roudsari et al., 2013) that simulate daylight models. The Honeybee and Ladybug plugins connect to Open Studio and EnergyPlus for energy-related simulations, and to Daysim and Radiance for daylight issues (Goharian and Mahdavinejad, 2020; Pilechiha et al., 2020). For this study, the Grasshopper plugin in Rhinoceros was used to parametrically define the space and light pipe system, the Ladybug plugin, the transfer of weather files (EPW) related to the location, and the Honeybee plugin creating material, sky conditions, daylight simulations with ray tracing and to visualize the results.

## 3 Case study

For the case study, first of all, the spatial and outdoor properties were determined as fixed data and algorithmically defined for Ankara, Turkey through the software tool Grasshopper. In the calculations, the 'worst case' was considered the cloudy sky conditions in the CIE 173 report. In this study, it is aimed to investigate the performance of the elbowed light pipes for the most unfavorable conditions. Accordingly, it was determined from the CIE Standard Sky conditions in the Honeybee plugin via the Cloudy Sky software tool. Accordingly, the CIE in the Honeybee plugin was determined from Standard Sky conditions via the Cloudy Sky software tool. For the analysis time, the date of June 21, when the sun's rays reach the northern hemisphere at the most perpendicular angle, was determined as 12:00 for the time. The space where the analysis will be carried out is 5.0 × 5.0 m in size and 4.0 m in height. An opaque material is defined on the wall, floor and ceiling surfaces.

### 3.1 Modelling and simulation process

Following the space and outdoor features, fixed data were also determined for the light pipe system. The model consists of three components: collector, transporter pipe and diffuser, as in passive light transport systems. Since the study was intended only to evaluate elbow effectiveness, the model was kept fairly simple. Two light pipes with a length of 0.40 m ($\ell 1$) and 0.90 m ($\ell 2$) and a diameter of 0.52 (D) m were combined at an angle of 90° and different geometry experiments were made single elbow. In the designed model, the collector located on the roof surface transfers the incoming rays to the L-shaped pipe, and the rays emitted from the diffuser added to the end of the pipe first reach the opposite wall. Therefore, a vertical working plane with a distance of 2.0 m with the diffuser and 0.1 m with the wall was defined in Figs. 1 and 2.

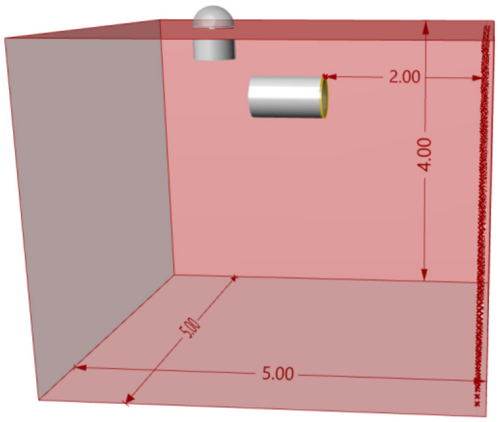



**Fig. 1** The perspective view of the analysis room

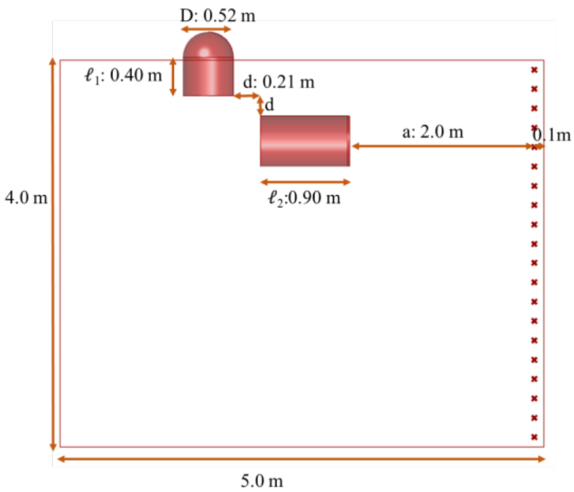



**Fig. 2** The section and dimensions of analysis room

As a collector, the Plexiglass dome with high light transmittance and more durable material feature than glass, for the transporter component, a pipe with a mirror inner surface, and for the diffuser 0.02 m thick Lambertian Diffuser material were used. For the light pipe model, the material properties of these materials and the analysis space were defined as Radiance materials and their properties are given in Table 1. In the case study, the modeling of the elbows was carried out in two stages.

Analysis space properties, light pipe components, material properties of the room and the components are added to the simulation tool for the light pipe system as input to the daylight simulation, which includes outdoor properties.

### 3.2 First stage

For the first stage, since the elbow geometry used in analytical calculations is not the same as the in the models produced for the commercial products, first it was desired to make a comparison of this situation. In analytical calculations, the E1 model was defined as the elbow typology formed by combining from a single point ($d$ = 0). As the elbow typology used in products, the distance $d$ defined horizontally and vertically between the two pipes is defined. The distance 'd' was used as the elbow typology in applications, defined horizontally and vertically between the two pipes. This distance was determined as optimum 0.21 m at the end of the study for a pipe with a diameter of 0.52 m. The pipe parts in the elbow were accepted as modules and different versions were tried. The E2 model is considered as the most commonly used variety in practice, and as a new proposal, the concave pipe surface between the vertical pipe and the horizontal pipe is linearly connected in the E3 model. All models are given in Table 2. In these models, 90° elbow pipe is rotated with 3 pieces of module with 30° angle.

In the study, the level of illumination (lux) carried from the external environment to the indoor working plane was determined as a performance criterion. Daylight levels on the plane were reached by running the Honeybee component, Point in Time Grid Based. The daylight levels obtained in the first stage after the models are defined are shown in Table 3.

In line with the results of the analysis shown in Table 3, higher luminance levels were reached in the E2 model used in products than in the E1 model used in analytical calculations. In the E3 model, which is defined as a proposal for a new elbow model, the highest level of illumination was reached.

### 3.3 Second stage

After determining the model with the best light distribution in the first stage, the second stage of the study was started.

E4 model consisting of 6 modules with 15° angle, E5 model consisting of 3 modules with 15°–60° angle, E6 model consisting of 2 modules with 45° angle, single piece E7 model with 90° angle, curvilinear E8 model

**Table 1** Radiance properties of materials for room and light pipes

| | Surfaces | Optical properties | | | |
|---|---|---|---|---|---|
| | | Radiance material | Reflectance | Transmittance | Refractive index |
| Room | Walls | Opaque | 0.7 | – | – |
| | Floor | Opaque | 0.8 | – | – |
| | Ceiling | Opaque | 0.7 | – | – |
| Components | Collector | Translucent | – | 0.91 | 1.4 |
| | Light pipes | Mirror | 0.984 | – | – |
| | Reflector | Mirror | 0.984 | – | – |
| | Diffuser | Translucent | – | 0.70 | 1.5 |

**Table 2** Light pipe models in the first stage

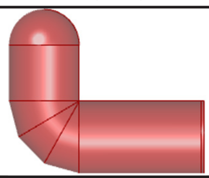
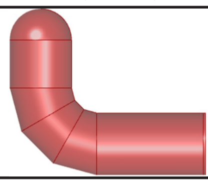
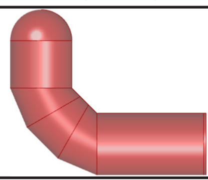
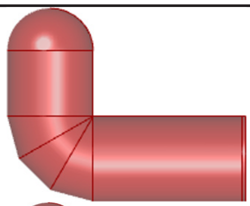
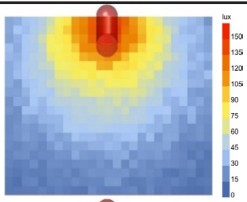
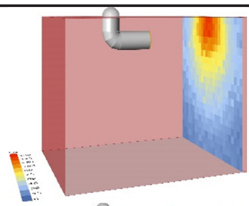
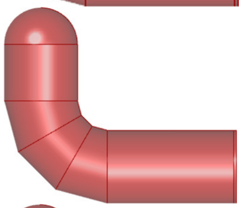
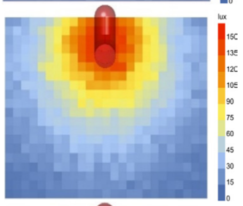
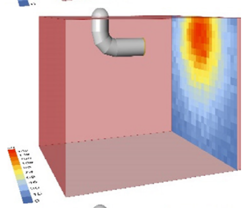
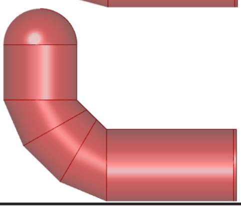
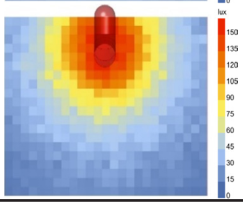
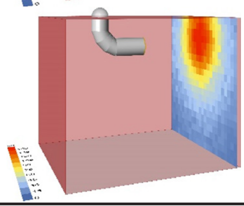
| | E1 ($d$ = 0) | E2 ($d$ = 0.21) | E3 ($d$ = 0.21) |
|---|---|---|---|
| First step |  |  |  |

**Table 3** Comparison of illuminance between E1, E2 and E3 models

| | Light pipe model | Distribution of light | Perspective | Illuminance |
|---|---|---|---|---|
| E1 ($d = 0$) |  |  |  | Max ill: 139 lux<br>Avr ill: 38 lux |
| E2 ($d = 0.21$ m) |  |  |  | Max ill: 146 lux<br>Avr ill: 44 lux |
| E3 ($d = 0.21$ m) |  |  |  | Max ill: 159 lux<br>Avr ill: 48 lux |

with 90° angle were defined as different elbow transitions. All identified models are given in Table 4.

After the models were defined, the daylight levels obtained in the second stage were reached by running Point in Time Grid Based in Honeybee plugin and the results are given in Table 5.

## 4 Results

In addition to the daylight level on the working plane, the Daylight Factor, which is widely used in daylight lighting studies, is determined as another performance measure. The daylight factor (DF) refers to the ratio of daylight illumination at a given point to the light received in a horizontal plane from an unobstructed cloudy sky. The outdoor ambient light level in cloudy sky condition at the specified date, time, location is 18314 lux. In all light pipe models, the distributed level results for the working plane are shown in Fig. 3 and the daylight factor values are shown in Fig. 4.

There are differences between the results from the varying elbow geometries in the elbowed light pipe models. Accordingly:

- the elbow model with the lowest daylight performance is the E1 model, which is calculated in analytical studies with a maximum light level of 139 lux in the working plane, 0.75 DF;
- in the first stage, the E3 model, which is based on the E2 model used in light pipe applications, is the highest performing elbow model with a light level of 159 lux and 0.86 DF in the working plane;
- in the second stage, the lowest levels were reached with the E7 model, which consists of a flat and single module;
- with a light level of 163 lux in the working plane and a DF of 0.89, the E4 model is the highest performing elbow model;
- as the number of fractured modules in the convex line of the elbow geometry increases, and the inner line conversely approaches linearity, the maximum efficiency is achieved;
- although the performance of the model is close to the E4 model when the E8 model is defined as curvilinear and installation, it is thought that the applicability of this elbow model is lower when evaluated in terms of production, assembly, and usability.

## 5 Conclusion

For the elbow light pipes investigated in this study, except for a series of analytical calculations, a study on the evaluation of daylight performance using different methods has not been previously discussed. The performance analysis of the elbow light pipes examined in the study in terms of elbow geometry is an innovation among the light pipe studies.

As a result of the study, light levels close to each other were obtained in the comparative study conducted in the same outdoor environment, space, light pipe components characteristics, but in different elbow models. It can be said that the minimal differences between the results are at a level that can be ignored under normal conditions.

**Table 4** Light pipe models in the second stage

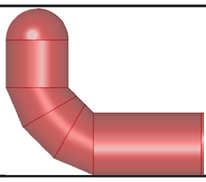
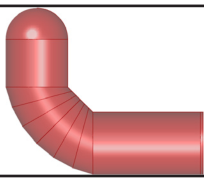
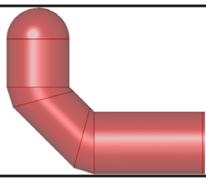
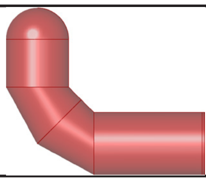
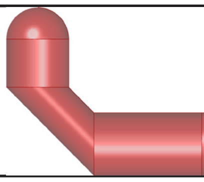
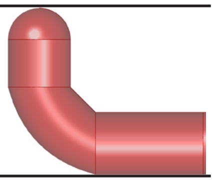
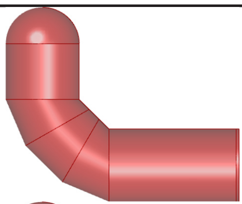
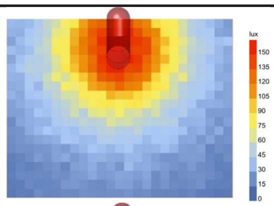
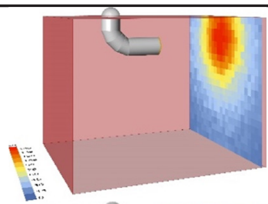
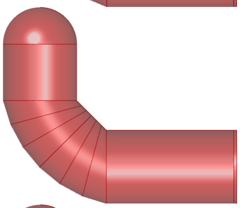
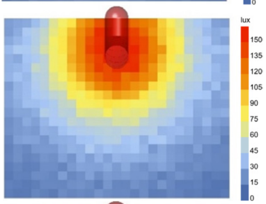
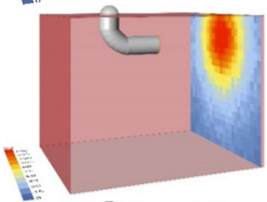
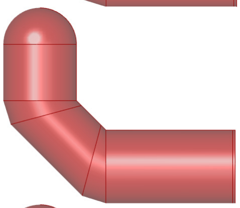
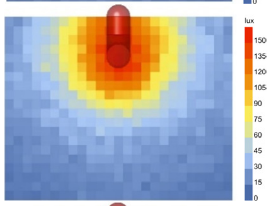
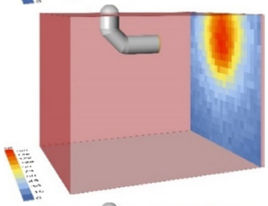
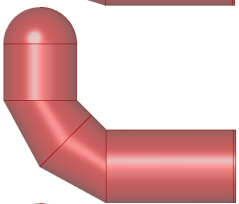
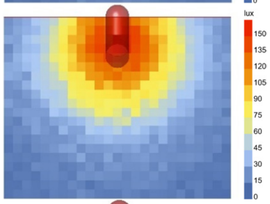
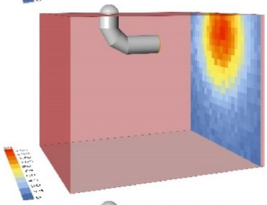
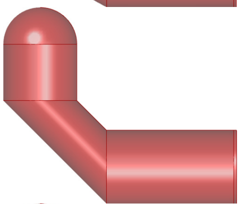
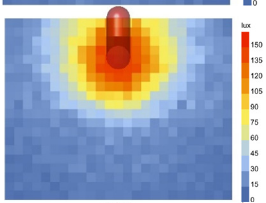
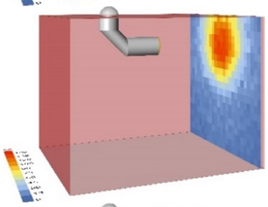
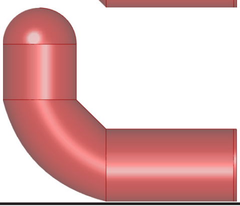
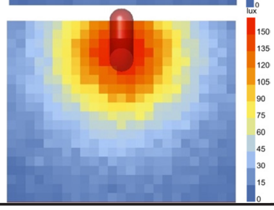
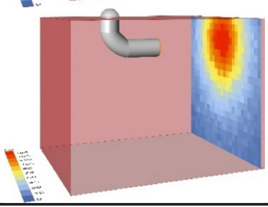
| | E3 (30° angle 3 module) | E4 (15° angle 6 module) | E5 (15°–60° angle 3 module) | E6 (45° angle 2 module) | E7 (90° angle single module) | E8 (Circular single module) |
|---|---|---|---|---|---|---|
| Second step |  |  |  |  |  |  |

**Table 5** Comparison of distribution of light between E3, E4, E5, E6, E7 and E8 models

| | Light pipe model | Distribution of light | Perspective | Illuminance |
|---|---|---|---|---|
| E3 (30° angle 3 module) |  |  |  | Max ill: 159 lux<br>Avr ill: 48 lux |
| E4 (15° angle 6 module) |  |  |  | Max ill: 163 lux<br>Avr ill: 49 lux |
| E5 (15°–60° angle 3 module) |  |  |  | Max ill: 155 lux<br>Avr ill: 40 lux |
| E6 (45° angle 2 module) |  |  |  | Max ill: 146 lux<br>Avr ill: 42 lux |
| E7 (90° angle single module) |  |  |  | Max ill: 139 lux<br>Avr ill: 33 lux |
| E8 (Circular single module) |  |  |  | Max ill: 153 lux<br>Avr ill: 43 lux |

However, when we look at the study as a whole, these levels are important because only small changes in elbow geometry are involved. Considering that more complex systems will be installed under different conditions in future studies, the results obtained will also be more variable, and the differences defined as minimal will be quite important.

Whether the light levels reached as a result of the analyses alone are sufficient to illuminate the space will vary depending on the dimensions, function and duration of

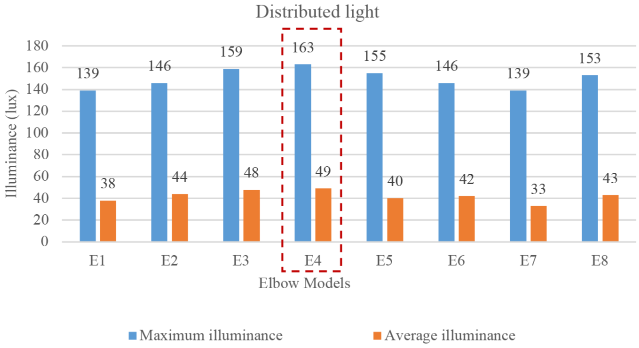



**Fig. 3** Comparison of distributed light levels of light pipe models in the work plane

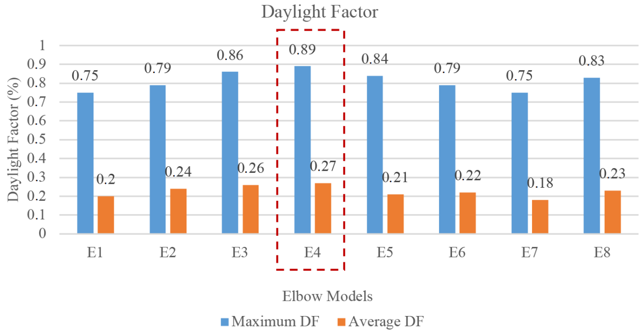



**Fig. 4** Comparison of Daylight Factor of light pipes models in the work plane

use of the space. In the use of the E4 model, it has been determined that it may be sufficient in some activities with a daylight multiplier of 0.89. However, light pipes have always been used in conjunction with electric lighting, helping to reduce the building's electricity consumption.

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