Equalizing Daylight Distribution

*Digital simulation and fabrication of optimized inner reflectors and bottom extractors for a light-duct*

Shinya Okuda¹, Xiaoming Yang², Stephen K Wittkopf³
¹,²National University of Singapore, Singapore, ³Lucerne University of Applied Sciences and Arts.
¹akiso@nus.edu.sg, ²yang.xiaoming@ymail.com, ³stephen.wittkopf@hslu.ch

Abstract. The present paper explores the implementation of a light-duct in order to equalise daylight distribution in an office space. While the illuminance level near windows in a building tends to be higher than that necessary for the working environment, artificial lighting is often used to ensure that the workspace further away from the windows has the required level of illuminance. Equalising daylight distribution from the periphery to the inner part would thus provide significant advantages for energy-efficient lighting as well as the flexible and efficient use of office space. In order to achieve this goal, anti-glare devices in the perimeter zone such as louvers and daylight distribution devices such as light-ducts are required. In this paper, we focus on light-ducts in the first instance, with an emphasis on their two key components for controlling the direction of daylight, namely inner reflectors and bottom extractors.

Keywords. Day lighting; Digital Fabrication; Performance; Parametric; Algorithm.

INTRODUCTION

Good lighting requires equal attention to its quantity and quality components, as visibility often depends on the way in which the light is delivered. In extreme cases, unevenly distributed light could result in a high level of contrast and cause discomfort because of glare problems. Windows are the most common way to admit daylight into buildings. However, daylight levels decrease asymptotically with the distance from the window and thus daylight distribution systems such as light-ducts supplement windows in order to achieve better illumination for workspaces. A light-duct system consists of three main components: a collector on the outside to gather light from the sky, a highly reflective duct integrated into a suspended ceiling that leads midway into the office and an inner reflector to control the direction of the emitted light (Gilles Courret et al., 1998). Although such a system is able to direct daylight deep into a room and thus improve daylight penetration, current designs incorporate relatively small inner reflectors at the end of the light-duct that only illuminate a limited area under the reflector. As a result, daylight is distributed non-uniformly.
This paper uses a performance-based design approach in order to optimise light-duct components and thus equalise the daylight distributed via such a system. The proposed design is based on the following three explicit performance criteria developed in the initial stages (Turrin et al., 2010): (i) under a standard overcast sky, (ii) in a 7.5 m-deep room and (iii) the light-duct is able to compensate for the insufficient daylight provided by a rear window to achieve uniform horizontal illuminance in a workspace. As all the light illuminated from the light-duct is redirected by the inner reflector via the bottom extractor, the most critical components that affect daylight distribution are these two components [Figure 1].

The hypothesis of this research is that by optimizing the opening design on the bottom extractor and the shape of 3-D inner reflector by ray-tracing algorithm, fabricated by digital fabrication technologies, the light-duct could effectively achieve uniform illuminance value on working plane at the rear half of the testing room.

EQUALISING DAYLIGHT DISTRIBUTION

As the correlation of the influences of the bottom extractor and inner reflector is unclear, these two target components need to be tested separately in the first instance. Therefore, we take the following steps in order to optimise the light-duct for equalising daylight distribution.

Firstly, the degree of daylight distributed through the existing light-duct is examined. Secondly, the opening shape of the bottom extractor to be optimised is verified through simulations and

Figure 1
Cross-section of a room with a light-duct proposed for equalising daylight distribution.

Figure 2 (left)
1:5 scale light-duct prototype.

Figure 3 (right)
Inside of the 1:5 scale light-duct prototype. (Yellow dotted lines indicate the position of the base opening in the bottom extractor.)
lab/outdoor testing. Thirdly, the 3-D curved inner reflector geometry is optimised using a ray-tracing algorithm. Finally, we compare the digital simulations with physical testing in order to draw conclusions.

**Base model**
To compensate for the natural daylight, the opening of the bottom extractor of the light-duct is placed at the point where the horizontal illuminance level from the window falls below that required in a typical office environment. Following preliminary simulation studies using Radiance (Berkeley Lab, version 4), we identify this cut-off point to be approximately 3.5 m from the peripheral window. A simple 250 mm × 4500 mm rectangular opening in the centre of the rear half of the light-duct is made in order to ascertain the fundamental daylight distribution into the deeper part of the light-duct [Figures 2 and 3]. The result indicates that the larger the distance from the peripheral window, the lower the amount of daylight is distributed. Thus, this base model is not effective at compensating for the deteriorating horizontal illuminance levels from the window.

**Bottom extractor**
Considering the fact that the illuminance level decreases asymptotically with the distance from the window, the amount of light distributed through the light-duct should be increased contrary to the distance from the window. The opening on the bottom panel is thus defined based on the difference between the illuminance level from the window and the target equalised illuminance level [Figure 1]. The difference is then distributed symmetrically from the centre line of the light-duct, which is defined by the width of the opening. The wider the opening, the more light is distributed [Figure 4]. Further, a series of laser-cut mirror surfaces could be engraved within the area of the opening in order to diffuse the direction of emitted light where necessary and improve the visibility of the opening surface [Figure 5].

After running an evolutionary optimisation algorithm, namely Galapagos (Grasshopper, version 0.8), we observe that the overall quantity of daylight distributed through the bottom extractor is insufficient to compensate for the deterioration in the illuminance level from the window. However, we also find that the digital simulation result and the lab/outdoor testing outputs correspond well [Figure 8 Left]. Therefore, we assume that the shape of the bottom extractor is about correct for equalised daylight distribution, while another factor controls daylight distribution more dominantly, which must be the inner reflector.

**Inner reflector**
Similar to the positioning of the bottom extractor, the inner reflector is also placed 3.5 m from the window and end wall. A new ray-tracing algorithm is developed using Grasshopper in order to re-evaluate performance. The surface of the inner reflector is parametrically controlled by a set of grid points that generate numerous doubly curved geometries. During the optimisation process, the collector receives
rays from a virtual hemisphere in order to represent the overcast conditions outside. These rays are reflected through the light-duct and redirected by the inner reflector. As a result, a proportion of these rays intersect with a horizontal working plane set at a desktop height. By counting the number of intersection of rays and the working plane, the degree of daylight distribution can be measured. Different colours on the desktop-height working plane indicate the number of rays hitting the surface [Figure 6].

Using the evolutionary optimisation algorithm, with 10,000 rays and after 4500 rounds of iterations, the doubly curved inner reflector surface is finally optimised. Using the Radiance simulation, we confirm that it can effectively compensate for deteriorating daylight distribution in the deeper half of the testing room [Figure 8 Right].

As a result of this optimisation process, the shape of the inner reflector is shown to be a complex doubly curved surface, which would require accurate and smooth mirror finishing. Fabricating such a doubly curved surface with accurate mirror finishing economically would be a challenging technical task. Indeed, articulating a complex doubly curved surface into a series of developable surfaces may require advanced discretisation processes (Kajjima, 2007). As we do not have access to costly aluminium solid milling, grinding and mirror deposition processes, applying non-stretchable mirror foils onto a layered MDF mould is the only option available. We thus experiment with discretising the doubly curved surface before the laser-cut non-stretchable mirror foils are applied onto the inner reflector surface as well as possible [Figure 7]. However, the result of the lab/outdoor test is discouraging. It shows that the amount of illuminance compensated for in the deeper part of the room is far below the level required for equalising daylight distribution [Figure 8 Right].

**Comparison of the simulation/prototype testing results**

We compare the results of the simulations with those of the lab/outdoor testing of the bottom extractor and inner reflector in order to understand the advantages and disadvantages of each method and testing procedure. Our key findings are as follows:

1. For the optimised bottom extractor, a high degree of similarity is observed between the digital simulation result and lab/outdoor testing using the 1:5 scaled prototype. This similarity seems to be achieved because of the relatively simple shape of the opening, which is also easily fabricated by laser engravers with a high degree of precision.

2. However, the overall illuminance level solely controlled by the bottom extractor is not sufficient to compensate for the asymptotically deteriorating daylight distribution from the window and thus it also needs to be controlled by the inner reflector.
3. The digital simulation of the optimised doubly curved inner reflector achieves the closest level to the ideal target illuminance compensation, while its physical counterpart results in significantly lower scores. We presume that the major cause of these huge differences is the number of invisible gaps among the triangular developable mirror foils, which may result in the inaccurate reflection of rays.

CONCLUSION
This paper explores the new form-finding algorithm for the bottom extractor and inner reflector of a light-duct in order to equalise daylight distribution in a deep room. These optimised forms are then verified both in a digital and in a physical environment. A relatively simple optimised bottom extractor achieves a high degree of similarity between the digital simulation and physical testing, whereas the complex 3-D curved geometry of the optimised inner reflector shows larger differences. In the digital world, which is a fully controlled environment, the complexity of forms is no issue. By contrast, the physical world usually requires a certain degree of tolerance, especially when dealing with complex forms and geometries. The lighting simulation itself also seems to be less tolerable compared with other types of simulations, such as structural or thermal performances, which often include some safety factors in order to absorb the required tolerances.

To make this equalising daylight distribution study more convincing, further efforts to narrow the gap between the digital simulation and physical testing are required. In future research, it would also be necessary to find a more accurate and economical fabrication method, not only at the prototype level but also at mass production scales.

The combination of the window and improved light-duct could provide uniform daylight in deep spaces, resulting in an even better visual environment compared with the verified original light-duct. However, in order to achieve fully functional equalised daylight distribution, further studies of anti-glare devices, such as louvers, must be carried out. Once fully functional, this improved light-duct could supply enough ambient light for the entire open space, thereby reducing the energy required for artificial lighting through proper lighting controls. It could also have promising architectural applications for buildings that have large recessed ceilings in which good lighting is critical such as museums and laboratories [Figure 9].
REFERENCES
Kaijima, S and Michalatos, P 2007 ‘Discretization of continuous surfaces as a design concern’, *Predicting the Future - 25th eCAADe Conference Proceedings*, Frankfurt am Main, Germany, pp. 901-908.