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Simulation-based performance prediction of an energy-harvesting façade system with selective daylight transmission

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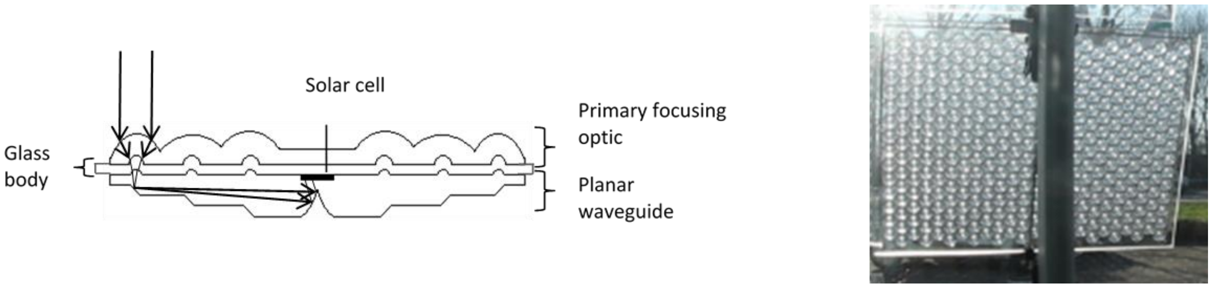
Abstract

Shading devices are effective in controlling glare and solar heat gains in buildings. However, this occurs at the expense of daylight and outside view. This paper evaluates the thermal and daylight performance of Lumiduct, a sun-controlling dynamic façade system that permits only diffuse radiation inside the building, while producing electricity. This imparts Lumiduct a unique characteristic of acting as a shading device while providing useful daylight and view to the outside. The first part of the paper briefly illustrates the working principle of Lumiduct and its functional characteristics and then, introduces the basic principles of the modelling and simulation strategy used to predict its performance. To demonstrate this strategy we use *TypeDLT*, a TRNSYS type that performs integrated thermal and daylight simulations by coupling TRNSYS' multi-zone building model with Radiance's three-phase method. This strategy relies on the use of customized and time-controlled bidirectional scattering distribution functions (BSDF) to characterize the separate treatment of direct and diffuse radiation and the sun-tracking behaviour of the façade. In the second part, we demonstrate the performance of Lumiduct in comparison to a high-performance window with and without a dynamic venetian blind system as a shading device for a typical office room for the climate of Amsterdam. The results show a significantly higher daylight utilization along with a reduction in glare and energy use for heating and cooling the building.

1 Introduction

Daylighting plays an important role in achieving high-performance buildings. It not only reduces the dependency on artificial lighting to achieve desired illuminance levels but also aids positively in the perceived comfort of the occupants. The recent interest in developing highly glazed facades is a direct consequence of this importance. However, large glazing areas can also negatively affect the energy performance of the building by admitting unwanted solar gains along with the daylight. Glare discomfort is another issue that needs to be tackled when designing buildings with glazed facades. Although external static shading solutions such as overhangs and fins can keep direct sun away under specific circumstances, it comes at the cost of insufficient indoor illuminance on overcast days and reduced view to the outside. Manually operated shading systems such as venetian blinds and roller shades are rarely deployed efficiently, due to large dependence on user interaction [1][1]. Hence, there is increasing interest in dynamic shading systems such as automatically controlled blinds, switchable glazing, etc. [2 & 3]. A missed opportunity that is shared by the majority of shading systems is that solar radiation is either absorbed or reflected, but not turned into something useful. The application of thin film solar cells with dynamic shading system allows simultaneous production of electricity [4] but it limits penetration of useful diffuse light into the building.

The use of Fresnel lenses with solar tracking has been suggested for capturing direct solar energy while allowing diffuse radiation to illuminate the interiors [5 & 6]. However, these systems tend to be bulky for façade applications due to the presence of a focal distance between the lenses and receivers. To overcome this issue, Lumiduct, a solar-controlling dynamic façade system based on planar optics (Fig. 1a) was developed that permits only diffuse radiation inside the building [7]. It has a series of concentrating photovoltaic (CPV) modules that track the sun's movement throughout the day in order to block direct radiation and produce electricity from it. Each module has a number of planar optic receivers, as shown in Fig. 1b, which consist of a 4cm x 4cm planar focusing optic, a 1.3mm x 1.3mm TJ III/V solar cell, a bypass diode, a heat sink and integrated wiring [8]. These CPV modules are installed within the cavity of a double-skin façade, as shown in Fig. 2, in order to prevent the influence of dust and other outside environmental agents on the optical properties and the solar tracking mechanism. Currently, Lumiduct is at system demonstration phase and is still under development. Both experimental and simulation-based research and development activities are currently being carried out in order to study the visual, thermal and energy performance of the Lumiduct façade.

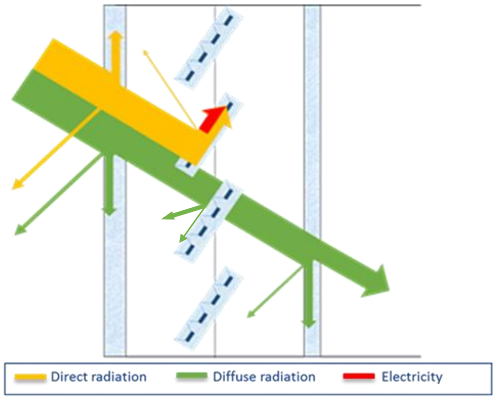


(a) (b)

Figure 1: (a) Schematic representation of the optical element of the receiver of the Lumiduct and (b) Photograph of a CPV module with multiple receivers [7]

The aim of this study is to evaluate thermal and daylight performance of Lumiduct in comparison to a high-performance window with and without an automatically controlled venetian blind system under different sky conditions for the climate of Amsterdam.


(a)



(b)

Figure 2: (a) Inside view of an office building façade mounted with Lumiduct modules and (b) representation of functional characteristics of Lumiduct modules with separate treatment of direct and diffuse radiation.

2 Modelling and simulation method

To adequately predict Lumiduct's visual and thermal performance, an interaction between these physical domains needs to be considered. The current capabilities of building performance simulation tools do not support performance prediction of a complex dynamic façade system with the characteristics of Lumiduct [7]. A custom-built model was therefore developed, by taking the *TypeDLT* TRNSYS type [10], as a starting point for coupling thermal and daylight performance predictions. This Type uses Radiance's three-phase method [11] for daylight predictions and can be coupled with TRNSYS' multi-zone thermal model (Type 56).

2.1 Modelling thermal and optical façade properties

There are two primary requirements that must be satisfied by Lumiduct's performance prediction model – (a) sufficient level of detail in characterizing the solar-optical properties of Lumiduct due to separate treatment of direct and diffuse radiation and (b) incorporation of dynamic sun-tracking behaviour. In this modelling approach, the Lumiduct system, with dynamic CPV modules installed in the cavity of a double skin façade has been reduced to a 3-layer fenestration system representing the outer glass façade, CPV modules and the inner glass façade. The optical and thermal properties of this fenestration system are modelled so as to represent those of the Lumiduct façade system. Details of the modelling and simulation strategy are described in the following sub-sections.

2.1.1 Direct and diffuse radiation separate treatment

Lumiduct is a complex fenestration system (CFS) whose optical properties such as solar and visible transmittance are dependent on the angle of the incoming solar radiation. In order to capture the angular dependencies of transmission and reflection, Bi-directional Scattering Distribution Function (BSDF) matrices were needed to be developed.

BSDF matrices discretize the front and back hemisphere of the CFS layer into 145 patches. For each of these patches, optical properties are specified depending on two angles; the incident angle formed between the outgoing direction (centre of the patch) and the normal to the CFS layer (θ), and the solid angle of the outgoing patch (Ω). A BSDF dataset containing file describes transmission (BTDF) and reflection (BRDF) properties by a 145x145 matrix which was calculated using equation 4.3b as described by Klems in [12] and equation 6 as described by Molina et al. in [13]. Since the Lumiduct façade system does not transmit any direct radiation when the modules are pointed towards the sun, BTDF matrices were obtained based on the diffuse radiation transmittance in the solar and visible spectrum for all incident and outgoing angles.

For the thermal model, the window properties were established using the software tool WINDOW 7.4. Upon importing the window description in a TRNSYS compatible format, the angular transmittances referring to direct sunlight in the solar and visible spectrum were set to zero in order to account for the separate treatment of direct and diffuse solar radiation. However, the CPV modules are dynamic in nature when following the sun's path to block direct radiation during the day and do not always cover the entire window area. The modelling and simulation strategy used to incorporate this behaviour in the model is described in section 2.1.2.

2.1.2 Sun-tracking strategy

While CPV modules track the sun, the area of the facade that they cover changes during the day. For a south facing façade, this area would be the lowest at dawn and dusk when modules are vertically facing due east and west respectively. This essentially means that the ratio of the area covered by the modules to the area of the façade changes during the day. We refer to this ratio as the variable cover factor (CF) of the modules, given by $(\cos \gamma_s * \sin \theta_z)$, where γ_s is the azimuth angle of the façade and θ_z is the zenith angle of the sun. The assumption made here is that the thickness of the modules is negligible compared to the length and width.

As CF varies during the day, some of the diffuse light passes through the outer façade, the modules and then the inner façade before entering the room, whereas, the rest of the diffuse radiation will only pass through the outer and the inner façade. To take this effect into account, the CF for every hour of the day was obtained and the optical properties of the window for each hour were modified by taking a weighted average of the properties with cover factor 0 and 1. In the TRNSYS multi-zone thermal model, this is implemented by variable window IDs corresponding to the cover factor of the hour at the desired location.

For the Radiance based daylight model, the optical properties of the diffuse solar radiation obtained upon implementation of cover factors were used to obtain BSDF coefficients. In order to restrict direct solar radiation from entering the building, the daylight matrix of the three-phase method has been used. The coefficients in the daylight matrix describe the percentage of luminous flux from a Reinhart MF:4 sky patch that is incident on the window in the direction of each Klems division [11]. This implies that the maximum percentage for a particular window patch is for the sky patch that is directly aligned towards it. The facade will receive direct radiation when sun is present in one of these sky patches that are directly aligned towards the window patch. In order to find the position of the sun with reference to the sky patches, the sky vectors generated using Radiance functions *gendaylit* and *genskyvec* were used. A sky vector contains a list of RGB values of the radiance for each of the discretized sky patches based on the sky description of the hour of the day and the contribution of the sun is included in three nearest patches distributing energy according to the centroid of these patches. Based on this concept, a computational program was developed in MATLAB which would first find the position of the sun, i.e. three sun patches, from the sky vector generated for the hour corresponding to the maximum radiance values in the vector. It would then, corresponding to each of these sun patches, look for the window patches that have larger coefficients relative to the other window patches in the daylight matrix. As a reference, a coefficient value of 0.001 has been chosen to be the lower limit for the patches to qualify as being directly aligned to the sun patches. The window patches thus derived are the ones for which BTDF coefficients are to be defined as zero for an hour of the day.

2.2 Simulation conditions and rendering properties

A single-person office zone with dimensions 3.6 m (width) x 5.4 m (depth) x 2.7 m (height), located at an intermediate floor with identical neighbouring office spaces and a south-facing exterior façade (87% window-to-wall ratio) was chosen as a case study for analyzing the performance of Lumiduct. The internal walls, roof and floor are considered to have adiabatic boundary conditions. The external wall has a U-value of 0.35 W/m^2K.
The installed lighting power density is 7.5 W/m^2 with continuous dimming control up to an indoor illuminance of 500 lux, other equipment gains are 10 W/m^2 (working hours are 9am-5pm). Artificial lighting is controlled using a sensor placed 2.7 m away from the façade and 1.8 m from the side walls. The thermal environment is controlled using an HVAC system with unlimited capacity based on the indoor air temperature, the set points for heating and cooling during working hours are 20ºC and 24ºC respectively, while during non-working hours it is 14ºC for heating and 32ºC for cooling. Infiltration is assumed to be constant at 0.15 air changes per hour while ventilation is active at 2.5 l/s (with 90% heat recovery) during the occupied hours. For the daylight simulations, a work plane height of 0.8 m is used. The reflectance of the materials of the ceiling, walls and floor considered were 0.8, 0.5 and 0.2 respectively. Table 1 provides a description of the other Radiance simulation parameters.

Table 1: Radiance simulation parameters

Ambient bounces (-ab)	Ambient division (-ad)	Ambient subdivision (-as)	Ambient accuracy (-aa)	Limit weight (-lw)	No. of sky divisions	No. of sample rays per Klems division
12	50000	0	0	2e-5	2305	1000

3 Results and discussion

A typical summer week (4th June – 10th June) with sunny and cloudy sky conditions for the climate of Amsterdam was chosen for this study. The diurnal variation of direct and diffuse solar radiation incident over the south façade is shown in Fig. 3. The performance of Lumiduct is compared to a high-performance triple glazing system with low-e coating at the rear pane with and without an externally mounted dynamic venetian blind system (slat width-16mm, spacing between slats-12mm and reflectance-0.7). The blinds when drawn can remain in three different slat angles: 0º, 45º and 90º. The blinds are automatically controlled based on the daylight availability at the sensor location so that the illuminance falls within the autonomous range (300-2000 lux) of the useful daylight illuminance (UDI) where supplementary artificial lighting will likely not be needed and the daylight illuminance levels are unlikely to cause visual discomfort.

A comparison of cooling load profile in Fig. 4 shows that on a typical sunny day, Lumiduct reduces the cooling load in comparison to the unshaded glazing due to the blocking of direct solar gains. A dynamic venetian blind installed with the glazing will need less energy for cooling since both direct and diffuse part of the radiation are reflected by the blinds. However, under an overcast sky condition when most of the solar gains are from diffuse radiation, the three fenestration systems show a comparable cooling energy need.

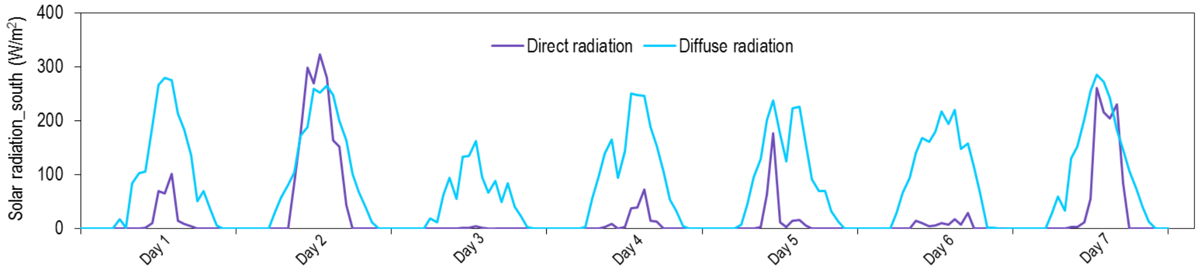


Figure 3: Diurnal variation of direct and diffuse solar radiation for south oriented façade in Amsterdam's climate

In Fig. 5, the hourly profile of the work plane illuminance for the week is shown for the three cases along with the shading state of the dynamic blinds. The work plane illuminance levels for Lumiduct remain higher than the dynamic blind system in sunny sky conditions when the blinds are drawn to keep the illuminance within the useful range. In cloudy sky conditions, results show similar daylight performance for Lumiduct and high-performance glazing without shading.

Fig.6 shows the horizontal illuminance received at 12 photocell sensors spaced equally across the middle of the room at 12 p.m. The first sensor is positioned at 0.45 m away from the south wall of the office space. The results show that with Lumiduct there is a significant reduction in the undesirable illuminance near the window on a sunny day (Fig. 6a) due to the same reasons as mentioned above. However, when compared with dynamic venetian blind system, it still provides higher illuminance levels on both sunny and cloudy sky conditions in deep office spaces.

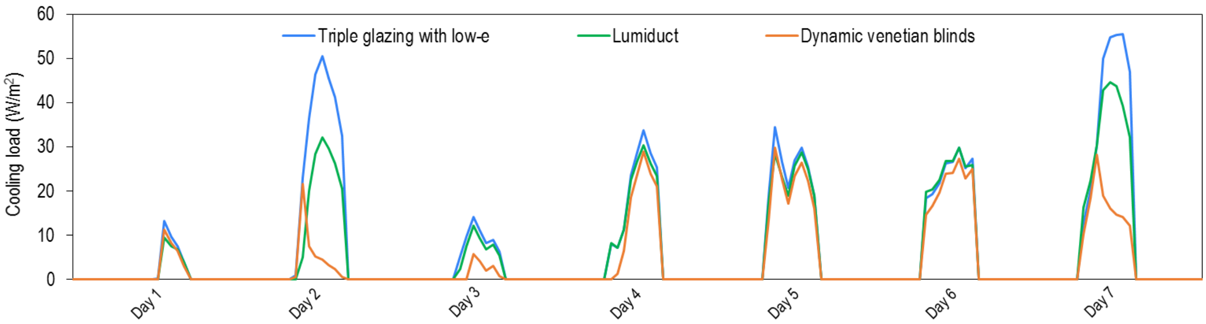


Figure 4: Cooling load profile (related to floor area) under different sky conditions

Figure 5: Weekly variation of work plane illuminance under different sky conditions and state of the blinds (0: no blinds; 1: 0° slat angle; 2: 45° slat angle; 3: 90° slat angle)

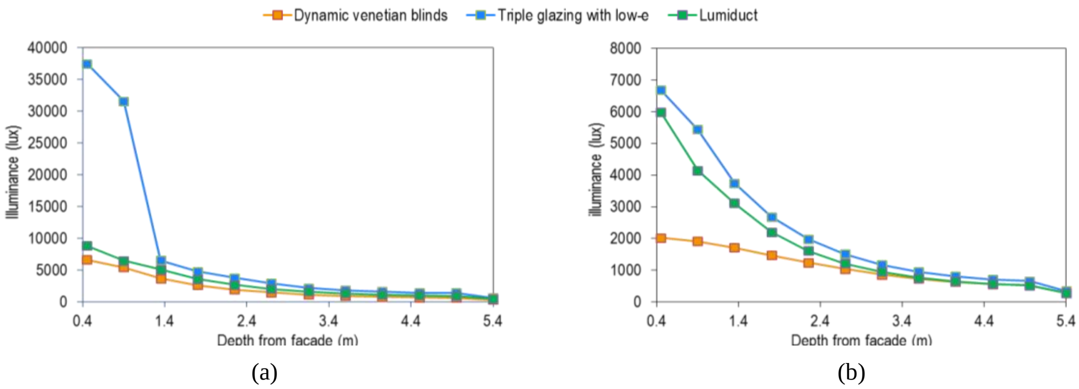


Figure 6: Horizontal illuminance plotted against sensors across the middle of the office space for (a) sunny day and (b) cloudy day at solar noon on Day 7 and 6 respectively

Due to space constraints, the results for a week in winter are not presented here, but simulations show that Lumiduct will lead to a higher heating demand in winter days compared to the high-performance window without blinds. However, in an office setup, it is common that due to the lower altitude angle of the sun the shades are drawn by the occupants in order to prevent glare discomfort from direct sunlight. This will lead to blocking of useful solar gains from both direct and diffuse radiation which will further be translated into higher energy use for heating and artificial lighting.

4 Conclusions

This paper has presented a modelling and simulation approach to evaluate integrated thermal and daylighting performance of Lumiduct, a multi-functional façade with selective daylight transmission. The approach developed can be used in modelling complex fenestration systems with solar control based on two-dimensional angular dependency of solar-optical properties such as visible transmittance and solar heat gain coefficient. TypeDLT, a TRNSYS type has been used for coupling thermal and daylight simulations. The results show that Lumiduct is able to lower the cooling load due to unwanted solar gains through an unshaded high performance glazed façade on sunny days without reducing the useful daylight availability on overcast sky conditions. Next to the development of a full-scale demonstrator, future studies will focus on incorporating glare discomfort and view to outside in the performance analysis framework.

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