X International Conference on Textile Composites and Inflatable Structures
STRUCTURAL MEMBRANES 2021
K.-U.Bletzinger, E. Oñate, R. Wüchner and C. Lázaro (Eds)

RETROFITTING OFFICE BUILDINGS: ENHANCED DAYLIGHTING PERFORMANCE WITH SWITCHABLE ETFE DOUBLE-SKIN FAÇADES

JAN-F. FLOR[*], YANYI SUN[†], PAOLO BECCARELLI[†], JOHN CHILTON[†] AND YUPENG WU[†]

[*] 19, Jalan SS1/29, Kampung Tunku,
47300 Petaling Jaya, Selangor, Malaysia
e-mail: janflor@gmx.de, web page: https://orcid.org/0000-0001-8740-5227

[†] Department of Architecture & Built Environment (DABE),
The University of Nottingham (UoN)
Energy Technologies Building, Innovation Park, Triumph Road,
Nottingham NG7 2TU, United Kingdom
Email: yupeng.wu@nottingham.ac.uk - Web page: https://www.nottingham.ac.uk/

Key words: Ethylene Tetrafluoroethylene (ETFE), Double-skin Façade, Daylight Simulation.

Summary. This paper addresses the natural daylighting qualities of spaces enclosed by ETFE multi-layer foil constructions with switchable features. The study focuses on the effects the adaptive shading mechanism has on the internal space in terms of useful daylight illuminance and natural lighting qualities. The overall aim of the study was to gain more knowledge of the daylighting effects of ETFE cushions in façade systems. Moreover, to understand the daylighting benefits switchable ETFE cushions could generate when employed in a double-skin façade as part of energy retrofitting measures to reduce the energy consumption of buildings. For this purpose, a virtual office space enclosed with an ETFE double-skin façade was evaluated using dynamic daylighting metrics. The simulation study was based on ray-tracing methods, using Radiance software for calculating illuminance levels across a test grid within the office space. To account for the light scattering and angle-dependent optical behaviour of double-curved ETFE cushions, bidirectional-scattering-distribution-function (BSDF) was employed based on experimental measurements of spectral transmittance. The simulation scenarios included different window-to-wall ratios, ranging from a small window size of 30% to an almost fully glazed façade of 90%. The simulation was based on annual weather data with hourly values to produce a comprehensive picture of the daily and seasonal daylighting performance in different climates. Results of the simulations were expressed with dynamic daylight metrics in terms of useful daylight illuminance (UDI). Compared to a standard glazed façade, the results showed that a double-skin façade with switchable ETFE cushions could significantly improve daylighting conditions for office work tasks. The annual percentage of hours UDI was achieved expanded significantly in most of the analysed scenarios when a switchable ETFE double-skin façade was applied. Generally, it was observed that the light was more evenly distributed throughout the room. Using BSDF data for weather-based daylighting simulations might suggest new ways of analysing the daylighting performance of adaptive ETFE façades more comprehensively.

1 INTRODUCTION

The global building stock of commercial buildings containing office spaces is largely outdated in terms of energy efficiency. Even though new office buildings that comply with the goals for carbon neutrality are on the rise, the environmental load of old buildings will not be compensated as fast as needed. Instead of demolishing and rebuilding, upgrading building fabric and services with energy retrofits is a viable path for extending building lifespan, reducing energy consumption, and conserving embodied energy [1].

The building envelope is a crucial component for unlocking potentials to reduce energy consumption. Limiting heat gains and losses and controlling daylight can lead to significant energy savings [2]. However, upgrading the building envelope performance of existing buildings is often limited by technical, financial, and legislative challenges. Attaching a second layer to the original façade using lightweight building materials might, in many cases, be an effective measure to improve a building’s environmental performance, despite the aforementioned limitations [3]. This study builds on the concept of double-skin facades (DSF) and focuses on investigating daylight availability and distribution in office spaces when ETFE foil is used in a façade retrofit. Such an ETFE DSF is shown in Figure 1, comparing the picture of the original façade with a rendered visualisation incorporating the attached secondary building envelope of ETFE cushions.

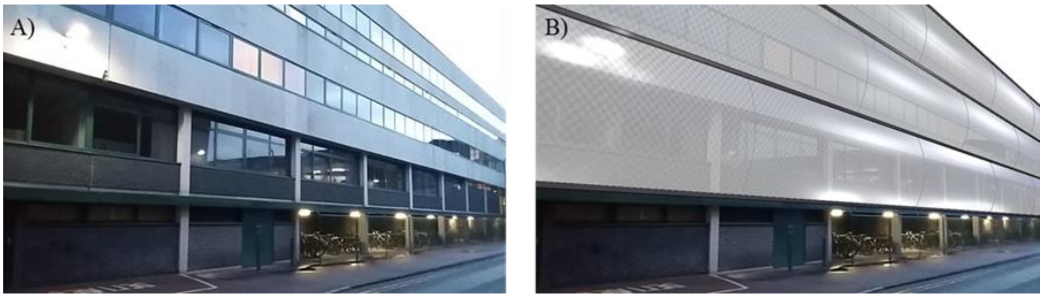

Figure 1: A) Picture of a south-east facing façade of an office building built in 1959, in Nottingham, UK. B) Artistic rendering showing a switchable ETFE double-skin façade added to the original building in A)

ETFE as a building material in façades has gained popularity in recent years, with many examples published elsewhere [4,5]. A wide range of tinted and fritted foils as well as novel low emissivity coatings have been used to control glare, and solar heat gains [6]. However, static control measures never satisfy the wide range of weather conditions throughout the seasons, and individual frit print designs are required for each project’s climate zone location. Adaptive systems for fritted ETFE foil provide a solution for this problem, responding actively to environmental changes modifying the façade’s overall light transmittance. Such an adaptive system with a switchable fritting pattern based on a triple layer system with a chequerboard reflective frit print is shown in Figure 2. The diagram shows an overview of the double-skin façade and illustrates the switching mechanism of the ETFE system, which is activated with air pressure moving the middle layer within the cushion chamber. A detailed description of the mechanisms can be found in previous publications by the authors [7].

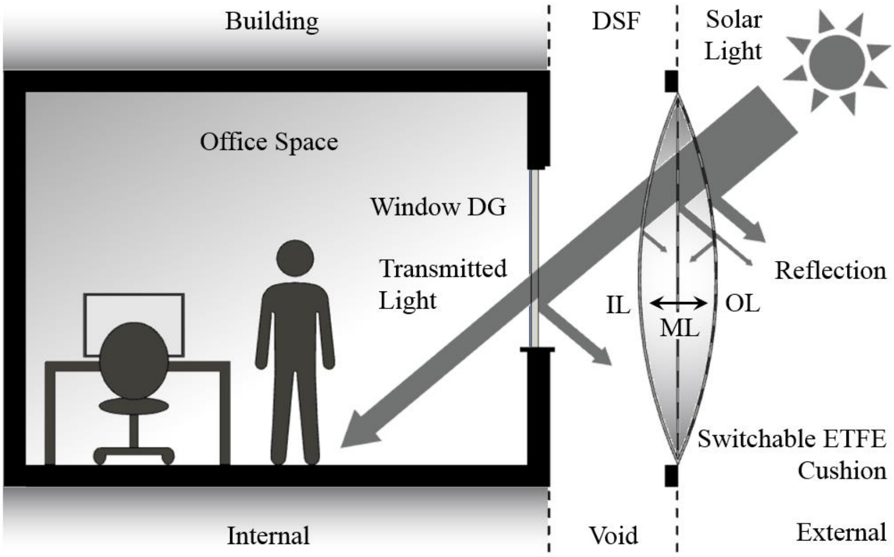

Figure 2: Office room with switchable ETFE double-skin façade; IL = inner layer (clear ETFE foil), ML = middle layer (fritted ETFE foil), OL = outer layer (fritted ETFE foil)

Despite the apparent advantages, a drawback to applying switchable ETFE systems more widely is the difficulty of predicting the performance with conventional methods. Simulating the daylighting performance of adaptive building components in glazing and façade systems is a complex matter. Various modelling and simulation methods have been proposed in the literature and are currently still under development [8,9,10]. The methods evaluated to be used in this study to investigate the natural lighting qualities of semi-transparent ETFE double-skin façades are centred around climate data-based daylighting simulations with radiosity simulation tools and matrix-based methods that rely on ray-tracing. The validated programme package Radiance [11] had been used in earlier studies to calculate the annual daylighting performance of office spaces employing DSF with different material combinations, an approach previously reported by Bueno et al.[12]. Dynamic metrics, such as useful daylight illuminance, build upon illuminance results that Radiance can generate yet describe the daylight performance more comprehensively. This metric had been employed in previous simulation studies as an alternative to the traditionally used, but insufficient, daylight factor to evaluate other transparent building materials [13,14,15].

2 METHODS

For the simulation procedures in this study, a new integrated parametric control approach was adapted [9], coupling several of the above-described methods and programs. This enabled efficient control of the simulation parameters and processes and increased accuracy of the results, using climate data to generate hourly results for an entire year [16,17,18]. Using UDI as an indicator for daylighting performance allows this study to evaluate different ETFE design options beyond point-in-time results. A simplified workflow diagram illustrating the connectivity and data flow between the programs used for the simulation procedure is shown in Figure 3, with a screenshot of the simulation model shown in Figure 4.

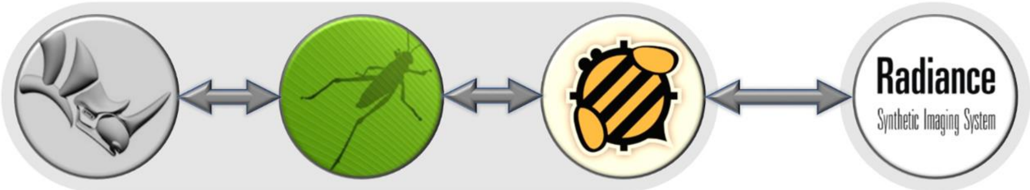

Figure 3: Workflow diagram for daylight simulation, showing interconnectivity and data stream between software programs and plug-ins

2.1 SIMULATION MODEL

Assuming that outdated office buildings will be refurbished eventually to suit the contemporary working culture and organisational structures of the 21st century, this study focussed on small-sized single desk offices. The modelled office space measured 3.4m in depth, 2.9m in width, and 2.75m in height, with a south-facing window orientation. The DSF was modelled with a proxy geometry for the secondary ETFE skin and an external wall with a variable window opening to simulate different window sizes of the original façade. In order to account for the characteristic light scattering and angle-dependent optical behaviour of clear fritted and switchable ETFE cushions, bidirectional-scattering-distribution-function (BSDF) was employed based on material data obtained from spectral measurements to generate models which would realistically represent the light transmittance properties of ETFE. The switchable ETFE cushion was controlled with a virtual illuminance sensor in the centre of the room and signalled the ETFE cushion to switch from one state to the other when a pre-set illuminance threshold was surpassed. A sensor grid layout of 10 by 16 with 160 sensors was evenly distributed over the model at desk height to record the incidence illuminance.

2.2 SIMULATION SCENARIOS

The simulation scenarios included different geographical locations, namely, London, Barcelona and Shanghai, corresponding to Oceanic, Mediterranean and Sub-tropical climate zones, respectively. Five material and façade combinations were evaluated in this study: double-glazing, clear ETFE DSF, fritted ETFE DSF, and two types of switchable ETFE DSFs. Another scenario defining parameter was the window-to-wall ratio of the south-facing façade, ranging in steps of 15% from a small window size of 30% to a nearly fully glazed façade of 90%.

2.2 SIMULATION PROCEDURE

The simulation procedure for this study followed the five-phase method, where the light transmittance from source to receiving surface is split into a view, transmission, daylight and sun matrix, with an additional matrix for direct sun. For the application of BSDF, the specular and diffuse transmission and reflection was precalculated for 145 patches of light ray incident angles on a Klems hemisphere on both sides of the DSF using the genBSDF program [11]. The daylighting simulation was controlled with Grasshopper/Honeybee using Radiance as a simulation engine for calculating illuminance levels across the test grid in the office space.

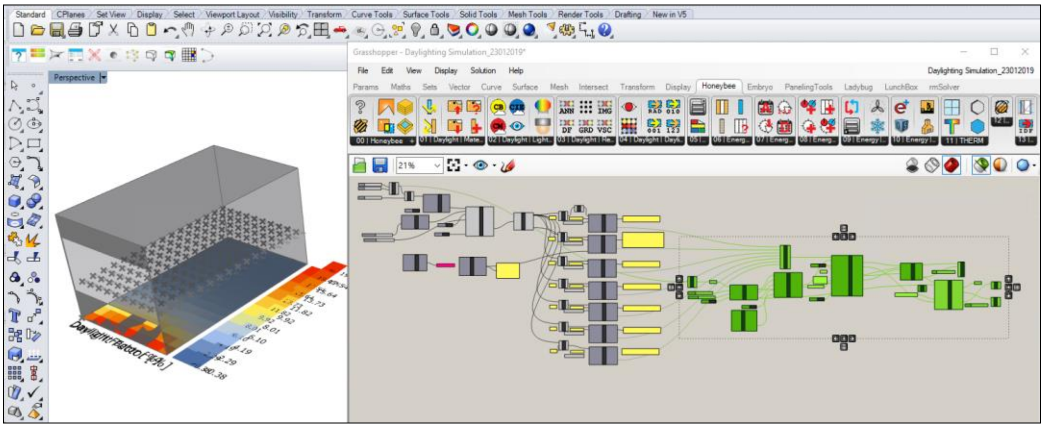

Figure 4: Screenshot showing the office model generated in Rhinoceros with projected daylight simulation results and Grasshopper/Honeybee simulation definition

3 RESULTS & DISCUSSION

A virtual office space enclosed with an ETFE double-skin façade was evaluated using dynamic daylighting metrics. The climate-based simulation results for the annual 8760 hours were plotted along the longitudinal centre axis of the room, showing the useful daylight illuminance across the room's section. The UDI represents a synthesis of the annual daylighting performance, indicating with percentages the total amount of time when the ideal illuminance range (500 – 2000lx) was achieved. The simulation results are shown in Figure 5.

With the parametric change of the window-to-wall ratio of the façade and the assignment of different material layer combinations of the DSF, it was possible to obtain detailed results for the lighting conditions in London, Barcelona, and Shanghai. Overall, the positive effects of retrofitting measures with ETFE were more noticeable in sunny climates like Barcelona and Shanghai. Here, especially for the wider window-to-wall ratios of 60 to 90%, the illuminance is more evenly distributed throughout the room, and even further away from the window, close to the back wall, the UDI is still achieved up to 60% of the time of the year.

The results also showed that double-skin façades with switchable ETFE cushions outperformed all other investigated design options in terms of total UDI percentage and evenness of daylight distribution. At the centre of the room, UDI availability was six times higher with a switchable ETFE DSF than the original façade with double glazing. Fritted ETFE was the second-best performing option with four times more UDI availability. DSFs with clear ETFE showed only minor notable differences to the original double-glazed façade. Scenario A1 with the smallest WWR (30%) in a London climate, was the only situation where double-glazing and a DSF with clear ETFE would provide better annual daylighting conditions than the other façade options. Further comparison of the results revealed that for the smaller window-to-wall ratios (30% to 60%), a higher contrast between the bright and darker zones. This effect is reduced, smoothing the transition from bright to darker areas, with the addition of fritted or switchable ETFE cushions to the façade. The light scattering behaviour of the fritted cushions is the most likely reason for this effect.

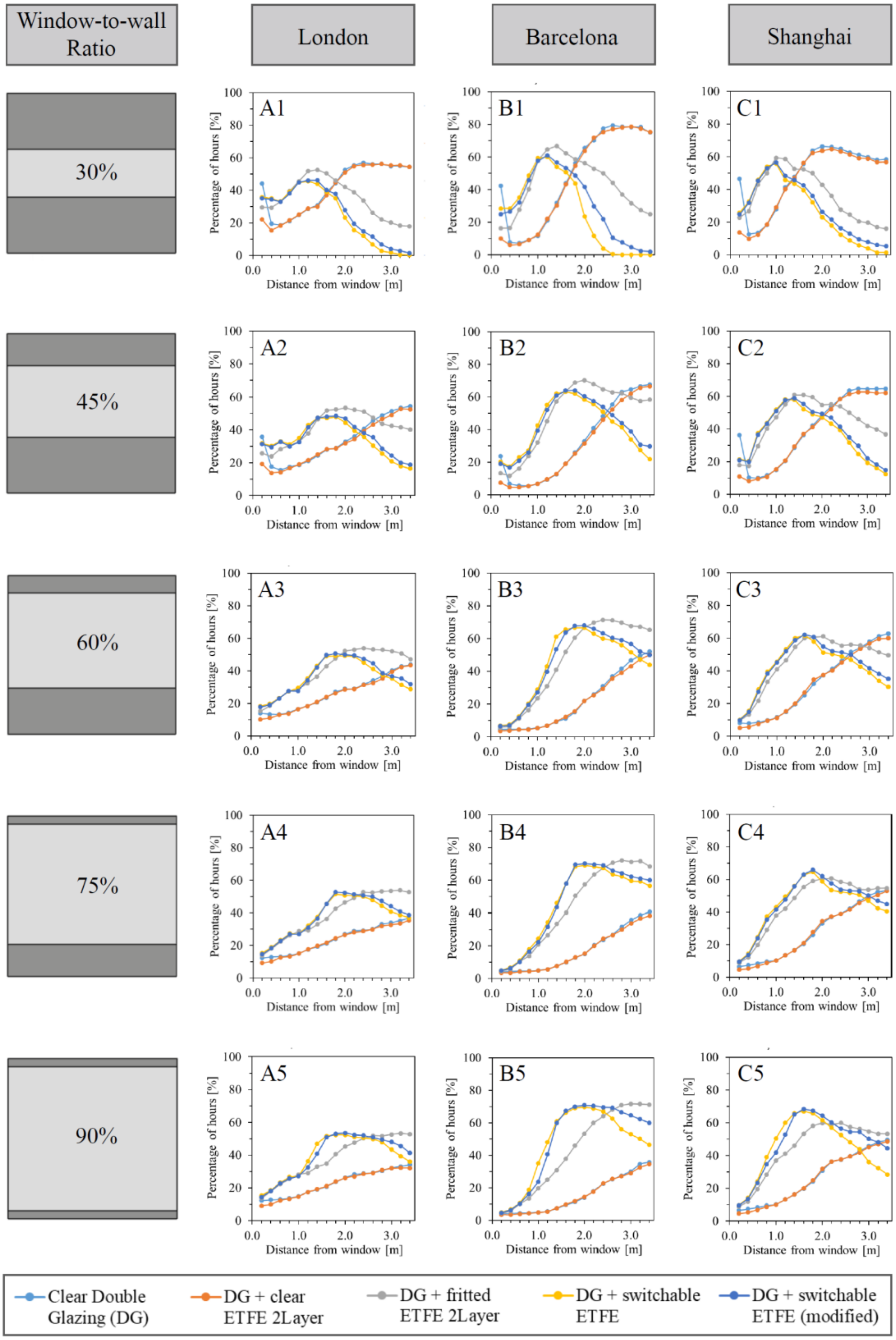

Figure 5: UDI across the section of a south-facing office with single and alternative double-skin façades

4 CONCLUSIONS

This study investigated the daylighting performance of switchable ETFE cushions compared to static ETFE cushions and standard double glazing. The overall aim of the study was to gain more knowledge on the daylighting effects of ETFE cushions in double-skin façades. Moreover, this paper asked specifically if switchable ETFE cushions, as part of an energy retrofitting measure for outdated office buildings, would also enhance daylighting in terms of useful daylight illuminance. The following conclusions were drawn based on the obtained simulation results:

- The results showed that Useful Daylight Illuminance was available up to 69% of the annual daylight hours when a switchable ETFE double-skin façade was applied, compared to 11% without. Fritted and clear ETFE facades provided a maximum UDI of 45% and 12%, respectively, on an annual basis.

- When fritted ETFE double-skin façades were employed, the light was generally more evenly distributed throughout the room with fewer high contrast areas and the highest UDI values distributed in the central space of the room where most of the office work would be performed.

- In general, the size of windows has a significant impact on the daylighting qualities of the office space. Large window façades in combination with switchable ETFE double-skin façades generate the best overall annual daylight conditions, with a spatially well-distributed UDI for most hours of the year. This combination would be most beneficial in lower latitudes within climate zones with intense solar radiation.

- The best performance of the ETFE DSF was observed for Mediterranean climates with a high annual solar radiation, followed by subtropical climate zones across all window-to-wall ratios scenarios. For oceanic climates in higher latitudes, the application of ETFE double-skin façades yielded a better daylighting performance only for office spaces with large WWRs.

Future research would be suggested to confirm the simulated results with experimental measurements or in-situ case studies of existing buildings. Other remaining questions regarding the effect on glare exposure and illuminance uniformity and whether the switching mechanisms can be calibrated to fit the climate conditions of specific regions will be explored in forthcoming research papers.

ACKNOWLEDGEMENTS

This work was supported by the Faculty of Engineering at the University of Nottingham through a PhD studentship awarded to Jan-Frederik Flor. Architen Landrell generously provided all ETFE samples used in this study.

REFERENCES

[1] Kunwar, N. and Bhandari, M., A Comprehensive Analysis of Energy and Daylighting Impact of Window Shading Systems and Control Strategies on Commercial Buildings in the United States, *Energies*. (2020) **13**

[2] Plörer, D.; Hammes, S.; Hauer, M.; van Karsbergen, V. and Pfluger, R., Control Strategies for Daylight and Artificial Lighting in Office Buildings - A Bibliometrically Assisted Review. *Energies*. (2021) **14**

[3] Monticelli, C. and Llorens, J. I. d. (Ed.), Membrane claddings in architecture, in *Fabric structures in Architecture*, Woodhead Publishing, (449-480), 2015.

[4] LeCuyer, A., *ETFE. Technology and Design*, Basel, Switzerland: Birkhauser Verlag AG., 2008.

[5] Grunwald, G., *Mechanisch vorgespannte, doppellagige Membranmodule in ihrer Anwendung als zweite Gebäudehülle*, Berlin, 2007.

[6] Liebhart, H.; Cremers, J.; Mirbach, D. & Marx, H., Wärmetransport und andere bauphysikalische Aspekte im Membranbau. *Stahlbau*. (2020) **89**

[7] Flor, J.-F.; Wu, Y.; Beccarelli, P. & Chilton, J., Dynamic environmental control mechanisms for pneumatic foil constructions, International Conference on Advances in Energy Systems and Environmental Engineering (ASEE17). *E3S Web Conf.* (2017) **22**

[8] Wienold, J., Dynamic simulation of blind control strategies for visual comfort and energy balance analysis. *Building Simulation.* (2007)

[9] Do, C. T. and Chan, Y.-C., Development of a New Framework for Daylighting Simulation with Dynamic Shading Devices. *International High Performance Buildings Conference.* (2018)

[10] A Simplified Approach for the Annual and Spatial Evaluation of the Comfort Classes of Daylight Glare Using Vertical Illuminances. *Buildings.* (2018) **8**

[11] Ward, G. L. and Shakespeare, R., *Rendering with Radiance: the art and science of lighting visualisation*, Morgan Kaufmann Publishers Inc., 1998.

[12] Bueno, B.; Wienold, J.; Katsifaraki, A. & Kuhn, T. E., Fener: A Radiance-based modelling approach to assess the thermal and daylighting performance of complex fenestration systems in office spaces. *Energy and Buildings.* (2015) **94**

[13] Nabil, A. and Mardaljevic, J., Useful daylight illuminances: A replacement for daylight factors. *Energy and Buildings.* (2006) **38**

[14] Santos, L.; Leitão, A. and Caldas, L., A comparison of two light-redirecting fenestration systems using a modified modeling technique for Radiance 3-phase method simulations. *Solar Energy.* (2018) **161**

[15] Fang, Y. & Cho, S., Design optimisation of building geometry and fenestration for daylighting and energy performance. Solar Energy. (2019) **191**

[16] Qingsong, M. & Fukuda, H., Parametric office building for daylight and energy analysis in the early design stages, Urban Planning and Architecture Design for Sustainable Development, UPADSD. *Sciences, P. S. & Behavioural (Eds.).* (2015)

[17] Ghobad, L., Daylighting and energy simulation workflow in performance based building simulation tools, Building Performance Analysis Conference and SimBuild co-organised by ASHRAE and IBPSA-USA, (2018)