A systematic workflow for retrofitting office façades with large window-to-wall ratios based on automatic control and building simulations

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Abstract

Fully glazed façades are still preferred by many architects due to their aesthetic features. Although this choice offers opportunities for daylighting and view contact with the outside, it can lead to overheating and glare problems if climate is not taken into account in the design. This paper presents a workflow for retrofitting that can be applied to different office façades with large window-to-wall ratios. The workflow consists of analysing the space from the point of view of the functions of its façade and then applying a retrofitting strategy based on state-of-the-art building simulations and automated shading control. The proposed workflow is illustrated through a case study at an office in Malaga (Spain), in which existing manually-controlled interior vertical blinds are replaced with automatically controlled interior roller blinds with a metallized reflecting surface facing towards the glazing unit. A full optical characterization of the roller blinds is presented. A simulation-based control strategy is applied to the motorized roller blinds in order to maximize view contact with the outside and daylighting while controlling glare and overheating.

Keywords: shading control; building simulation; Complex Fenestration System; Bi-directional Scattering Distribution Function; Directional Solar Heat Gain Coefficient; daylighting; glare; overheating; Radiance; Fener

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1. Introduction

The design of highly transparent façades in office buildings presents a particular challenge. The building façade provides the aesthetic signature of a building, but it is also in charge of important functions [1], such as visual contact with the outside, daylight provision, glare protection and solar gain management, which make the building usable and energy-efficient. These functions often oppose each other, so the selection and design of façade systems and their control for a certain building application should depend on those functions that the designer wants to promote to the detriment of the other functions. The risk of not designing carefully in this direction is that the initially planned functions may not play a role in practice, if the day-by-day use of the fenestration system is completely different to the plan [2]. A typical example is a fully glazed building designed for daylighting and visual contact with the outside. If glare is not appropriately included in the design, a glare protection device installed afterwards may compromise the initially designed functions of the facade (ie. daylighting and view contact).

The goal of this paper is to present an systematic workflow for retrofitting office façades with large window-to-wall ratios. The workflow consists of analysing a façade from the point of view its functions for a particular application. Then, a retrofit strategy is designed to optimize these functions, for which daylighting and thermal building simulations and automated shading control is required. Additionally, in order to build a reliable numerical model of the room, the fenestration system must be characterized and the model must be tested. An evaluation of the dynamic performance of the façade system and the room can then be carried out by annual building simulations. At this point, changes in the retrofit solution can be made before it is implemented and finally tested.

In summary, the steps of the proposed workflow are the following:

1. Analysis of the case study.
2. Design of the retrofit solution.
3. Characterization of the solar control system.
4. Evaluation of the numerical model.
5. Evaluation of the annual performance of the retrofit solution.
6. Testing the implementation of the retrofit solution.

The workflow described in this paper is illustrated by a case study consisting of a fully glazed office in Malaga (Spain). The problem to be addressed here is that, although the space offers open and valuable views of a semi-natural landscape, the existing manually controlled interior blinds are constantly activated by the occupants to mitigate glare and overheating, which prevent them from enjoying the views and, in many cases, from taking advantage of natural lighting.

In the selected retrofit intervention, the existing interior vertical blinds were replaced with interior roller blinds with a metallized reflecting surface facing towards the glazing unit. An automated control system was designed to maximize view contact with the outside and daylighting while controlling glare and overheating. Embedded in this controller, a computationally-efficient simulation engine reads real-time meteorological data and calculates the illuminance at different positions in the room [3, 4], eliminating the need for illuminance sensors. The controller evaluates the visual conditions in the room to decide on a trade-off between opposing aspects such as blocking of solar radiation to prevent glare and overheating and allowing enough daylight to enter the room and view contact to the outside. The controller calculates the optimal shading configuration internally before sending the signal to the actuators, decreasing unnecessary blind movement that would disturb the occupants.

The simulation engine of the controller requires information about the angular and scattering behaviour of the roller blind. For this, a detailed

	List of symbols
α_i	Incidence angle
λ	Thermal conductivity [W m^{-1} K^{-1}]
ρc	Volumetric heat capacity [J m^{-3} K^{-1}]
$\rho_{v,nh}$	Visible normal-hemispherical reflectance
$\rho_{e,nh}$	Solar normal-hemispherical reflectance
$\rho_{v,ndif}$	Visible normal-diffuse reflectance
$\rho_{e,ndif}$	Solar normal-diffuse reflectance
SHGC	Solar Heat Gain Coefficient or g-value
$\tau_{v,nh}$	Visible normal-hemispherical transmittance
$\tau_{e,nh}$	Solar normal-hemispherical transmittance
$\tau_{e,dirh}$	Solar direct-hemispherical transmittance
$\tau_{v,ndif}$	Visible normal-diffuse transmittance
$\tau_{e,ndif}$	Solar normal-diffuse transmittance
U-value	Global heat transfer coefficient [W m^{-2} K^{-1}]
ϕ	Azimuth angle of a sample (angle between a characteristic direction of the sample and the plane of incidence)
θ	Polar or incidence angle of a sample

optical characterization of the roller blinds is carried out, including photogoniometer and integrating sphere measurements at the TestLab Solar Façades at Fraunhofer ISE. The simulation engine is also used to evaluate the annual performance of the control algorithm in terms of window cover, daylighting, glare protection and cooling energy reduction. To do that, insitu measurements were used to verify the model of the office space. An evaluation of the actual implementation of the control system is presented at the end.

2. Analysis of the case study

The case study under consideration is an office at the Faculty of Health Sciences at the University of Malaga (Spain). The building, constructed between 2013 and 2015, was designed by the architect Juan Gavilanes, receiving an award by the Architects' Association of Malaga. The award committee commended to the light geometry of the building, the choice of materials, the building transparency and natural lighting (Fig. 1).

The office under consideration has one external façade of 4.75-m length and 3.17-m height, with all the other surfaces being internal partitions. The depth of the room is 3.57 m. The external façade is oriented south-west (-63° from south or zero-solar azimuth) and consists of a fully-glazed curtainwall (Schueco/Kawneer) with up to three white aluminium mullions. The window is composed of a double glazing unit filled with argon. The glazing unit has a low-e coating on the cavity-facing surface of the outside pane, which is suitable for warm climates.

Figure 1: Picture of the entrance of the Faculty of Health Sciences at the University of Malaga. Taken on February 13th, 2017, at 11:27.

The façade is equipped with vertical interior textile blinds (Fig. 2). Given the location and the dimensions of the room and the fenestration system, the transmittance of the blinds is sufficient to provide enough daylighting in the room during the central hours of the day. However, the interior blinds cannot prevent high solar heat gains in the afternoon, which produce a high cooling energy demand and even thermal discomfort during some days in the summer period in which the air-conditioning system is unable to meet the demand created by the high cooling loads.

The existing vertical blinds can be manually rotated or fully retracted. Still, operating the blinds require that an occupant stands up and gets to one of the façade edges to reach a cord. To retract the blinds, the cord has to be pulled repeatedly to move all the blinds to one of the window edges, which is time consuming and therefore infrequently done. The rotating operation, although easier than the retraction one, does not produce an unobstructed view to the outside and is also rarely done. As a result, and given the high irradiation levels on the façade in the afternoon, the blinds are in the closed position most of the time.

Having the blinds closed most of the time prevents the occupants from experiencing severe glare in the afternoon. The absence of direct transmission and specular reflections and the fact that people in southern Europe are intrinsically adapted to high luminance levels make the occupants generally satisfied with the visual conditions in the room, as was directly reported to the authors. However, the façade under consideration has open views to the semi-natural landscape of ”Valle del Guadalhorce”, ”Sierra de las Nieves”

Figure 2: Picture of the office with the existing interior vertical blinds. Taken on November 8th, 2016, at 14:28.

and ”Serranía de Ronda” (Fig. 3). The views are highly appreciated by occupants and visitors, and can be understood as one of the motivations for designing a fully-glazed façade despite the south-west orientation. The fact that the blinds are constantly closed due to an inconvenient manual control prevents the occupants from enjoying these views. Additionally, the existing roller blind material prevents any contact to the outside when the blinds are closed.

Figure 3: Picture of the outside views from the office. Landscape of ”Valle del Guadalhorce”, ”Sierra de las Nieves” and ”Serranía de Ronda” on the back. Taken on January 22nd, 2017, at 12:41

3. Design of the retrofit solution

The design of the retrofitting strategy is based on the conclusions of the analysis presented in the section 2. The conclusions can be summarized as follows:

1. The glazed façade has an important aesthetic function. It is the hallmark of the building because it provides a transparent character, which was considered symbolic for a public building.
2. The office room under study has valuable views to the outside, of which the occupants are not taking advantage. The manual control for retracting and rotating the blinds is inconvenient and therefore unused. In addition, the blind material does not allow any contact to the outside in the closed position.
3. The glare protection in the room is satisfactory for the occupants.
4. Overheating is an issue for the occupants. An intervention on the exterior side of the façade (i.e. exterior shading devices) can effectively improve the issue, as is shown in section 6. However, given the importance of the aesthetic function of the façade, the exterior intervention option was discarded for this study. It can nevertheless be re-considered in the future.

As a result, the retrofitting strategy consists of selecting a new interior solar control device and implementing an automated shading control algorithm. The new fenestration system and control algorithm must maximize the hours of uncovered façade to benefits from the outside views. At the same time, for the hours when the façade is covered, the control device must allow a certain contact with the outside. In addition, the system must preserve a glare-free space, it must maximize daylight as much as possible and it must not deteriorate the cooling energy demand of the room.

Textile roller blinds, due to their aesthetic features and simplicity, constitute a good architectural complement to fully glazed façades. These devices are rolled up when retracted, which allow them to be motorized and automated. When extended, a flat textile layer is placed in front of and parallel to the glazing unit. The chosen material in this study is Screen Nature Ultimetal. This textile has an openness coefficient that allows a view through the textile material, which the existing material did not (see section 4). The outer side of the Screen Nature Ultimetal material is metallized, which was presumed to have a high solar reflectance.

The automated shading control system operates on the basis of glare protection, including the glare from diffuse solar radiation, and daylight maximization. A computationally-efficient simulation engine reads real-time weather data and calculates horizontal and vertical illuminance at different positions in the room [3]. The simulation engine is also able to calculate indoor air temperatures [4]. However, physically based thermal building models are subject to important uncertainties with regard to their boundary conditions [5]. For example, the room under study is adjacent to a corridor, with which it shares a non-insulated and non-sealed door, and which presents very different thermal conditions that are not measured. Given these limitations, it is preferred that the controller uses a measured value of indoor air temperature, which can be achieved with a simple and discrete thermocouple or from the thermostat, instead of using the calculated air temperature from the model.

A shading control algorithm was developed to optimize the functions of the fenestration system. When the room is unoccupied, the algorithm compares the measured indoor temperature with a low temperature setpoint in order to decide whether to activate the shades during the day blocking solar heat gains or to deactivate them during the night enhancing heat transfer through the window. The low thermal setpoint is intended to be conservative in a cooling-dominated climate. When the room is occupied, a minimum daylighting level must be reached before the shade is closed. The average workplane illuminance setpoint must be low enough to ensure that, as a consequence of this condition, solar heat gains are not harmful. Once the daylight condition is fulfilled, the algorithm checks the maximum vertical illuminance and the indoor air temperature. If any of these variables reaches a certain threshold, the shades are activated. The vertical illuminance setpoint is chosen so that the corresponding Daylight Glare Probability Index (according to the simplified DGP method [6]) lies below the 'intolerable' limit. The resulting algorithm is written here in pseudo-code, indicating the selected setpoints:

```
if occupation:
   if average_workplane_illuminance > 400 lux:
      if indoor_air_temperature > 25C or
         max_vertical_illuminance > 3500 lux:
         CLOSE
      else:
         OPEN
```

```
    else:
        OPEN
else:
    if night:
        if indoor_air_temperature > 19C:
            OPEN
        else:
            CLOSE
    else:
        if indoor_air_temperature > 19C:
            CLOSE
        else:
            OPEN
```

An important feature of the control algorithm is that, whenever the conditions that would generate a change in the position of the shade are met, the algorithm checks that the new position of the shade also meets the conditions before sending the signal to the actuator. In this way, the controller avoids frequent changes of the shade position that may disturb the occupants. At anytime, the occupants are able to override the automatic control.

4. Characterization of the solar control system

The simulation engine of the controller periodically calculates the average workplane illuminance and the maximum vertical illuminance at eye level in the room in order to decide the position of the roller shade. A thermal model is also implemented in the simulation engine to evaluate the annual performance of the fenestration system (section 6). The calculation of these variables requires determining the optical and thermal properties of the fenestration system, which can be represented by Bi-directional Scattering Distribution Functions (BSDF) and Directional Solar Heat Gain Coefficients (DSHGC) [4]. A BSDF is a set of coefficients (transmittance and reflectance) defined by pairs of incoming and outgoing light directions. The latter refers to the light distribution inside the room, while the former relates to the acceptance of light from different sky regions [7]. On the other hand, the DSHGC is a measure of the total fraction of incident solar irradiance that is transmitted into the building through a fenestration system for different incoming directions. For each incoming radiation direction, the Solar Heat Gain Coefficient (SHGC) consists of two parts, the solar direct-hemispherical transmittance τ_e and the secondary internal heat transfer factor q_i, the latter resulting from heat transfer by convection and longwave radiation of that part of the incident solar radiation which has been absorbed by the system [8].

In this study, the BSDF of the textile materials before and after the retrofitting intervention are obtained from optical measurements at the TestLab Solar Façades at Fraunhofer ISE (Freiburg, Germany). Firstly, reference values for the normal-hemispherical transmittance and reflectance of the materials for the visible and solar spectral ranges are obtained using an integrating sphere (Lambda 9, Perkin-Elmer). An integrating sphere consists of a hollow spherical cavity with its interior covered with a diffuse white reflective coating and with small apertures for entrance and exit detector ports. For transmittance measurements, a sample is placed at a sphere aperture between the light source and the integrating sphere. A detector located at one of the ports of the sphere measures the spatially integrated scattered light from the sample due to multiple diffuse reflections at the internal sphere surface.

The measurement results with the integrating sphere are summarized in Table 1, where it can be seen that the existing material presents a slightly lower normal-hemispherical reflectance ($\rho_{e,nh} = 0.585$) than the proposed material ($\rho_{e,nh} = 0.601$). The reflectance of an interior shade is what deter-

	Proposed textile	Existing textile
$\tau_{v,nh}$	0.088	0.118
$\tau_{e,nh}$	0.087	0.159
$\tau_{v,ndif}$	0.043	0.084
$\tau_{e,ndif}$	0.042	0.126
$\rho_{v,nh}$	0.590	0.653
$\rho_{e,nh}$	0.601	0.585
$\rho_{v,ndif}$	0.587	0.653
$\rho_{e,ndif}$	0.598	0.586

Table 1: Summary of integrating sphere measurements of two samples: Ultimetal textile material (proposed) and the existing blind material (existing). transmittance (τ) and reflectance (ρ) values are obtained according to DIN EN 410. The subscripts v and e refer to the visible and solar spectral ranges, respectively. Normal-hemispherical (nh) and normal-diffuse ($ndif$) values are reported.

mines its solar control performance, reducing the SHGC of the fenestration system with respect to the one of the glazing unit. It also reduces the surface temperature of the shading device, which is relevant for thermal comfort. At the time of the demonstration project, a highly reflective shade material was not available by the provider. However, section 6 analyzes an upper limit situation, in which an interior shade material with $\rho_{e,nh} = 0.8$ and $\tau_{v,nh} = 0.1$ is used as roller blind.

It can also be seen from the measurement results that the daylighting performance of the existing material is better ($\tau_{v,nh} = 0.118$) than that of the proposed material ($\tau_{v,nh} = 0.088$). This, however, was not considered to be a disadvantage given the amount of daylight available in this particular case study.

On the other hand, the openness coefficient (measured with the normal-normal transmittance) of the old material is smaller ($\tau_{v,nh}$-$\tau_{v,ndif} = 0.034$) than that of the proposed material ($\tau_{v,nh}$-$\tau_{v,ndif} = 0.045$) and only the proposed material allows view contact through the material. Low openness coefficient of a textile material combined with light scattering prevents view contact through the material due to haze (see for example the classification proposed in EN14501 [9]).

At the same time, textile roller blinds with $\tau_{v,nn}$ values between 0.03 and 0.05 cannot be considered first-class glare protection devices when the sun disk lies within the occupant's field of view. Also, in this case, it is important to check that the metallized finishing does not produce haze at the hole edges, which would otherwise be another glare source. In the present study, glare is evaluated by using the maximum vertical illuminance for critical view points and screen positions as the glare metric. This metric neglects the effect of small glare sources such as the direct solar radiation transmitted through material holes [1]. Although the glare analysis presented in this study can be seen as a good indicator of the glare performance of the shading device, a more detailed analysis would be required in order to guarantee a glare-free environment for this case.

The light-scattering properties of the materials, which are required for daylighting calculations, were determined with a 3D-scanning photogoniometer. The scanning photogoniometer setup at Fraunhofer ISE (pgII, Pab Advanced Technologies Ltd) consists of an illumination system and a robotic arm that moves a sensor on a virtual sphere (radius = 1 m) around a sample [10]. A sample holder allows the rotation of the sample around two axes relative to the optical axis of the illumination system. For any source direction the robotic arm allows high-resolution measurements of scatter directions in the transmission and reflection hemispheres. In this experiment, a combination of a xenon lamp for the light source and a broadband silicon diode for the detector is used. A total of nine angles of incidence were measured.

By analysing the directional-hemispherical behaviour of the samples, it could be concluded that the rotational symmetry of the new material is more pronounced than that of the existing material, although this is still a valid assumption for both samples. The old material presents also a less flat angular response with respect to the polar angle (θ). The scattering behaviour of both samples is illustrated in Fig. 4 for an incident angle of 60° ($\theta = 60^\circ$, $\phi = 0^\circ$). The scattering plots show that the old blind material presents a more evenly distributed transmitted light scatter than the Ultimetal textil, which can also be inferred from the normal-diffuse values reported before. The scatter of reflected light is also more uniform for the existing white material than for the metallized Ultimetal, for which the scatter is more important in the plane defined by the incident and specularly reflected rays.

The characterization of the glazing unit is obtained from the information reported by the architect. The glazing system is composed of (from outside to inside): 6+6.1 mm laminated glass with climaguard coating on position 2, 12.0-mm gap with 90% argon gas fill and 4+4.1 mm laminated glass. This information is used to reproduce the glazing unit in LBNL's WINDOW tool, which generates a BSDF datafile. A summary of the properties of the glazing unit is presented in Table 2.

Once the BSDF of the two textile materials and of the glazing unit are obtained, the Klems method [11, 12] is applied to obtain the aggre-

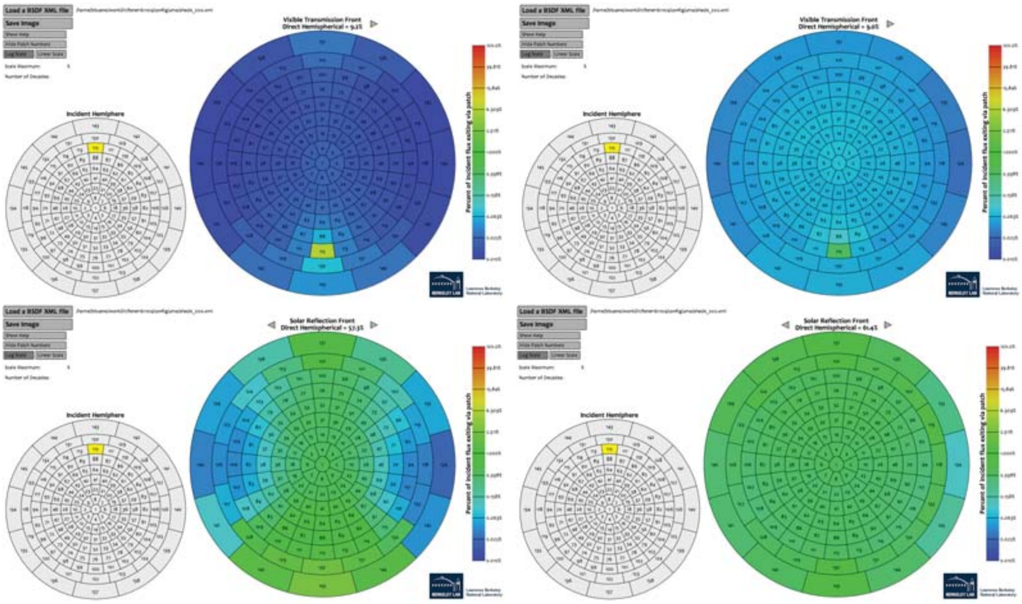

Figure 4: Scattered transmittance (upper row) and reflectance (lower row) of the Ultimetal textile material (left) and the existing white blind material (right) for an incident angle of 60° ($\theta = 60°$, $\phi = 0°$). The graphs are obtained from the LBNL program BSDFviewer.

gated properties of the complete systems (shade+glazing unit), including the angle-dependent absorptance values of each layer. Given that the fenestration system can be seen as a set of homogeneous, parallel and rotationally symmetric layers, it is justified to apply the ISO15099 model [13] to calculate the DSHGC of the systems.

The resulting properties are summarized in Table 2, assuming that the U-value of the fenestration system is the same as that of the glazing unit. Two additional systems are also included here to be used in section 6: a system with a highly reflective interior roller blind ($\rho_{e,nh} = 0.8$) and a system where the Ultimetal roller blind is placed outside the glazing unit.

Table 2: Properties of the fenestration systems considered in the analysis: solar control double glazing unit (DGU), DGU with the existing interior white blinds (existing), DGU with the proposed interior Ultimetal shade (proposed), DGU with a highly reflective interior roller blind (reflective) and DGU with the Ultimetal shade located outside the glazing unit (exterior). Solar Heat Gain Coefficients (SHGC) and solar direct-hemispherical transmittance values ($\tau_{e,dirh}$) are indicated for two different incident angles (α_i).

	U-value [W m^{-2} K^{-1}]	SHGC α_i=0°	SHGC α_i=60°	$\tau_{e,dirh}$ α_i=0°	$\tau_{e,dirh}$ α_i=60°	$\tau_{v,nh}$ α_i=0°
DGU	1.27	0.48	0.41	0.34	0.26	0.66
Existing	1.27	0.33	0.29	0.06	0.04	0.09
Proposed	1.27	0.31	0.30	0.04	0.03	0.09
Reflective	1.27	0.29	0.26	0.05	0.04	0.09
Exterior	1.27	0.07	0.07	0.04	0.03	0.07

5. Evaluation of the numerical model

In this section, results of the simulation engine (named Fener) are compared with in-situ measurements of horizontal illuminance. The validity of Fener to predict daylighting and thermal conditions in a room for well defined boundary conditions has already been demonstrated in previous studies [3, 4]. The objective of this section is, therefore, to test that the case study is correctly defined in the model and that the reading and processing of meteorological data is reliable.

Measurements took place mainly during unoccupied periods, between the 20th and the 23rd of January, between the 26th and the 31st of January, between the 4th and the 6th and between the 11th and the 13th of February, 2017. Meteorological data was obtained from the meteorological station located on the roof of the Engineering School at the University of Malaga, managed by the Energy Group of the University. Values of global and diffuse solar irradiance, outdoor air temperature, relative humidity and wind speed were recorded every 10 minutes. The same meteorological data was also automatically uploaded to the cloud, and then downloaded and used by the simulation engine every 10 minutes in order to run the shading controller.

The measurement equipment consisted of six Hobo sensors and one Testo 480 instrument, which allows light metering. The illuminance sensors of the Hobo devices were first calibrated against the Testo by exposing them to outdoor illuminance conditions during one hour before sunset (on the 17th of January, 2017, from 17:40 to 18:40). This covered an illuminance range from null to 3500 lux.

Once calibrated, the Hobo devices and Testo equipment were placed in the office forming a row perpendicular to the window at 3 m from the right corner of the window (from inside). The sensors are located at 0.75 m above the floor and at 0.4, 0.8, 1.6 and 2.0 m away from the window.

The simulation engine requires a set of input parameters, which in many cases have to be estimated based on observation and best knowledge. The reflectance of the surfaces that enclose the room is estimated to be 70% for white surfaces (walls and ceiling) and 20% for the floor. The exterior overhang of the room and the one of the room underneath have an albedo of 50% in the model, and the exterior ground has an albedo of 20%. Apart from the overhang, no external obstructions cast shade onto the façade. The list of input parameters is detailed in Table 3.

The comparison of average workplane illuminance is shown in Fig. 5. Based on a qualitative visual evaluation of the graph, the agreement of workplane illuminance is considered to be satisfactory. As a consequence, it is assumed that weather data reading and processing is reliable, that the fenestration system is well characterized and that the geometrical and optical properties of the case study are well defined in the model.

Table 3: Input parameters of the case study used for the annual dynamic simulations. LT refers to local time and ACH refers to air changes per hour. Internal heat gains refer to square meters of floor area.

Location	Malaga
Latitude	36.67° North
Longitude	4.49° West
Orientation	south-west (-63° from south)
Zone dimensions (interior)	4.75 m x 3.57 m x 3.17 m
Window dimensions	Four vertical panes of 1.15 m x 3.07 m
Frame dimensions	Three mullions of 0.05 m thickness
Exterior overhang depth	1.4 m
Sky view factor	0.5
Interior surface albedo	floor 0.2, walls and ceiling 0.7
Exterior overhang albedo	0.5
Ground albedo	0.2
Worktime schedule	8-18 LT (weekdays)
Infiltration/ventilation	1.0 ACH
Electric lighting power	2.0 W m^{-2}
Equipment heat gain	10.61 W m^{-2} (worktime)
Equipment radiant fraction	0.0
Occupation sensible heat gain	4.13 W m^{-2} (worktime)
People radiant fraction	0.5
Cooling thermal setpoint	26 °C
Interior surfaces construction	Exterior finish (1cm) Massive material (5cm) Interior finish (1cm)
Property exterior finish	λ = 0.25 W m^{-1} K^{-1}
Property insulation	λ = 0.03 W m^{-1} K^{-1}
Properties massive material	λ = 2.3 W m^{-1} K^{-1} ρc = 2.3e^6 J m^{-3} K^{-1}
Grid of horizontal illuminance sensors	Five rows perpendicular to the window with five sensors each, evenly distributed.
Grid of vertical illuminance sensors	Five pairs of sensors evenly distributed parallel to the window, at 1.65 m from it. At every position, two sensors face opposing directions parallel to the window.

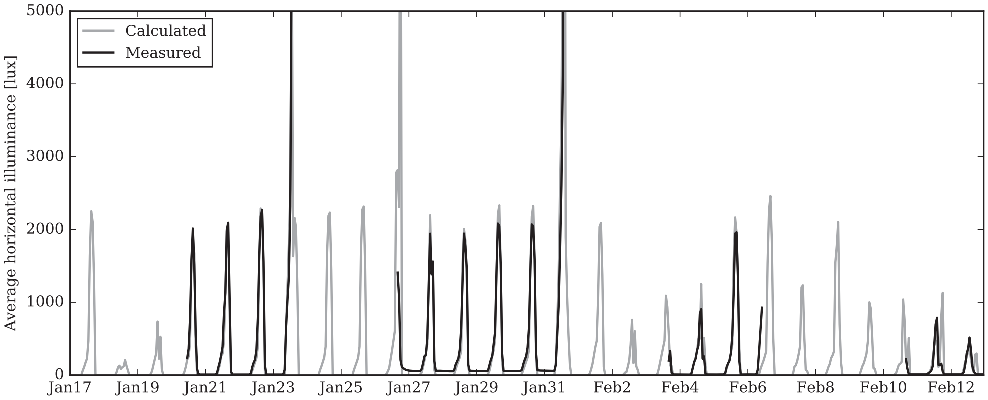

Figure 5: Average workplane illuminance calculated by Fener between January 17th and February 13th and measured during January 20-23, January 26-31, February 4-6 and February 11-13. Meteorological data is collected from the meteorological station located on the roof of the School of Engineering at the University of Malaga. During this period, the shading device is closed except for January 23, from 9h-16h, January 26, 9h-14h, and January 31, 9h-16h (local time).

6. Evaluation of the annual performance of the retrofit solution

In this section, the numerical model of the office is used to evaluate the annual performance of the retrofit solution as compared to a baseline scenario. Dynamic simulations are carried with the Fener model under the boundary conditions indicated in Table 3. In addition to what has been previously reported, the office under study has two work stations with two computers of 90 W, which at the time of this study were used occasionally. For the dynamic annual simulations, however, normal office use between 8:00 and 18:00 local time (LT) is assumed. The cooling thermal setpoint is assumed constant at 26°C. In addition, and based on in-situ observations, a relatively light building mass is assumed.

In the baseline scenario, the existing interior blinds are fully closed all the time, i.e. the window area is always covered. In the retrofit scenario, the proposed Ultimetal roller blinds are activated according to the control algorithm described in section 3. Results for the same control algorithm but with different fenestration systems are also analyzed (highly reflective interior roller blind and exterior Ultimetal roller blinds). The system properties of the baseline and proposed scenarios are indicated in Table 2. The comparison is reported in Table 4.

Figure 6 shows a temporal map of uncovered window area (dark color)

Table 4: Relative comparison of the annual performance of different retrofit solutions and a baseline scenario. In the baseline scenario, the existing interior blinds are fully closed all the time. In the retrofit scenario, roller blinds are activated according to the control algorithm described in section 3. Three retrofit alternatives are analyzed: interior Ultimetal roller blind (prop), highly reflective interior roller blind (refl) and Ultimetal roller blind located outside the glazing unit (ext).

	prop	refl	ext
Reduction of occupied hours with average horizontal illuminance lower than 400 lux	84%	84%	85%
Reduction of occupied hours maximum vertical illuminance lower than 3500 lux	2%	1%	2%
Reduction of cooling energy demand	0%	12%	70%
Reduction of occupied hours with closed roller blinds	60%	54%	61%

according to the proposed control algorithm. By having the months of the year as the x axis and the hours of the day as the y axis, each pixel of the graph represents one hour of the year. By taking only the occupied hours (workdays from 8 to 18 LT), the results indicate that the window is uncovered during the mornings for a total of 60% of the occupied time. This means that the occupants would have undisturbed view contact with the outside during all the morning hours. In addition, the hours in which the daylight in the room is not enough (average workplane illuminance lower than 400 lux) decreases by 84% of the occupied hours, at a cost of having an environment without glare (maximum vertical illuminance lower than 3500 lux) for 2% less hours. The simulation results also confirm that the cooling energy demand of the room does not deteriorate with the proposed solution as compared to the baseline scenario. The fact that the cooling energy demand is very similar in spite of having the window more frequently uncovered can be explained by the slightly improved solar control performance of the new material (see section 4) and by the ability of the control algorithm to open the shade only when the risk of overheating is low.

With these scores, it can be concluded that the retrofit solution fulfils its design goals (section 3). Similar results would have been obtained by using the same textile material by the automatic roller blinds as for the existing vertical blinds, except for the view out through the material. However, the existing material of the vertical blinds could not been recycled because of the need for motorized roller blinds for the automation.

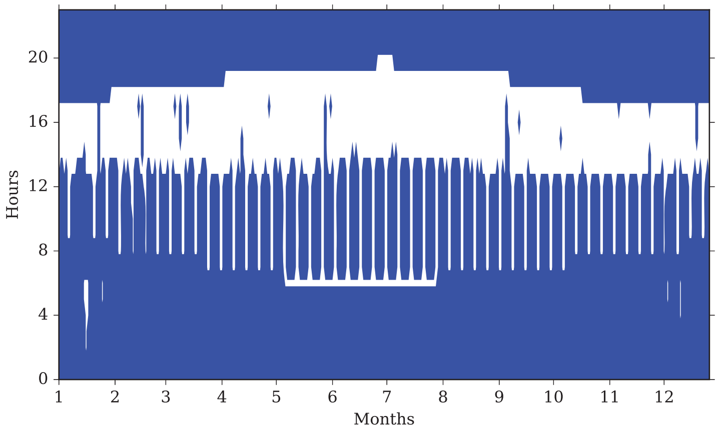

Figure 6: Temporal map of uncovered window area (dark) according to the proposed retrofit solution. Each pixel of the graph represents one hour the year (the x-axis represents the months of the year and the y-axis represents the hours of the day).

Two additional scenarios are included to illustrate that the same control strategy applied to a highly reflective interior roller blind could actually reduce the cooling energy demand by 12% and that the same control strategy applied to an exterior Ultimetal roller blind would result in an important reduction of cooling energy demand (70%). Other figures are similar to the interior Ultimetal roller blind (Table 4).

By looking at Fig. 6, it can be also concluded that a scheduled control that closes the shades at fixed hours during the day would also have similar performance and a much easier implementation for this particular case study. The specific time at which it opens or closed could change during the year to improve the performance and be defined based on these simulation results for the proposed control algorithm.

7. Testing the implementation of the retrofit solution

The motorized roller blinds and the controller's electric connection box were installed on January 23, 2017. Two roller blinds with Ultimetal textile were installed in an office of the second floor of the Faculty of Health Sciences of the University of Malaga. Each roller blind was 2.3-m wide and actuated by a motor. The two roller blinds did not cover the whole window, leaving 5-cm gaps at the edges and at the centre of the window. The latter was partially covered by one of the mullions of the façade. The controller electric connection box was taken from a previous installation in Freiburg (Germany). It consists of a field bus system that is used as the communication link for all input and output modules.

In this installation, the two different motors were controlled by the same signal from the electric connection box. This turned out to be problematic because the two roller blinds have to be perfectly synchronized in order to avoid cross-signals from one motor to another when the shades get all the way down or all the way up. This was impossible in practice, and led to damage of some of the relays of the electric connection box. The solution was to set-up the controller in a way as to prevent the roller blinds from reaching their upper and lower limits.

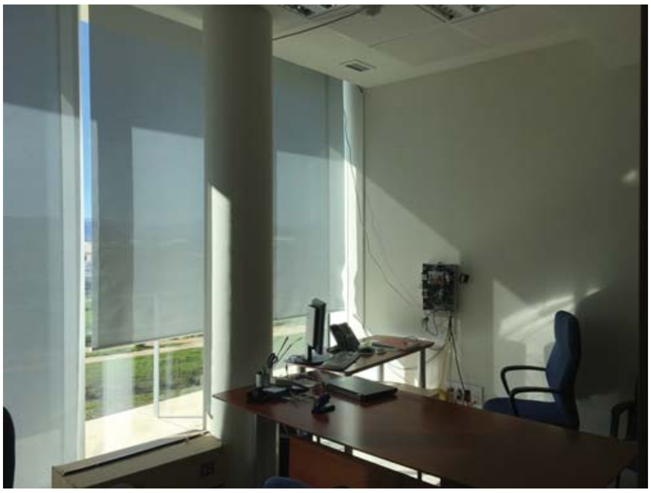

Figure 7: Picture of the office with the new Ultimetal roller blinds and the controller electric connection box. Taken on January 23th, 2017, at 10:13.

Given the on-off nature of the control, large differences in the visual conditions occur when the shades close or open. In this situation, the controller prioritizes the existing conditions over the new ones, leading to a glare situation at midday during a few minutes before the shade closes. To correct this issue, the controller could incorporate intermediate positions of the shades for the transition periods.

The processing of meteorological data that was used in this project reported average values of the last 10-minute measurements. Added to this is the time required to extract meteorological data for one timestep, upload it to the cloud and download it by the controller. This led to at least 7-minute delays between current meteorological conditions and actuation of the controller. For rapidly changing weather conditions, such as for example isolated clouds, the controller might actuate late producing severe glare conditions or too low daylight levels during 10-min periods. A better synchronization with meteorological data will mitigate these situations. In addition, a special module to detect rapidly moving clouds could be developed. Under these circumstances, the controller should be set-up to a much more conservative mode to avoid severe discomfort.

Another improvement of the controller could be the immediate reaction to changes in occupation. At present, the controller is run every ten minutes. When the occupant arrives in the morning, the shades are positioned according the non-occupied mode, and the occupant must override the control or wait until the next timestep for the shades to recognize his/her presence.

8. Conclusions

A systematic workflow for retrofitting office façades with large window-to-wall ratios has been presented. The workflow consists of analysing the level of importance of the different functions of a façade for a particular application and then applying automated control and building simulations to optimize the operation. The studied functions are aesthetics, view contact with the outside, daylight provision, glare protection and solar heat gain management (there can be other functions). The proposed workflow requires the optical charactization of the fenestration system, which is also described in detail in this study.

The proposed workflow was applied to a case study in a south-west office at the University of Malaga (Spain). Here, it was identified that the occupants had constantly activated an interior blind system in order to protect themselves from high irradiation levels in the afternoon. As a consequence, valuable views of a semi-natural landscape were not enjoyed, and the room was dark during the first hours of the morning. In the designed retrofit intervention, the existing interior vertical blinds are replaced with interior roller blinds with a metallized reflecting surface facing towards the glazing unit. An automated control system is designed to maximize view contact with the outside and daylighting while preventing glare and overheating. By applying this control strategy, the occupants have undisturbed view contact with the outside during the whole morning hours totalling 60% of the occupied time. In addition, the number of hours in which the daylight in the room is not sufficient decreases by 84% of the occupied hours, as compared to a baseline scenario in which the existing blinds are constantly closed. The control strategy does not worsen the glare status and cooling energy demand of the room as compared to the baseline scenario. Besides, if a highly reflective white material were to be used instead of the metallized one, the cooling energy demand could be reduced by 12% by applying the same control strategy. Alternatively, if the metallized roller blind were to be positioned outside the glazing unit, the cooling energy demand could be reduced by 70%.

It must be noted, however, that the textile material that was chosen in this case study has an openness coefficient of 4%, which allows view through the material. The ability to protect against glare of this material was evaluated with a metric that neglects potential glare sources produced by the material holes. A detailed glare analysis is, therefore, still required in order to fully recommend this material as a glare-free shading device for this application.

The proposed shading control strategy periodically reads real-time meteorological data and indoor air temperature and decides on the best shading position based on imposed conditions on the calculated visual and thermal conditions in the room. However, for this particular case study, a much easier implementation of the control strategy would consist of setting up a schedule that closes the shades at fixed hours during the day. The opening and closing times could be predefined based on annual building simulations with the proposed control algorithm.

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