Advanced Shading Control Strategy for Shopping Malls: A Case Study in Spain.

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Abstract

The management of solar radiation access inside buildings with large glazed façade requires considerable attention when energy saving and interior comfort has to be provided.

This paper aims to present a control strategy for venetian blind applied on a shopping mall building located in Spain. The shading control strategy is based on a hierarchical decision-making approach, which aims at optimizing shadings configuration to reduce heating and cooling need and to improve thermal and visual comfort. The control has been tested using detailed thermal and daylighting annual simulations. The results in terms of energy consumption, visual and thermal comfort are compared against two standard controls strategy, and show the effectiveness of the proposed control.

Introduction

Shopping malls can be featured by large portion of glazing in the façades. These large openings have a relevant impact on the interior environment with respect to thermal and visual comfort as well as to energy consumption in terms of lighting, heating and cooling.

Figure 1: Mercado del Val glazed façade.

Therefore, controlling solar heat gains and daylight entering the space by means of shading devices is essential in order to provide an adequate occupants comfort and the reduction of energy demand. In the field of shading and façade systems, the concept of Complex Fenestration Systems (CFS) has been introduced. CFS are those systems that incorporate non-specular layers and whose optical and thermal properties present complex dependence on angle of incidence and wavelength (De Michele et al. 2015), allowing for a better management of solar radiation. Moreover, CFS, when combined with a proper shading control, have the potential to optimize the use of solar gains to reduce heating and cooling need and to improve thermal and visual comfort (Bueno et al. 2015). Often these aspects are competing among each other because optimizing simultaneously all the criteria is not possible (Kuhn et al. 2001). As an example, during heating season the optimization of shading control to reduce energy need would result in limited shading use to maximize solar heat gains On the other hand, limited shading use might cause visual discomfort due to increased risk of glare. For this reason, a hierarchical decision-making is necessary to define a shading system control. The decision hierarchy and the control might vary depending on local climate conditions, building functionality, internal layout distribution, and external obstructions. Therefore, the shading devices control cannot be standardized, but each application requires a tailored approach.

Moreover, simulation of complex shading system with dynamic control and its interaction with building energy consumption and thermal comfort requires the use of models able to accurately describe their thermal and optical behavior. In fact, several studies (Kuhn et al. 2001; De Michele 2015) demonstrated that using simplified thermal modeling of shadings against detailed modeling can lead to differences up to 99% in the building energy demand when a control strategy uses interior temperature as control parameter.

This study presents a multi-objective shading control strategy designed for a refurbished market hall located in Valladolid, Spain. The shading control strategy is based on a hierarchical decision-making approach which aims at optimizingshadings configuration to reduce heating and cooling need and to improve thermal and visual comfort.The control has then been tested employing detailed models for both the modeling of the shading system itself and the thermal and daylighting dynamic simulations. The results in terms of energy consumption, visual and thermal comfort are compared against two standard shading configurations (i.e. no control, and standard control).

Shading control strategy

The “Mercado del Val” is an historic market hall in Valladolid (Spain) that has been refurbished by emphasizing the existing iron structure through a modular glazed façade all over the perimeter. The facade adapts to the existing structure and aims at integrating thermal, daylighting and ventilation functions, being responsive when internal and external loads change. In particular, the south façade modules have been equipped with an external dynamic shading system (i.e. venetian blinds) to control solar radiation.

Due to the large dimension of the façade, the shading system has been divided in four groups (i.e. G1, G2, G3 and G4), as shown in Figure 2. Each group is controlled by a different command. The façade shadings are divided considering a uniform division of the façade, the shade effect of neighborhood buildings, and the sensors' location inside the building.

The sensors used to control the shading system are listed in Table 1. External vertical radiation, external air temperature, and wind velocity are measured by a weather station located on the building roof. In particular, the pyranometer is oriented according to the south façade exposure. Two pairs of interior sensors, air temperature and luminosity, are located on two of the market stalls facing towards the south façade, as shown in the bottom image in Figure 2.

The design team identified, in descending order of importance, the following functions for the shading system:

- Solar radiation control to avoid overheating during the cooling season and to maximize solar heat gains during the heating season
- Visual contact from outside toward inside
- Daylight and glare control

Table 1: Sensors used for the shading control

Sensors	Measured variable
Pyranometer	External radiation on vertical plan [W/m2]
Dry bulb temperature sensor	Dry bulb temperature [°C]
Anemometer	Wind velocity [m/s]
Indoor temperature sensors	Indoor air temperature [°C]
Luminosity sensors	Vertical illuminance [lux]

These requirements are the basis for the hierachical decision-making process implemented in the shading control strategy and represented by the conditional chart flow in Figure 3. The decision path is driven by several conditional blocks. The first conditional block prevents blinds to lower at wind speeds higher than 13 m/s, as recommended by the technical specifications for the lamella system. The second conditional block defines the market opening hours and the season. The season is identified by the average of the outdoor dry bulb temperature over the previous 24 hours (*Tout_24*). If *Tout_24* is greater than 12 °C, the control switches to summer mode. In summer, the shading activation depends on the vertical irradiance on the façade (*Is*). If *Is* exceeds the threshold value of 120 W/m^2, the shades are set to cut-off position, i.e. the blind tilt angle that prevents direct radiation entering the space while providing the maximum view to outside.

In winter mode (*Tout_24*≤12 °C), the shading activation is associated to both the zone air temperature (*Tin*) and the vertical irradiance on the façade (*Is*). In particular, if the zone air temperature is lower or equal to the heating set-point temperature (*Tset,h*) shadings are raised to

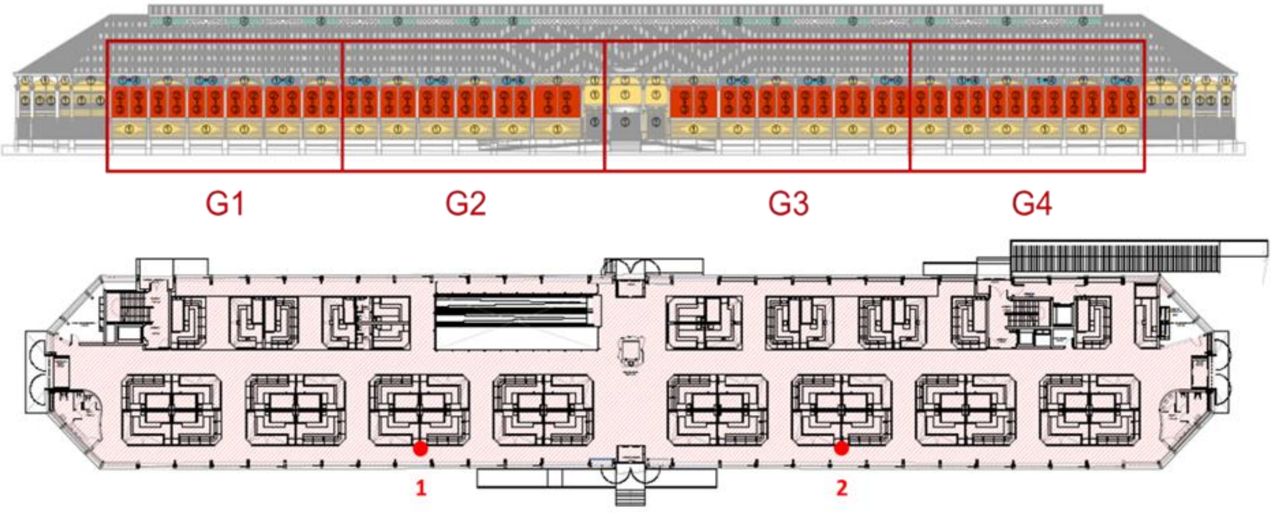

Figure 2: The top image shows the division of the south facade into the four shading groups. The interior sensors location is displayed in the bottom image.

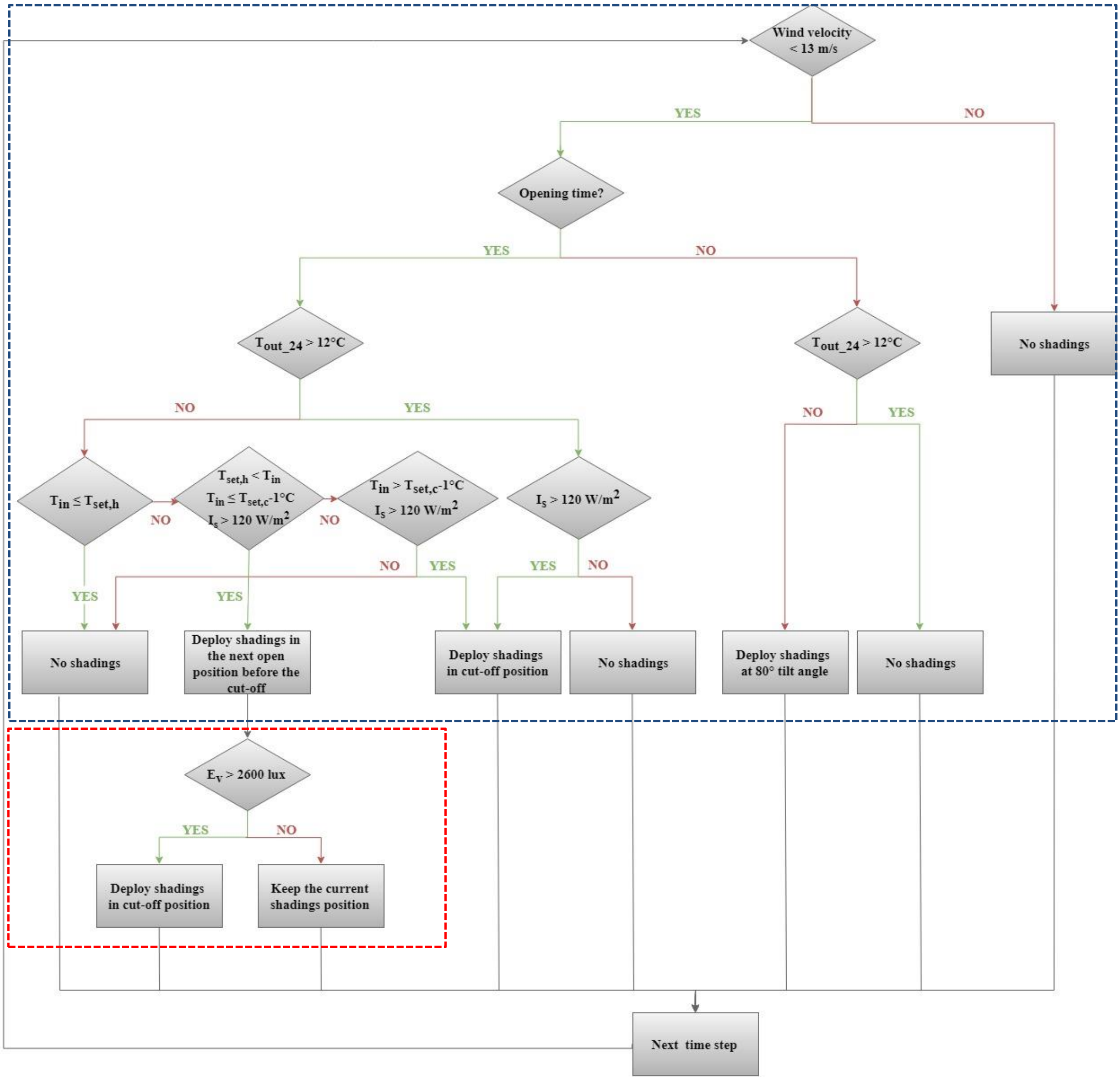

Figure 3: Chart flow of the control strategy.

maximize solar gains and to reduce energy consumption for heating. On the other hand, if the zone air temperature is higher than the cooling set-point temperature (*Tset,c*) minus 1 °C and *Is* is higher than 120 W/m^2, the control behaves the same as in summer mode. This conditional block allows to avoid overheating in winter and to prevent the activation of the cooling system.

When *Tin* is lower than the *Tset,c* minus 1 °C, but still higher than *Tset,h*, and *Is* exceeds the threshold limit, the shades are lowered and lamellas are tilted to an angle that is a step opened before the cut-off (e.g. if the cut-off is 35°, shades are deployed at 20° tilt angle); as soon as an acceptable value of vertical illuminance (*Ev*) is measured. Otherwise, if measured vertical illuminance exceeds 2600 lux, glare risk is considered high. Therefore, shades are lowered and tilted to cut-off angle. This control setting allows for a higher access of solar gains when solar radiation does not cause visual discomfort.

The threshold value for the vertical illuminance has been calculated by converting the Daylight Glare Probability (DGP as defined by (Wienold 2009)) limit for imperceptible glare (0.35) in vertical illuminance (2680 lux). In particular, the equation (1) for the calculation of simplified DGP has been applied.

$$DGPs = 6.22\ 10^{-5} \cdot Ev + 0.184 \qquad (1)$$

Finally, in order to reduce the heat losses during the winter time and to improve heat control during the summer, during market closing time the shades is deployed at 80° tilt angle or not activated respectively in winter or summer season. Coupled thermal and daylight simulation

The design and evaluation of the control strategy required the use of several tools to define a database of shading cut-off angles, to generate a reliable model of the shading system, and finally to perform detailed thermal and optical simulation assessing the expected benefits. This section explains the several steps followed to implement and to analyse the control strategy.

Slat angles database

A cut-off angles database has been pre-calculated for a whole year over a hourly time-step according to the sun position and façade exposure, and considering five lamellas tilt angles between 0° and 60°. The step between two states is defined considering a step of 10° angle of sun altitude. Table 2 shows the cut-off angles related to the range of sun altitude.

Table 2: Cut-off angles for the range of sun altitude.

Sun altitude	Lamella cut-off	IDstate
> 40°	0°	1
30°-40°	20°	2
20°-30°	35°	3
10°-20°	50°	4
< 10°	60°	5

Since the surrounding buildings have a relevant impact in terms of shade on the market hall façade, the cut-off angles database was cross checked with shades generated by surrounding buildings over a year on the four façade sections corresponding to the shading groups (G1, G2, G3, and G4). Shades are raised if the surrounding buildings shade the facade. In particular, if the neighbour buildings shade the 90 % of the area corresponding to each single group, the shades are raised. The shadows database contains a series of Boolean values (I/O) for every hour of the year calculated with Ladybug+Honybee (Sadeghipour Roudsari & Pak 2013) tool.

The lamella state command sent by the control system to the shading system results from shadows and cut-off database cross check: for each hour of the year the shadow database suggests whenever the shading devices need to be lowered for each single group, while the cut-off database determines the optimal tilt angle for the lamellas.

Glazing system modelling

Two different glazing systems are installed on the building; both the systems are double low-e glass filled with a gas mixture of argon (90%) and air (10%). However, the typology mounted on the south façade (i.e. MVal_glass_S) provides a stronger control of the solar radiation. In fact, the g-value is 50% lower than the other system, as reported in Table 3.

Table 3: Glazing systems characteristics.

Glazing system	U-value	g-value	Tvis
MVal_glass_S	1.4	0.3	0.3
MVal_glass_WNE	1.4	0.6	0.75

The shading system is a standard curved lamella with solar and visible reflectance of 0.7. The blinds dimensions are reported in Table 4.

In order to use the advanced thermal and daylighting models of TRNSYS18 and Radiance, as explained in the next paragraphs, a detailed model of the whole glazing system (glazing layers and blinds) was generated using LNBL WINDOW7.5. Concerning the thermal simulation, an .idf file with the BSDF data over the solar spectrum of the whole system, the absorption and thermal characteristics (IR emissivity and IR transmission) of each layer was generated. While the BSDF over the visible spectrum was calculated for the daylighting simulation.

For each possible blinds state a separate model containing all the previous characteristics was generated.

Table 4: Venetian blind dimension

	Dimension [mm]
Slat width	100
Spacing	87
Thickness	0.45
Rise	4

Thermal modelling

In order to evaluate the performance of the control strategy, a detailed approach has been used for both thermal and daylighting simulations. Concerning the thermal analysis, TRNSYS18 has been used since it relies on a new detailed simulation module to evaluate the performances of Complex Fenestration System (Hiller & Schöttl 2014). In particular, this module is included into the building Type56 and treats the thermal transmission through the façade element (glazing and shading) according to the ISO 15099 (Standard 2003) algorithm, while the solar transmission and absorption of each layers are evaluated using the BSDF-data.

Daylight modelling

Daylighting simulation is performed with a TRNSYS's type called "*TypeDLT*" (DayLighTing) (De Michele et al. 2015) that enables the 3-Phase Method (Saxena et al. 2010) of Radiance (Ward, J 1989) for dynamic, climate-based analysis of Complex Fenestration Systems. TypeDLT takes in input the BSDF data of the complete system, and exchanges easily and dynamically shading states by changing the BSDF data inside the matrix equation at the base of the algorithm. Moreover, TypeDLT allows for controlling up to 10 glazed surfaces independently. This characteristic was essential in this case study since the controlled zones have also other glazing surfaces that do not have a shading system (i.e. north façade).

Illuminance values over two sensor points, located in the position of the real sensors, are calculated by the daylighting model at each time-step of the simulation taking in input the same weather data of the Type56.

In this specific case, the illuminance values are used to control the shading state, and have not been used to control the artificial lighting.

Implementation of the control strategy in TRNSYS

TRNSYS architecture allows for a flexible use of input and output from all the types in the simulation studio that can interact and share information among them.

The control was implemented using a set of equation types that take inputs from weather file, Type56CFS and TypeDLT. Due to its complexity, control required a two phase implementation. The first equation type contains all the statements based on indoor air temperature (dark dotted square in Figure 3). The second equation type contains the statement on the vertical illuminance level, red dotted square in Figure 3. This arrangement was needed because of the conditional block on vertical illuminance. First equation output is the shading state, equal to *IDstate-1*, which is used as input by TypeDLT. The second equation compares the calculated vertical illuminance Ev with the illuminance threshold: if Ev is lower than *Ev_limit*, the shading state remains equal to *IDstate-1*. Otherwise, *IDstate* is the actual configuration and is passed to TypeDLT in order to update the final illuminance value and to Type56 for the thermal analysis.

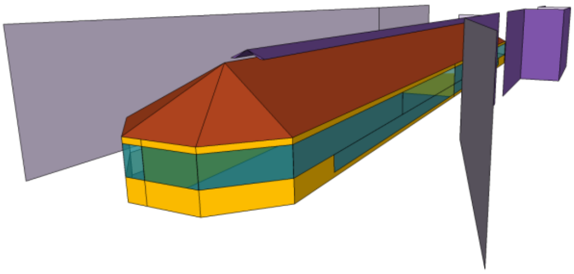

Figure 4: 3D model of the building with the neighbour obstructions

Building model setup

The 3D model of the building with shadings due to surrounding buildings is shown in Figure 4. Figure 5 shows thermal zoning and building orientation. Zone F01_SW and F01_SE are the two zones where shadings are controlled dynamically. A fifth zone is located above the four zones and under the roof. A second and more detailed geometrical model was used for the daylighting analysis. In fact, for the lighting analysis, the structural element of the façade and the interior layout, as the presence of stalls, have been considered in order to get more reliable simulation results.

The thermal and optical characteristics of the transparent elements are reported in Table 3, while the opaque element transmittance and reflectance are reported in Table 5.

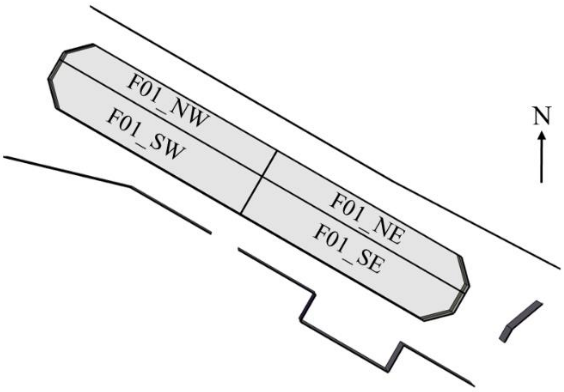

Figure 5: Section of the building and subdivision of the thermal zones.

Table 5: Thermal transmittance of the opaque elements. External and internal element are identified as ext and int in the table below.

Surface	U [W/m² K]	Reflectance
Wall	0.743 (ext) – 2.621 (int)	0.5
Roof – Ceiling	0.410 (ext) – 0.763 (int)	0.8
Floor	0.379	0.2

The market opens every day at 06:00 am and closes at 08:00 pm. Ventilation rates, as well as heating and cooling temperature setpoints are set according to minimum requirements for indoor environment quality - category II defined in the standard EN15251:2007 for department stores. Temperature set point in cold season is 17.5 °C, while in the warm season 24 °C. The heating and cooling system has unlimited power and is always available. Ventilation rates are set as 7.35 kg/h-m² during opening hours and 3.00 kg/h-m² during closing hours. A heat recovery system with an efficiency of 0.5 is active during the heating season. Infiltration rate is assumed to be constant in each thermal zone and equal to 0.40 ACH over the whole simulation time. Table 6 reports the internal gains set in the model. The internal gain due to the presence of persons has been quantified by considering a specific density of 0.20 person/m². The EN ISO 7730 standard recommends to consider a total heat flux of 185 W/person for retail store case where people are standing and performing light work. This value takes into account sensible (90 W/person) and latent gains (95 W/person). The internal gains due to lighting and appliances are assumed by considering the replacement of existing lighting with LED lighting system and the other electric equipment installed in the market.

Table 6: Internal gains set into the building model.

Typology	Heat gain	Unit
People	90	W/person
Appliances	5	W/m²
Lighting	10	W/m²

Shading controls scenarios and benchmark

Three control strategies are implemented in the simulation model and compared in terms of energy consumption and comfort:

No Control: no shading system on the south façade. This strategy have been tested because a first proposal of the design team was to do not employ shading devices on the south façade, relying on the low glazing g-value (i.e. 0.3) for the solar control.

Standard Control: blinds are deployed in cut-off angle on the whole façade when the exterior vertical radiation exceeds 120 W/m^2.

Optimized Control: blinds activation and lamella tilt angle are set according to the control strategy proposed.

Results

Results are reported for the main zones F01_SW and F01_SE, which are the areas where the control is applied. The control strategies are compared in terms of annual ideal energy load, vertical illuminance, DGPs and operative temperature.

Table 7: Heating and cooling ideal load.

		Heating [MW]	Cooling [MW]	diff Heating	diff Cooling
F01_SW	no Control	92.6	107.2	-	-
	Standard Control	96.7	96.2	4%	-10%
	Optimized Control	91.8	96.6	-1%	-10%
F01_SE	no Control	89.0	106.4	-	-
	Standard Control	93.8	94.5	5%	-11%
	Optimized Control	89.4	95.2	1%	-11%

Table 7 shows the heating and cooling load for the two zones south exposed. Similar results are obtained for the two building zones. Compared to the reference case with no shadings and no control, the standard control reduces the cooling load by 10-11%, while increases the heating load by 4-5%. The latter result is reasonable since the shadings cut the solar gain off also in winter. Compared to the Standard Control, the Optimized Control offers the same cooling load reduction (10-11%) at lower increase of the heating load. In fact, during cooling season the Optimized Control behaves similar to the Standard one, while in winter according to the interior temperature and to the shadows database, the lamellas are activated in order to maximize solar heat gains maintaining the visual comfort.

Figure 6 shows the vertical illuminance values for the three control strategies for zone F01_SW, results for zone F01_SE are not reported because very similar. Without any shading, illuminance values often exceed the comfort values (i.e. red square in the graph), mainly in winter season. The standard control provides always a good management of the interior illuminance due to the used of cut-off angles all over the year. The optimized control, due to the control hierarchy that prioritizes energy consumption reduction over visual comfort, allows higher daylighting level during the heating period compared to the standard control, increasing glare risk.

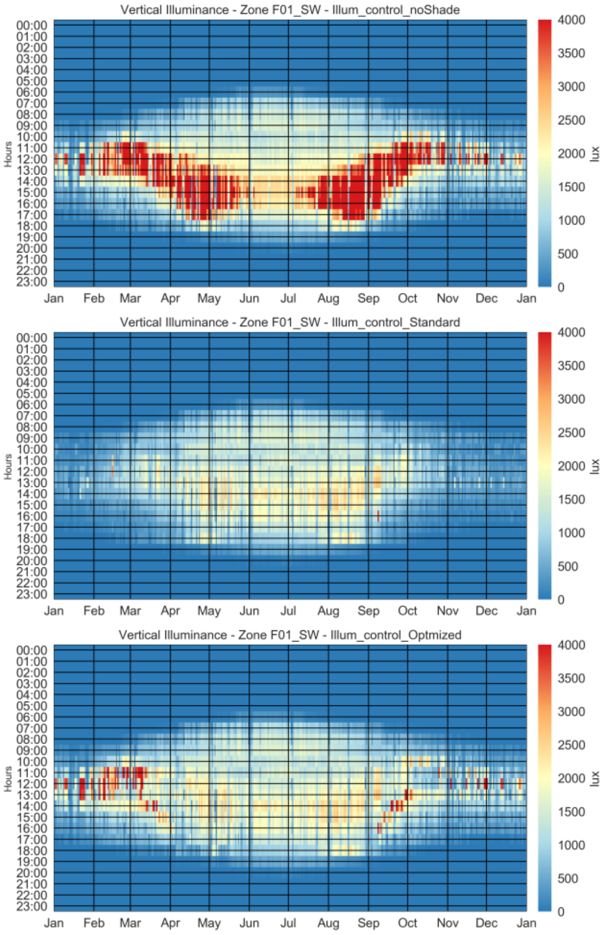

Figure 6: Hourly annual vertical illuminance for zone F01_SW with no control (top), standard control (middle) and optimized (bottom) control.

However, the number of hours during the year when vertical illuminance is greater than the threshold value are in the range of glare acceptability. In fact, as reported in Table 8, the DGPs limit (Wienold 2009) for the optimized control is into the B-class comfort (i.e. perceptible glare) for both the zones.

Table 8: DGPs limit values calculated for each control and zone.

		95% DGPs limit	Mean DGPs (5%)	Comfort Class
F01_SW	no Control	0.54	0.69	discomfort
	Standard Control	0.31	0.34	A
	Optimized Control	0.33	0.39	B
F01_SE	no Control	0.54	0.70	discomfort
	Standard Control	0.31	0.33	A
	Optimized Control	0.33	0.39	B

As expected, without the use of shading system, the glare in proximity of the south façade is inacceptable. The standard control provides the better glare prevention, comfort class is A, i.e. glare is imperceptible.

Observing the operative temperature trends of zone F01_SW (Figure 7), the building performs well from thermal comfort point of view for all the three controls strategies. The curves remain into the II category limit suggested by the standard EN 15251: 2007. Similar trends have been found for zone F01_SE.

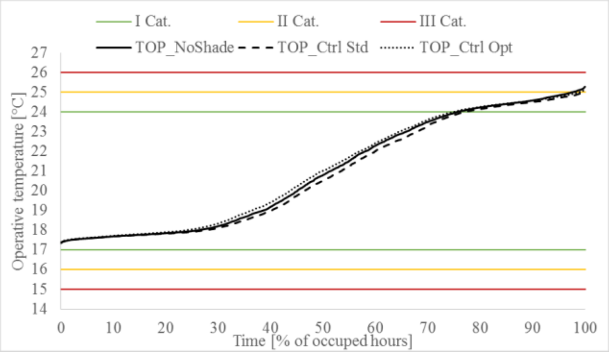

Figure 7: Cumulative operative temperature curves for the three control cases.

Conclusion

The study presented a multi-objective shading control strategy applied to a real shopping mall located in Spain. The control optimizes the shading configuration according to different criteria (i.e. energy saving, thermal and visual comfort, and view to outside/inside) according to a specific hierarchy, which has been discussed and decided together with the design team. If heating or cooling system is active, the energy saving has priority over visual comfort; while in intermediate condition (i.e. HC system is not running) the shading position is optimized considering visual comfort and view to outside as well.

The evaluation of the control was carried out employing detailed simulations models, and comparing the results against two standard configurations (i.e. no control, and standard control). In particular, a detailed model of the shading system, including visual and solar BSDF and thermal properties was generated for each configuration. The shading model was then used into the Type56CFS and TypeDLT of TRNSYS 18, which enabled the ISO15099 coupled with BSDF model and the Radiance Three-Phase Method relatively. The use of TRNSYS was crucial on two sides: the possibility to implement easily the control strategy designed and the use of detailed models for a reliable evaluation of the performance, both of the shading system itself and of the system when dynamically controlled.

The annual simulations results show that the proposed control strategy is effective. In fact, the strategy allows for 10% of cooling energy saving in both the controlled zones. On the other hand, the optimized strategy, due to the multi-objective control, allows higher daylighting level during the heating period compared to the standard control, slightly increasing glare risk to acceptable condition but reducing heating energy demand.

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