Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Départmenet fédéral de l'environnement, des transports,
de l'énergie et de la communication DETEC

Ofiice fédéral de l'énergie OFEN

Final report 31 October 2012

Automatic control of an electrochromic window

LESO-PB
LABORATOIRE D'ENERGIE SOLAIRE
PHYSIQUE DU BÂTIMENT

EPFL
ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Mandant:
Office fédéral de l'énergie OFEN
Programme de recherche Energie dans les bâtiments
CH-3003 Berne
www.bfe.admin.ch

Cofinancement:
LESO-PB/EPFL, CH-1015 Lausanne
EControl-Glas GmbH & Co., D-93437 Furth im Wald

Mandataire:
LESO-PB/EPFL
EPFL-ENAC-LESO-PB, Bâtiment LE, station 18
CH-1015 Lausanne
http://leso.epfl.ch/

Auteurs:
Nicolas Morel, LESO-PB/EPFL, nicolas.morel@epfl.ch
Nikos Zarkadis, LESO-PB/EPFL, nikos.zarkadis @epfl.ch

Responsable de domaine de l'OFEN: Andreas Eckmanns
Chef de programme de l'OFEN: Charles Filleux
Numéro du contrat et du projet de l'OFEN: 103320 / 154379

Table of contents

Abstract

The goal of the project is the development of an advanced control algorithm for an electrochromic (EC) glazing, taking into account at the same time an optimal use of the direct solar gains and the (visual and thermal) comfort of the users. The algorithm includes the following features:

- A predictive control of the window transmission, needed because the EC glazing has an important reaction time (around 15 minutes) and because the solar radiation can vary significantly by variable sky (alternating cloud and clear sky zones);

- An optimization of solar gains in relation with the season (the solar gains are welcome during the heating season, and should be rejected during the hot season).

The project includes a theoretical algorithm development, considering also the other building services (heating, electric lighting), an experimental measurement phase on an office room of the LESO building equipped with EC glazing as wells as a parametric study (simulations) comparing the developed algorithm and experimental setup against other control and setup scenarios.

The project has been extended until 30 June 2012, due to the effective start on 1 February 2010, without any additional funding from the OFEN. Problems with experimental setup have caused an additional delay until 31 October 2012.

Keywords: electrochromic windows, advanced automatic control, building energy saving, visual and thermal comfort, adaptive and predictive control algorithms, sun and clouds motion prediction

1. INTRODUCTION, GOALS OF THE PROJECT

Electrochromic (EC) glazing has been commercially available the last few years as an alternative to the combination of standard window glazings with mobile solar shadings (very often discarded by the architects) or to permanently tinted solar protection glazings. EC glazing has the ability of changing dynamically its optical properties and modulating the transmission of visible light and heat solar gains through the window, while maintaining at all times the view towards outside. EC windows might replace in the future the vast existing stock of permanently tinted solar protection glazings which are often unsuitable to varying weather conditions while at the same time they are usually not effective for protecting against overheatings due to their high solar gains. The EC glazings commercially available provide a transmission dynamics with a large enough range [1; 2] (in the experimental tests, we used EC glazings with a dynamic range of around 1 to 3), thus representing a good protection against the overheating, although this range is not large enough to be efficient against glare [3].

Studies carried out until now have essentially considered a manual control of the EC glazing transmission. Some rather elementary automatic control strategies have been investigated, such as the closed loop control based on the measurement of the inside daylighting contribution. Nevertheless, the time characteristics of EC glazing (delayed response of the transmission variation after a command, usually between 5 and 15 minutes, cf. 4.1) have not been taken into account in these elementary automatic control strategies. In these conditions, a predictive control algorithm appears as a good solution, in a way similar to the heating control where an anticipated response to variations of heat load is desirable. Taking into account that the EC glazing alone cannot avoid glare, the use of light internal or external shading can provide a suitable protection against glare, but in this case a smart algorithm should control both the EC glazing and the blind in a coordinated way.

The project includes three main phases:

1. The development of an optimized control algorithm (taking into account both the energy and the visual comfort aspects), with a short term prediction of incident solar radiation and including the user preferences;
2. An experimental check of the control system on an office room of the LESO Building. This room has been equipped completely with EC glazing (both for the lower window and the anidolic daylighting system). The experimental check has been carried out with real persons, allowing therefore the acceptance of the system by the users;

3. Simulations where different control scenarios were tested against a long period of time (one year) and against varying meteorological conditions. The simulations allowed for the comparison of the energy consumption for heating and electric lighting, the estimated thermal comfort and the estimated visual comfort.

2. CONTROL ALGORITHM

2.1. Concept

The control issue of EC glazings has not been addressed adequately as the vast majority of proposed control schemes till now failed to address the time the EC glazing requires to switch between the bleached and dark states.

The developed algorithm predicts an optimal setting for the EC glazing, the blinds and electric lighting taking into account all the available data on instantaneous weather condition and building state, including data on room occupancy and user wishes/actions, workplane illuminance, internal air temperature. The algorithm predicts this optimal setting at a time horizon corresponding to the EC glazing latency time (ideally from 5 to 15 minutes; *cf. 4.1*). Electric lighting is used only complementary when daylight is not sufficient, while blinds are likewise only employed to protect from glare and/or to avoid overheating when protection from EC windows is not sufficient. A longer time horizon is taken into account for the thermal aspects. Moreover, when the room is occupied priority is given to visual comfort, while if the user is absent the algorithm is optimized for thermal comfort.

The developed algorithm constitutes of 2 parts:

1. A ‘child’ algorithm that uses a sky scanner approach: the sky is continuously monitored by a simple web camera connected to a computer and the possibility of clouds obscuring the sun is deducted at short time steps (1 min).
2. A ‘mother’ algorithm that uses the input of the child algorithm along with all other inputs mentioned above and finally implements the control of EC Windows, Electric lights and blinds.

2.2. Sky prediction part

To solve the problem of the slow switching speed of the EC windows we implemented a predictive algorithm based on the image manipulation of sky images taken by a standard web camera.

In particular, Matlab software (MathWorks, Inc.) is installed in a LESO PC, to which a standard USB web camera has been connected. The camera is placed below the skylight of an office room which so it can have almost unobstructed view of the sky. It faces towards the south at a measured angle ‘z’ from the zenith, making sure the sun trajectory is included in the images taken. A fish-eye lens, capturing the whole sky dome is important and maximizes the prediction window. In this project, no wide angle lens was used, therefore the prediction window stays at about 5 min. The camera was setup to take automatically images of the sky in time intervals of 30 s. It was observed that for low or moderate wind speeds the time interval of 1 to 2 min is sufficient for the observation of changes in the sky concerning the motion of clouds. However, higher wind speeds require a shorter time interval hence this time step of 30 s has been chosen.

The images taken with the camera are stored in the PC and processed in a way that:

1. the relative motion of clouds between 2 consecutive images is detected;
2. analysis of the cloud motion using a series of images is performed;
3. the possibility of clouds to obscure the sun during the next 5 minutes is deducted and passed on to the "mother" control algorithm so it can issue on time the appropriate commands to the EC windows, blinds and electric lighting.

Figure 1 shows 3 consecutive images taken 30 s apart.

Figure 1. Original images taken on 07.06.2012 at 10h15m30s, 10h16m00s and 10h16m30s (left to right).

For the first step, the relative motion of clouds between 2 consecutive images is detected with the use of Correlation Image Matching [4]. Template matching between the two images is applied within a predefined search area. We use random square parts of the first image as filters upon the 2nd image. As the filter is square and has an odd number of elements, it is represented by a (2N+1)x(2N+1) matrix. Given a square filter, we can compute the results of correlation by aligning the center of the filter with a pixel. Then we multiply all overlapping values together, and add up the result. We can write this simply as:

$$F \circ I(x,y) = \sum_{j=-N}^{N} \sum_{i=-N}^{N} F(i,j) I(x+i, y+j)$$

When areas matching a pattern from the 1st image are discovered in the second image, the position of the best match is identified and subsequently, the motion vector is determined by the best match position [5]. This process is repeated and verified after several matches are identified. However that does not mean that motion vectors in the image should all be uniform; clouds in the sky can move towards the prevailing wind direction while others can "stay in the same part of the sky" simply changing forms. In any case we only take into account the motion vectors that repeatedly are identified in consecutive image correlations and they are heading towards the sun position.

The sun position is known at every time step and is mapped on the image. We use Matlab code to compute the sun position (zenith and azimuth angle at LESO-PB location) as a function of the local time and coordinates [6]. We then apply the zenith angle 'z' of our camera to correctly map the computed sun position with the actual one onto every image.

The possibility of the clouds to obscure the sun during the next 5 minutes is estimated and –if necessary – modified every minute (that means after every 2 image correlations) by means of angular speed of the detected motion vectors. The time frame of the prognosis can be higher than 5 minutes if the sky image remains the same for longer periods but it can fall down to 2 or 3 minutes if clouds are moving fast relative to the sun in the images or if the sun is located close to the edge of the images with prevailing wind blowing from that edge.

The inclusion of a fish-eye camera would undoubtedly improve on this, providing a larger time-frame. At the same time, some alterations to the algorithm would be necessary to correctly compute cloud speeds close to the horizon (at the edges of the image) as every fish-eye lens uses a type of projection on the image plane (i.e. Hemispherical or angular).

2.3. Building systems integration

Once we have the output of the sky prediction algorithm, we use it as an input to the 'mother' algorithm that is responsible for the integration of all possible controllable building systems. For the implementation of this part we use a rule based fuzzy logic control, building on work previously performed in LESO-PB [7; 8; 9].

For example: *IF sun=obscured in 5' AND user=1 AND user action=1 THEN ec, el, bl = C,*

mandates that no action (*C*=constant) is assigned to EC windows (*ec*), electric lights (*el*) and blinds (*bl*) by the mother algorithm when the user is present (*user=1*) and he or she has performed an override action on one of the building elements (*action=1*), despite the fact that the sun is going to be obscured by the clouds in about 5 minutes (*sun=obscured in 5'*).

As seen by this example, one of the important rules of the control algorithm is the prevalence of user actions over any automatic control. Experience and bibliography suggests that user presence and user wishes is a key factor to consider when implementing an advanced building control system. Earlier studies carried out in LESO concerning intelligent blind controllers proposed that user presence should determine the adopted control strategy at a given time: When user is present in the room then visual comfort is a priority, while in the absence of users a strategy favouring long term thermal aspects and maximum energy conservation should be implemented [8; 9]. As a result, user wishes are respected by the developed algorithm at all times while at the same time they are logged and treated as learning database so the control system can learn and adapt to the user specific needs.

Similar to the above example, a rather complex set of rules has been built comprising all available input from the LESO-PB EIB system: instantaneous weather condition (Irradiances and illuminances, external temperature) and building state (room occupancy, user wishes/actions on building systems, workplane illuminance, and internal air temperature). Additional variables including “season” (based on average external temperatures on the last 48 hours) are also incorporated in the rule base. Next, the framework of the Fuzzy Rule Bases is given.

2.3.1. User Present, “EC Tv” Fuzzy Rule Base

Inputs (fuzzy values):

- Sky obscured probability
- Global vertical South illuminance (Evgs)
- Outdoor average temperature on the last 24 hours (Season)
- Room temperature
- User interaction with EC windows (EC.user)

Output (crisp value):

- EC Windows visible light transmission (Tv)

2.3.2. User Absent, “EC Tv” Fuzzy Rule Base

Inputs (fuzzy values):

- Global vertical South illuminance (Evgs)
- Outdoor average temperature on the last 24 hours (Season)
- Room temperature

Output (crisp value):

- EC Windows visible light transmission (Tv)

2.3.3. User Present, "Blinds" Fuzzy Rule Base

Inputs (fuzzy values):

- Workplane illuminance (DeskLux)
- EC windows Tv
- Solar altitude (SolH)
- Solar azimuth (SolA)
- User interaction with Blinds (Bl.user)

Output (crisp value):

- Blind position (α_{blind})

2.3.4. User Absent, "Blinds" Fuzzy Rule Base

Inputs (fuzzy values):

- EC windows Tv
- Global vertical South illuminance (Evgs)
- Outdoor average temperature on the last 24 hours (Season)
- Room temperature

Output (crisp value):

- Blind position (α_{blind})

2.3.5. User Present, "Lights" Fuzzy Rule Base

Inputs (fuzzy values):

- Workplane illuminance (DeskLux)
- EC windows Tv
- Blind position (α_{blind})
- User interaction with Lights (EL.user)

Output (crisp value):

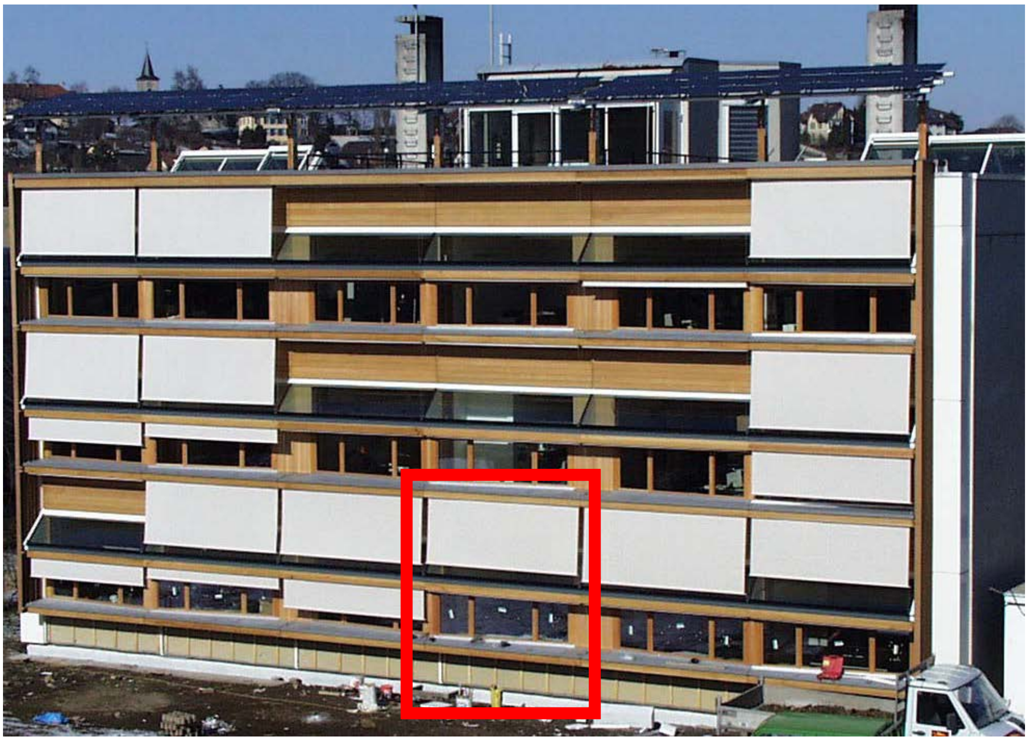
- Electric lights power (Plights)

3. EXPERIMENTAL SETUP

This section deals with the description of the office room used for the experiment and includes information about the EC glazing.

3.1. Room description and characteristics

The experimental office room LE 003 is part of the LESO-PB experimental building which is located in EPFL campus near Ecublens and Lausanne. All office rooms (18 in total) of the LESO building are equipped, on their South facade with both a conventional window and an Anidolic Daylighting System (ADS), designed to increase the daylighting illuminance provided at the rear of the room [10; 11]. The chosen room of the LESO building can be seen on the picture and plan drawing of **Figure 2** and it is the one used previously by Page et al. [12] where EC glazings were coupled with an ADS. EC glazings both for the normal windows (lower part) and for the anidolic daylighting system (upper part) were installed.



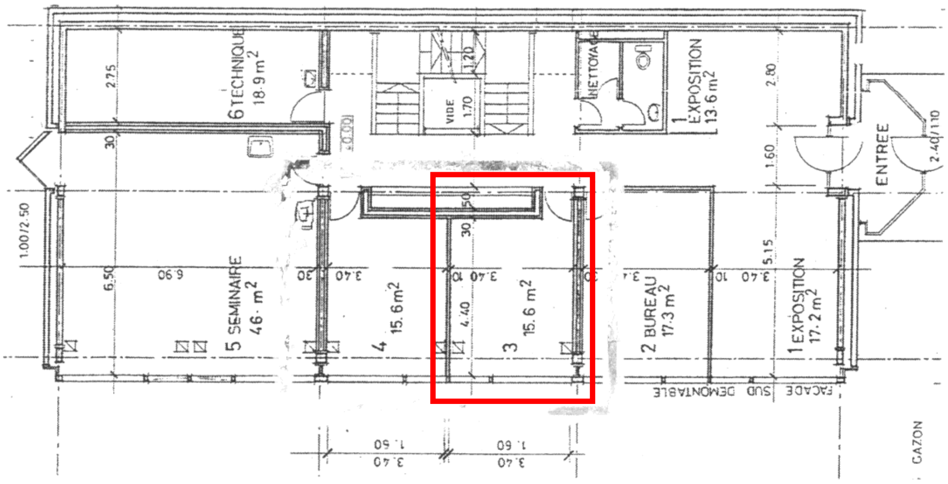


Figure 2. Picture and plan drawing of office room LE 003 where the EC glazings have been installed.

3.2. Electrochromic glazing

The total area of glazings is 5.10 m^2, their Visible light Transmission (Tv) is in the range of 0.15 - 0.50 while their Solar Heat Gain Coefficient (SHGC) is 0.12 - 0.38. The glazings have been installed by the industry partner (EControl-Glas GmbH & Co. KG) on February and March 2011.

The EC glazings can be seen in the two pictures below (**Figure 3**), one taken with the glass at maximum transmission and the other with the minimum transmission (dark configuration). A dominant blue color can be seen when the system is in the dark configuration.

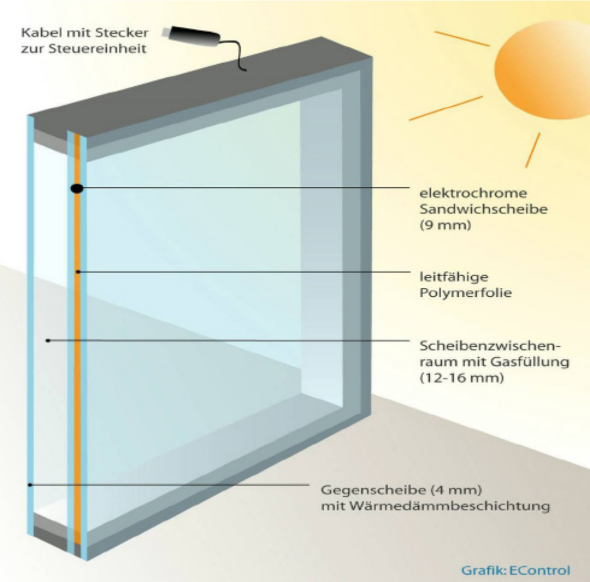
EC glazings in the clear configuration (Tv=50%, SHGC=38%)

EC glazings in the dark configuration (Tv=15%, SHGC=12%)

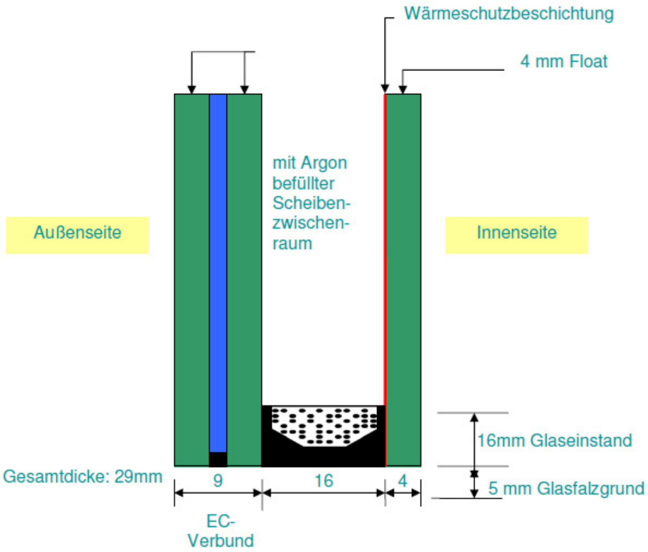
Figure 3. EC glazings in the bleached (clear) and fully tinted (dark) states

The principal characteristics of the installed EC glazings are summarized in the table and in the two pictures below (documentation of EControl-Glas).

	dark configuration	**clear configuration**	unit
Light transmission (Tv)	0.15	0.50	-
Energy transmission (SHGC)	0.12	0.38	-
U-value	1.1		W/m^{2}K
type of glazing	double glazing with argon filling and low-e coating		-



Schematic view of an EC glazing (EControl-Glass)



Cross section of an EC glazing (EControl-Glas)

3.3. Control and communication protocols

The LESO building is equipped with an EIB/KNX building bus. All the sensors, actuators and user commands are connected to this bus, which is itself connected to a server computer (EibServer). This server is used as an interface both for data acquisition (all the telegrams on the bus are recorded in a continuous manner, as well as the current status of all the connected devices, and stored in a MySQL database), and for experimental control algorithms implemented on another computer and connected to the EibServer through Java/RMI protocol.

The EC glazings are connected to manually operated control units through a dedicated cable. Two control units are provided, one for the normal window and one for the anidolic system (upper window). Each control unit includes a series of pushbuttons which can be pressed by the user to choose a transmission level (5 transmission levels are possible). Moreover, each control unit is connected to a dedicated computer implementing the automatic control algorithm, through an RS485 serial link interface. At a later stage, it is envisioned to completely integrate the EC glazings with the EIB/KNX building bus.

The “conversation” between the computer and the EC glazings through the control unit is rather complex and had to be implemented directly by the LESO-PB. The industrial partner of the research project and procurer of the EC windows (EControl-Glas GmbH & Co. KG) did not provide us with communication software but instead we were given the specifications for the communication protocol of the control unit of the glazings (provided in full detail in Appendix 8.2).

Finally, the necessary communication modules described in the protocol were built from scratch using Matlab software platform [13].

4. FIELD MEASUREMENTS AND USER EVALUATION OF THE EC GLAZINGS

The field measurements aimed essentially at the investigation of visual and thermal comfort felt by the user, including the acceptance of the control system and the EC glazing by the occupants.

4.1. Definition of switching time curves of the EC windows

The switching speed of an EC varies with its temperature, size, depth and direction of switching (transition from dark to bleached is generally faster than the opposite [14] but not verified with our measurements below). Following the installation and communication setup between the EC windows and the control computer, the switching time curves[1] were defined for further use into the newly developed algorithm as well as into the simulations. Values derived from in-situ measurements of the installed EC glazings and are specific to them. EC glazings were given numerous times the command to switch between their 2 extreme states (clear and tinted). Their status during transmission change was recorded continuously and logged to a text file.

For the switch from clear to dark blue (at about 26°C), the measured Tv values were fitted almost perfectly (R^2=0.9992) to the equation:

$$y = -0.0049x^3 + 0.3071x^2 - 6.4843x + 65.015$$

With: x = time [min]; y = Tv (**Figure 4**).

For the reverse change from dark to clear (at about 26°C), the measured Tv values were fitted also perfectly (R^2=0.9992) to the equation:

$$y = -0.0012\mathrm{x}^4 + 0.0367x^3 - 0.2111x^2 + 1.4903x + 18.037$$

With x,y as above (**Figure 5**).

The technical specifications provided by the manufacturer mention the extreme transmission values of the glazings (%): Tv EC=[18,64]; Tv IGU =[15,50] [2]; SHGC=[12,38]. These extremes were used to extrapolate the values of Tv IGU and SHGC (given in the Appendix 8.3) from the measured Tv EC values. No significant differences were observed between the anidolic and the lower glazings hence there is no necessity for introducing separate fitted curves and matrices.

---

[1] Their transmission value by the time required when switching from one extreme state to the other.

[2] Tv EC is the transmittance of the visible light through the EC element (laminated unit) of the windows, while Tv IGU is the resulting visible light transmittance of the double pane window (Insulated Glass Unit)

As it can be observed in **Figure 4**, the switching curve from clear to dark (under the given temperature and glazing dimensions) resembles an exponential decay, where "*the curve steeply decreases during the first minutes, then the curvature changes and the profile is flat until the process finishes.*" [15].

These observations can help us to describe in a theoretically accurate fashion the terms "switching speed/time" cited in this document and to define switching speed *U(t)* as follows:

$$U(t) = d\frac{Tv(t)}{dt}$$

where *Tv(t)* is the visible transmittance curve of the EC glazings as a function of the transition time *t (see also **Figure 4**).*

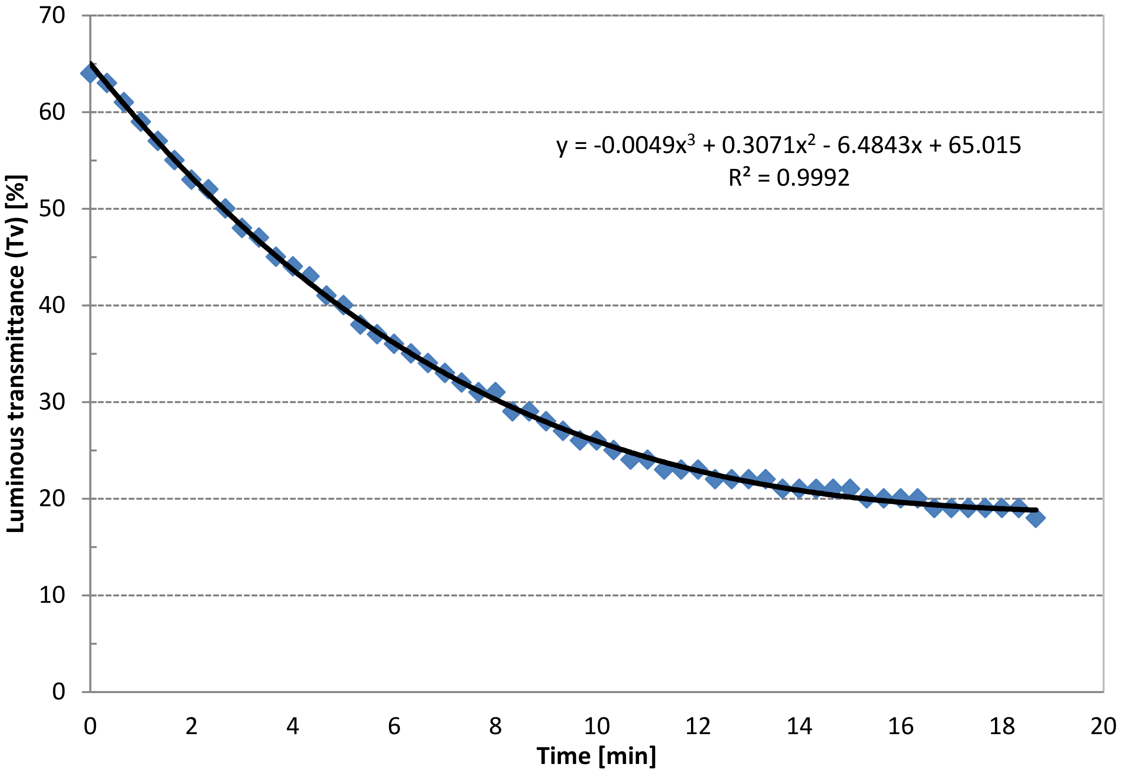


Figure 4. Switching decay curve for the installed EC glazing showing Tv levels (%) vs. switching time (min) during transition from bleached to coloured states for a given temperature (26^{o}C).

However, this notion of theoretical approach can have little practical meaning, especially due the non-linear form of the switching curves. In practice, it is useful to define speed as the time required by the EC glazings to obtain a certain percentage of the total switching depth. Hence, **Table 1** provides some meaningful alternative to the theoretically defined EC glazings speed. Transition from dark to bleached (clear) is remarkably faster than the opposite (e.g. EC glazings perform 50% of the full switch from clear to dark in less than 5 min). On the other hand, a complete change from dark to clear requires 18 min, while the opposite direction full transition takes more than 25 min.

Depth of switching [%]	**Time required** [min]	
	From clear to dark	**From dark to clear**
30%	2.5	8.5
50%	4.6	11.2
70%	7.4	13.5
80%	9.4	14.7
90%	12.4	16
100%	26	18

Table 1: Switching speed of EC Glazings (time required by the EC glazings to execute a certain percentage of the total switching depth).

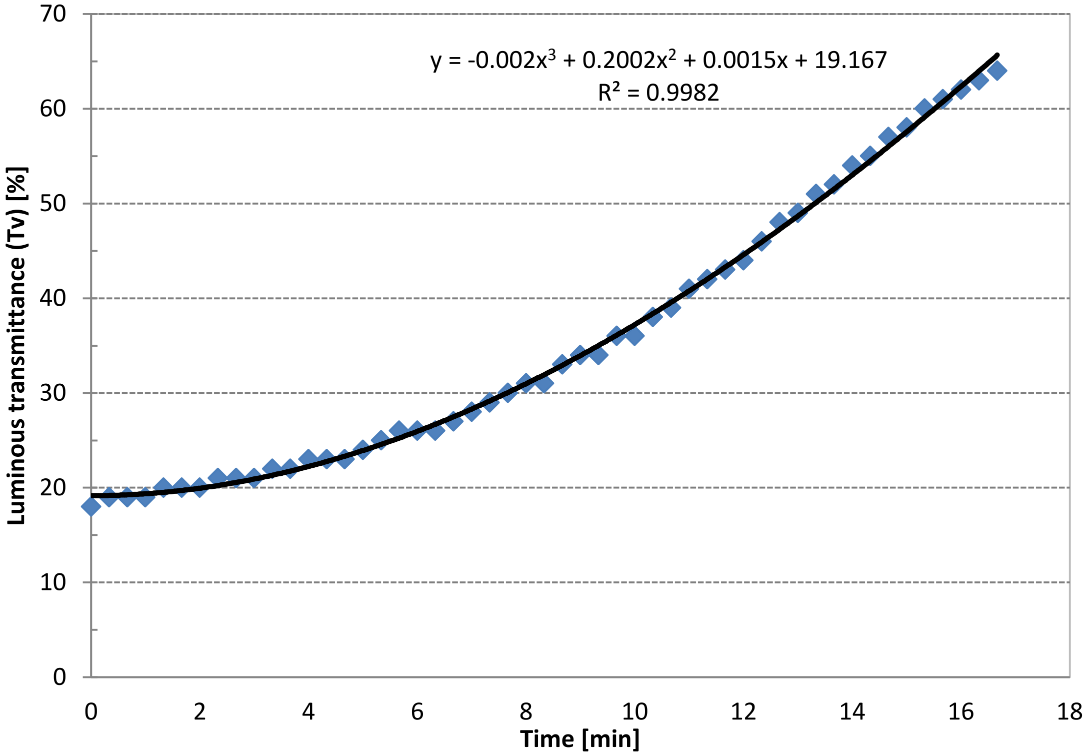


Figure 5. Switching decay curve for the installed EC glazing showing Tv levels (%) vs. switching time (min) during transition from coloured to bleached states for a given temperature (26^{o}C).

4.2. Daylight Factor (DF)

Measurements to determine the daylight factor (DF) were carried out during diffuse light conditions and included multiple measurements of the global horizontal illuminance on the roof (unobstructed 180^o view of the sky) and on 5 points on the desktop level of the office room LE 003 where the glazings are installed. The 5 points were situated on the central axis of the room (vertical to the south facade) and they were having equal distances (~90 cm) from each other. The first point was chosen at a distance of about 90 cm from the windows plane while the last one was at 30 cm from the back wall. Measurements were performed with the EC windows fully bleached and fully tinted. Values are presented on **Table 2** and on **Figure 6**:

DF for Tv level	**Distance from the windows** [m]				
	5	**4**	**3**	**2**	**1**
DF-50	0.68%	0.84%	1.83%	3.08%	4.35%
DF-15	0.38%	0.56%	0.84%	1.43%	1.50%

Table 2: Daylight factors for the 2 extreme Tv levels of the EC windows and for each point.

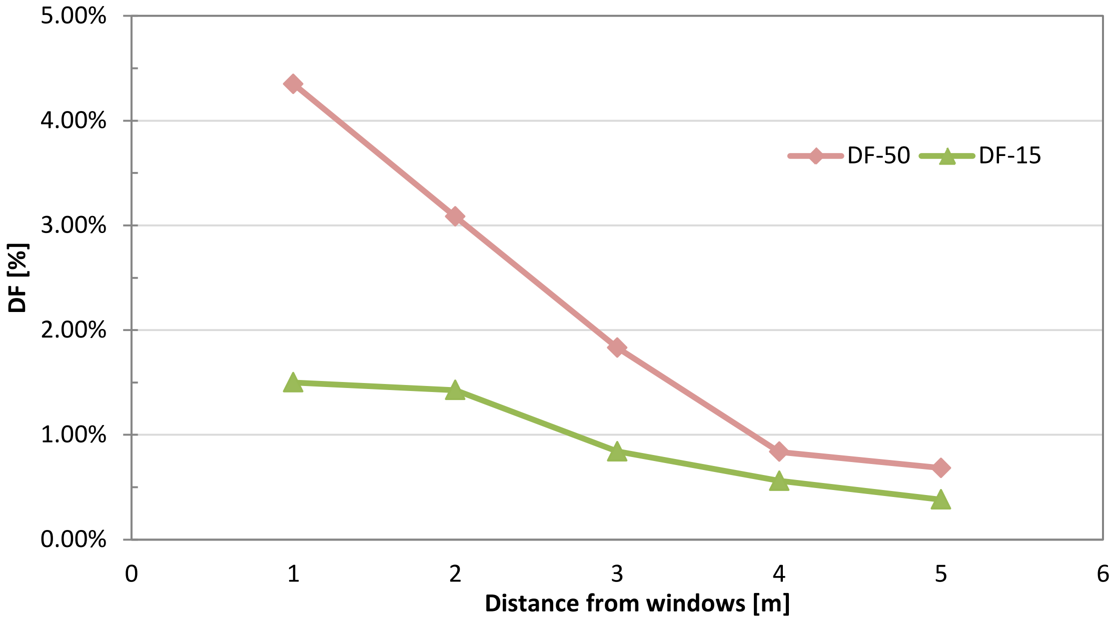


Figure 6. Daylight factors for the 2 extreme Tv levels of the EC windows as a function of the distance from the windows.

4.3. User evaluation of manually controlled EC glazings

Short satisfaction surveys were conducted with 9 subjects who volunteered to spend some time inside the office room were the EC glazings are installed. This survey allowed a short-duration assessment of the EC windows with several persons staying in the room for about 2 hours (with similar weather conditions for all the persons). The subjects spanned all age groups, both genders (2 female and 7 male) and spent their time doing ordinary desk work (mainly reading from paper, and computer work) facing all possible directions inside the office room (windows, side and back walls).

Most users were not satisfied by the unnatural colour rendering of the room and/or that of the view when looking outside, especially when the windows were fully tinted (Persian blue colour). Glare issues were also mentioned by half of the persons, which eventually motivated them to use the blinds. This was true in cases that direct sunlight hit the desk and/or the computer monitor. Also, some users expressed the wish for a bigger dynamic range of possible transmissions (on both ends). However, most users are willing to oversee any inconveniences or disadvantages of EC windows and they are generally positive when comparing this daylighting system to a standard one (i.e. blinds) mainly due to the unobstructed view that EC windows offer at all times. Users did not express dissatisfaction regarding the manual control of the EC Windows nor did they seem to consider negatively the slow switching time between different transmission levels.

Interesting additional comments included:

- Since the transition from one state of transmission to another one happens without the user actually noticing the change, there is no way for the user to know if the manual command given to the EC windows is sufficient, underestimated or overestimated (e.g. when blinds are deployed by the user to reduce illuminance or glare, user gets an instant feedback and stops the deployment as soon as they feel satisfied with the resulting visual environment).
- Manual control panels could use a small LCD screen instead of the 5 LED diodes to indicate their transmission level.
- The colour of the EC windows (also) when windows are fully bleached could be more “clear” and natural. For the tinted state the light Persian blue seems to be cold or dull by many.
- If the person working inside the office leaves the room to visit an adjacent office equipped with normal double glazings, then upon their return time is needed to adjust to the different visual environment and colour rendering.

4.4. Algorithm testing (automatic control)

Tests of the algorithm were not extensive but they allowed for a short check of the elaborated algorithm on the experimental level. Regarding the visual comfort, workplane illuminance was measured by a hand held luxmeter (BEHA 93408) while the EC was controlled automatically. Workplane illuminances were mostly kept inside acceptable visual comfort levels (at around 450-1000 lx) most of the time during a day with intermediate sky (**Figure 7**).

Hardware and technical issues arose during field testing. The computer that communicated with and controlled the EC windows experienced stop errors ('Blue screen') even after the switch to different operating systems and hardware configurations. Most likely this issue originates in the serial port card but so far no solution has been found. The meteorological station of LESO-PB and the system that interfaces with the EibServer experienced some serious malfunction and it was out of operation during most of the testing of the algorithm (particularly affected were the sensors of Global Horizontal Illuminance and Vertical South Illuminance). The waterproof web camera that was purchased for the project proved to be a non-wide angle camera, despite the specifications given by the manufacturer[3]. What is more, the camera seized to operate after about 6 months of its purchase.

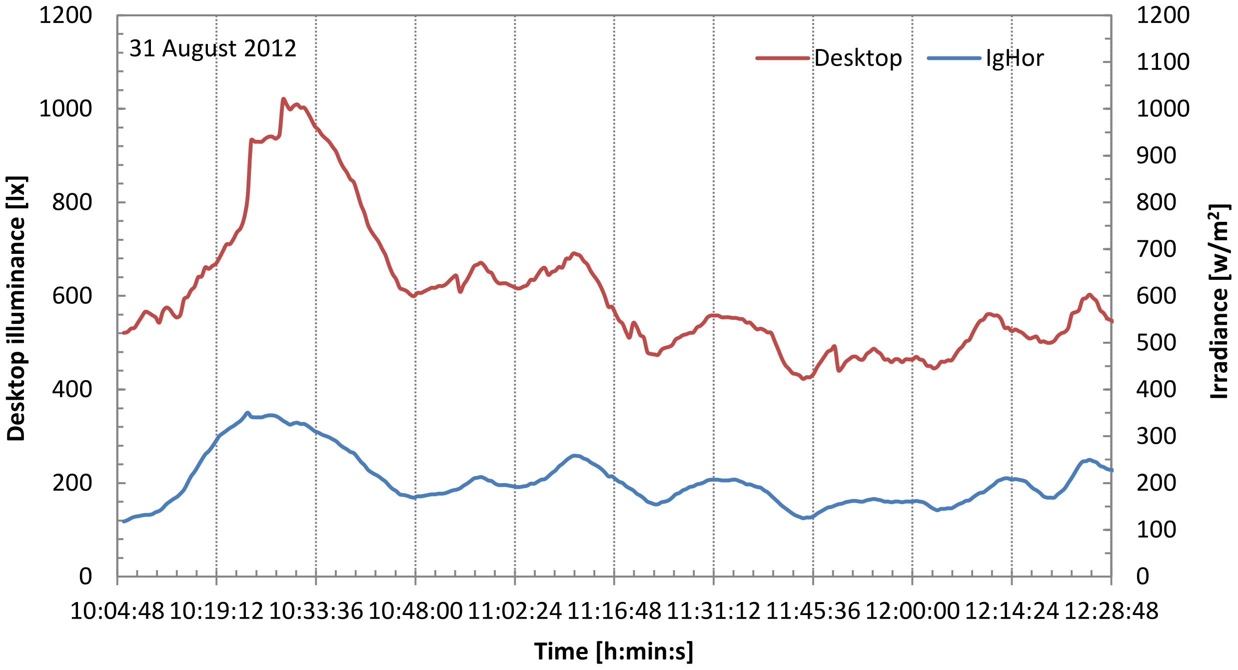


Figure 7. Desktop illuminance and Global Horizontal Irradiance (IgHor) measurements before and around noon time on 31 August 2012 (day with intermediate sky conditions).

---

[3] Bullet HD Pro 1080; http://www.bullethd.us/bullethd-best-wearable-sports-waterproof-helmet-camera/bullethd-pro-1080p-helmet-camera/

4.5. Future field work

Extensive experimental tests will take place in LE003 office room of the LESO building. They will include long-term data acquisition in the database of the building's central management system of all the relevant parameters from sensors or actuators as instantaneous weather conditions, room conditions as well as user wishes. Simultaneously, EC transmission data will also be logged and user actions will be used as a learning input for the implemented control algorithm. This process will likely introduce some refinements to the control algorithm.

Further, detailed assessment of the user satisfaction (visual and thermal comfort) and acceptance through on-line questionnaires being displayed several times a day on the users' personal computers will be performed.

In addition, glare risk could be evaluated using novel high dynamic range (HDR) imaging techniques, following recent research studies published by LESO [16].

Upon the completion of thorough field measurements, the results will be published in peer-reviewed scientific journal(s).

5. PARAMETRIC STUDY AND SIMULATION RESULTS

5.1. Introduction

The field measurements realized on LESO building did not allow for a detailed energy comparison, because EC glazings equipment is installed in only one office room. Thus, simulation allowed for the testing of different control scenarios over a long period of time (one year) and against varying meteorological conditions. The simulation presents results for the following parameters:

1. Energy consumption for heating;
2. Energy consumption for electric lighting;
3. Estimated thermal comfort;
4. Estimated visual comfort;

Simulations were performed using the Matlab environment of MathWorks [13]. They were based on dynamic thermal simulations code that has been developed by LESO laboratory. The choice of Matlab has been on the grounds of robustness, customization and flexibility. The code was modified and expanded accordingly to include:

- An appropriate module to take into account the EC glazing features (switching curves) and control algorithm
- A module for electrical lighting (illuminance levels on desktop and energy consumption)
- An occupancy feature
- A visual and thermal comfort prediction feature

5.2. Simulated scenarios

The parametric study compared the following cases of windows for a South-facing office room:

1. Conventional transparent double glazing;
2. Conventional transparent double glazing coupled with blinds;
3. Solar protection glazing with SHGC=0.38 and Tv=0.50;
4. Solar protection glazing with SHGC=0.12 and Tv=0.15;
5. EC glazing with simple control;
6. EC glazing with the proposed control algorithm;

5.3. Simulation model description

The model used in all simulations was a simplified nodal model of a South-facing office room similar to the LESO building room LE 003 where the EC glazing was installed. North, West and East are partition walls adjacent to other offices and the corridor. Ceiling and roof are also adjacent to other offices. The blinds considered are made of textile tissue and they can roll up (completely open) and down (when closed). For the electric light use, the visual and the thermal comfort we consider the presence of a user only during the working hours with a 9-hour daily schedule of 08.00 to 18.00 with a lunch break from 12.00 to 13.00, from Monday to Friday. Window surface was modelled as a single conventional window instead of the coupling of a conventional window with ADS.

Main characteristics:

- Floor area of one room: 15.7 m^2
- Room height: 2.8 m
- Facade wall (to South): 5.4 m^2 light wall (2 cm plaster panel + 12 cm thermal insulation [0.04 W/m·K] + 3 cm wood) + windows (see below)
- Window area including frames: 5.10 m^2
- Standard glazing: SHGC= 67%; Tv=78%; U-value 1.1 W/m^2K (U-value the same for all types of glazings)
- Blinds: Textile tissue with 20% solar gains transmission when completely drawn
- Light partition walls with bricks: 10 cm thickness
- Floor screed: 6 cm (concrete)
- Ceiling slab thickness: 25 cm (concrete)

5.4. Meteorological data

The meteorological data used for the simulation were generated by the Meteonorm software [17]. Data for one year were generated for the village of Ecublens near EPFL and LESO building. Time interval was set at one (1) minute to account for our sky prediction developed algorithm. Simulations used the same time-step (1 minute). The generated data included date, time, external temperature, global horizontal solar radiation, diffuse horizontal solar radiation, global vertical south solar radiation as well as solar height and azimuth angles.

5.5. Heating control system

The heating controller is a simple on/off, closed-loop system based on the internal air temperature and the season. The set point for the temperature is 20°C (no night setback schedule is implemented) and the controller turns the heating on or off (with no hysteresis) to keep the internal temperature equal or above the set point when the season is set to “winter/heating season”. Heating season is not implemented using the calendar. Instead, we consider a given simulation time step as being “winter” if the average external temperature over the last 7 days is below 10°C.

No cooling system is employed, just like the case of LESO building.

5.6. Electrochromic windows and blind control

A separate module for the EC windows that gives at any time step the values of the solar heat and visible transmission of EC glazings was implemented and inserted into the simulations code. As explained in the experimental setup chapter (4.1), tabular values of switching time curves were produced (cf. Appendix 8.3) and inserted into this simulation module. The time step of the simulation was the same as the time step of the switching curves (1 min).

For the simulation scenario 5 (EC simple control), a simple closed-loop control is used based on the global vertical south solar radiation (Igvs) and the season[4]. In the cooling season the EC windows are kept fully bleached for an Igvs below 100 W/m^2; fully tinted if it exceeds 300 W/m^2 and assigned linearly interpolated **target** values of SHGC (between 12 and 38%) and Tv (15-50%) for solar radiation values between 100 and 300 W/m^2. By “target value” we mean that EC windows at a certain time-step are assigned a desired transmission value. This value cannot be assigned instantly; instead it will be achieved in the next time steps (next minutes) following the incorporated switching time curves. In the winter, all solar gains are accepted and EC windows act like low solar gains windows with SHGC=38%.

For the simulation scenario 6 (EC with the developed algorithm), we use the same control variables and limits as above but we consider that a perfect sky prediction allows the EC windows to achieve desired transmittance values for every time step. In this case, the EC windows are always assigned with the right transmission values, as required by the control variables.

---

[4] The internal air temperature (Tair) was initially also considered in the control: In the summer, solar gains were allowed only when Tair<20°C and during winter were rejected if Tair>25°C. Simulation tests showed no difference so it was excluded from the algorithm.

Regarding the blinds control in the second simulation scenario, we follow exactly the same control as above: In the summer, they are fully rolled up if Igvs is lower than 100 W/m^2; fully deployed if it exceeds 300 W/m^2 and in an intermediate position linearly interpolated for solar radiation values between 100 and 300 W/m^2. Likewise, in the winter they are fully open.

Suggested by test simulations, the decision to permit all solar gains during the winter is a conscious compromise between visual comfort (which may be affected negatively due to extreme brightness and/or glare phenomena) and decreasing energy consumption for space heating.

5.7. Electric light calculation

Electric light is commissioned to maintain horizontal illuminance at the user's workplace on the desktop level at 500 lx when daylight is not sufficient. The dimmable light fixture considered is the one that actually is found inside the office LE 003 of the LESO experimental building and can deliver 250 lx of illuminance on the user's workplace at maximum power of 4x36 W. On top of the nominal power of the 4 lamps (144 W), we assume 15% overconsumption due to the fixture ballasts (21.6 W). This power is considered as base power and it is consumed during all work hours when the fixture is not completely switched off. The fixture's power consumption from 21.6 to 165.6 W is linearly correlated with the required artificial lighting illuminance of 0 to 250 lx. Evidently, 0 lx of electric light is required when available daylight illuminance is greater than or equal to 500 lx and 250 lx electric lighting is required when available daylight illuminance is smaller than or equal to 250 lx).

To calculate if any additional desktop illuminance is needed, the desktop illuminance due to daylight is first computed. It depends on the Global Horizontal Illuminance (Egh), EC windows Visual Transmission level (Tv) and blinds position. To calculate Egh from Global Horizontal Irradiance (Igh), one normally has to resort to a physically accurate model such as the Perez model [18; 19]. On the practical level, this simulation use an approximation which is only correct for diffuse light conditions according to which the Egh is correlated to Igh: 1 W/m^2 of Igh corresponds to 179 lx of Egh (luminous efficacy of 179 lm/W) [20]. As noted, this is not valid for intermediate or clear sky conditions with a direct illuminance component. We assume that in such cases corresponding illuminance would be higher, resulting in a slight over-estimation of energy used for electric lighting.

We use our measurements of the Daylight Factors (DF) as described previously (cf. 4.1) for the given position in the room (at approximately 1.8 m away from the windows) and for the 2 extreme states of the EC windows ($DF_{\text{fully bleached}}$=3.13%; $DF_{\text{fully tinted}}$=1.43%). We interpolate linearly the DF for the given EC transmission. Finally, the multiplication of the DF with the estimated Egh, gives us the amount of desktop illuminance due to daylight.

For the simulation scenario where we have standard glazing with the use of blinds, we resort to a study previously performed in LESO-PB by Bauer et al. including an identical office room [8]. We estimate the value of DF for the blinds completely rolled up to be $DF_{no\ blinds}$=10.4%, while for blinds completely rolled down is DF_{blinds}= 1.8%. For an intermediate blind position the resulting DF is a linear interpolation between the two values.

5.8. Energy consumption

The results of the simulation study regarding the energy consumption for heating and electric lighting are shown on **Table 3** and on **Figure 8**. As expected, standard (clear) glazing permits high solar gains during the winter which results in significantly low energy demand for space heating. In these cases, energy required for electric lighting is also reduced when compared to other cases due to the abundant daylight penetrating inside the room. However, both cases of standard glazing offer the worst visual and thermal comfort (overheating and extreme illuminance) as seen next.

Scenario 3 appears on the other extreme in terms of energy demand. This case features a low solar gain glazing with a very low constant coefficient of solar radiation transmission of 0.12. Solar gains are mostly cut-off and energy demand for heating escalates to over the double in comparison to the other scenarios. Energy demand for electric lighting is also significantly higher (about 40%) when compared to scenarios 3, 5 and 6. This is due to the constant low visible light transmission and the subsequent more frequent use of electric lighting.

The energy demand of the case of low solar gain glazing with a constant coefficient of solar radiation transmission of 0.38 (scenario 3) is comparable to the energy demand by the scenarios 5 and 6 with the EC glazings. It is important to compare these 3 scenarios in respect to the predicted visual and thermal comfort they offer.

Simulation scenario	**Heating** [Kwh/m^2]	**Electric lighting** [Kwh/m^2]	**Total** [Kwh/m^2]
1: Standard glazing	2.7	5.6	8.3
2: Standard glazing+Blinds	4.2	5.6	9.8
3: Low Solar gain glazing (0.38)	13.6	7.9	21.5
4: Low Solar gain glazing (0.12)	36.4	11.1	47.5
5: EC Simple control	14.9	8.0	22.8
6: EC Predictive control	14.9	7.9	22.9

Table 3: Annual energy demand for space heating and electric lighting for different simulation scenarios.

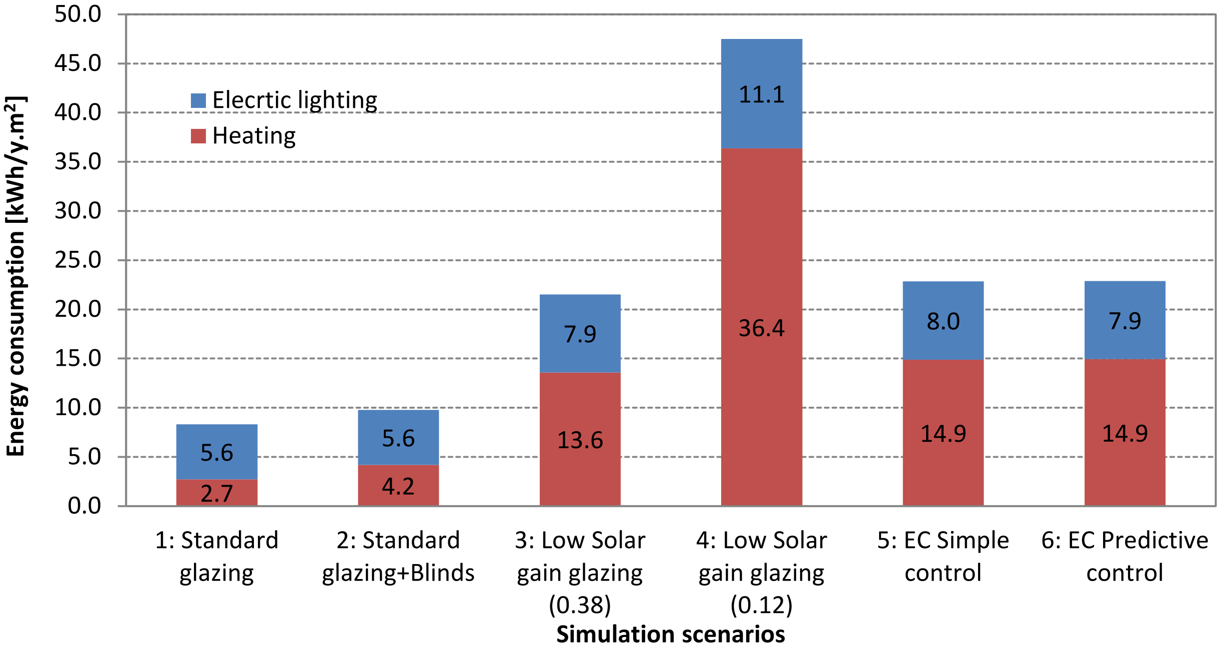


Figure 8. Annual energy demand for space heating and electric lighting for different simulation scenarios

5.9. Thermal comfort

5.9.1. Indoor air temperature

As a first indication of thermal comfort, we compare the indoor temperature across the different simulation scenarios. We observe unacceptable temperatures for the cases with the standard glazing (1 and 2). In particular, scenario 1 demonstrates very high indoor air temperatures between 30-40°C for all months except those during winter (**Figure 9**). Scenario 2 is slightly improved but still unacceptable overheating occurs during some days in late winter and, to a lesser extent, during some days in late autumn with internal temperatures over 30°C (**Figure 10**). However, it should be noted that high temperatures are expected since neither cooling nor any form of ventilation is considered in the building model. Naturally, overheating can be partially mitigated by simply opening the window during mid-season or summer.

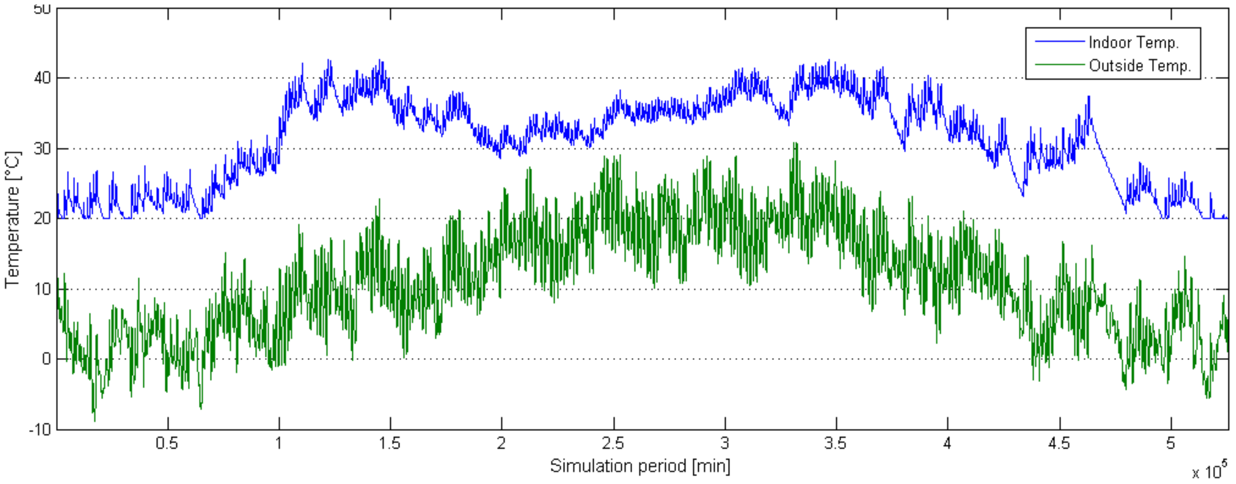


Figure 9. Temperatures variation for Scenario 1 (Standard glazing; no blinds). Overheating is observed from March to November.

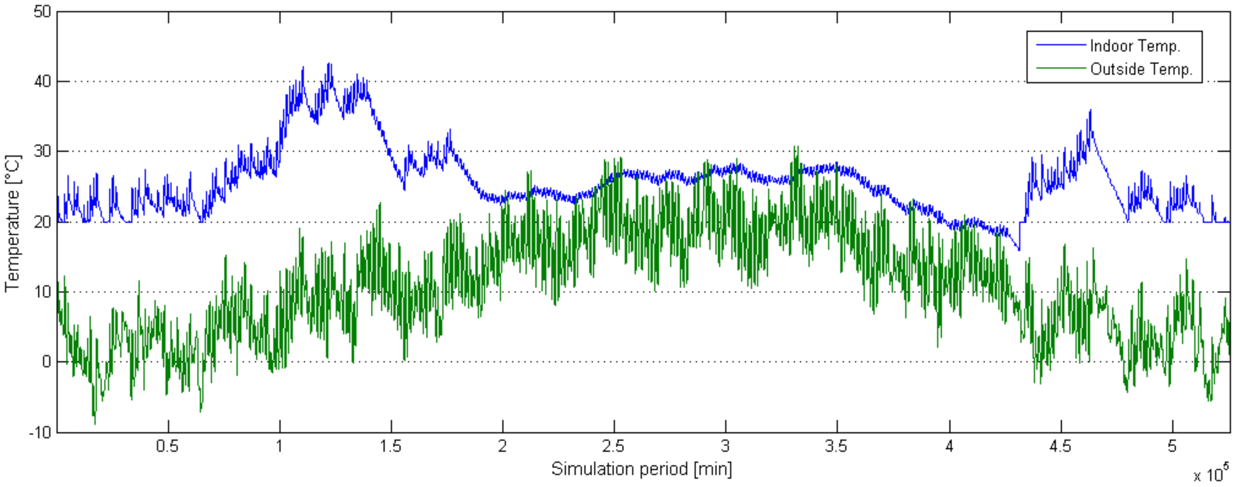


Figure 10. Temperatures variation for Scenario 2 (Standard glazing + blinds). Internal temperature exceeding 30°C is observed during intermediate season.

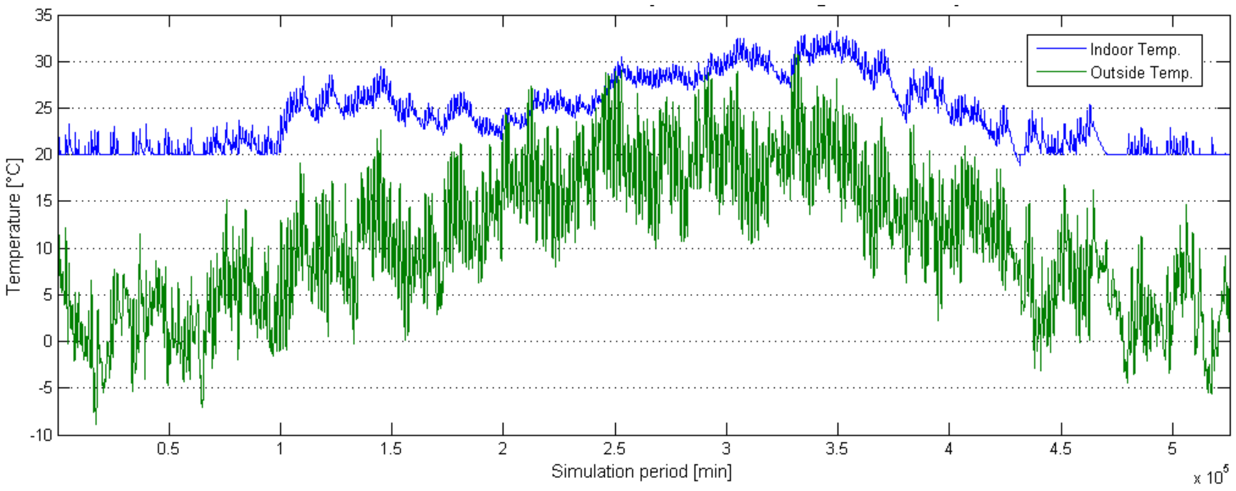


Figure 11. Temperatures variation for Scenario 3 (Low Solar gain glazing; SHGC=0.38).). Internal temperature around 30°C is observed for about 75 days during the year.

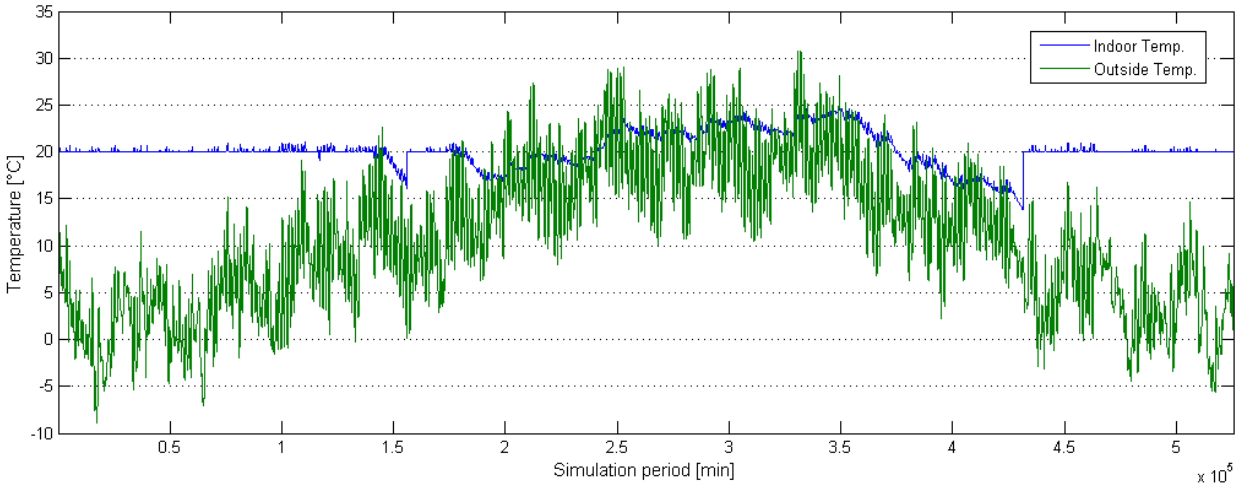


Figure 12. Temperatures variation for Scenario 4 (Low Solar gain glazing; SHGC=0.12)

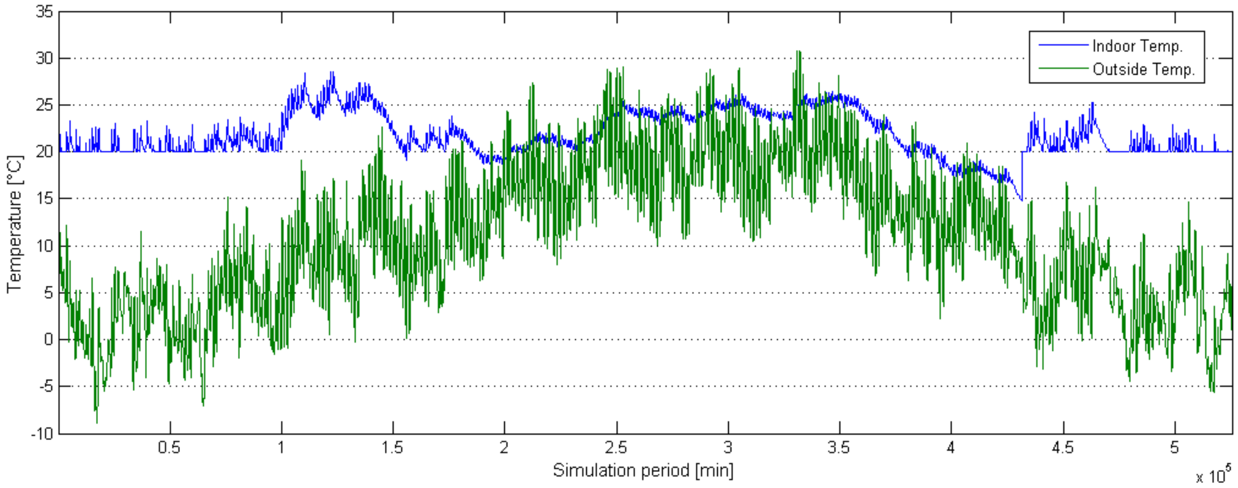


Figure 13. Temperatures variation for Scenario 5 (EC simple control)

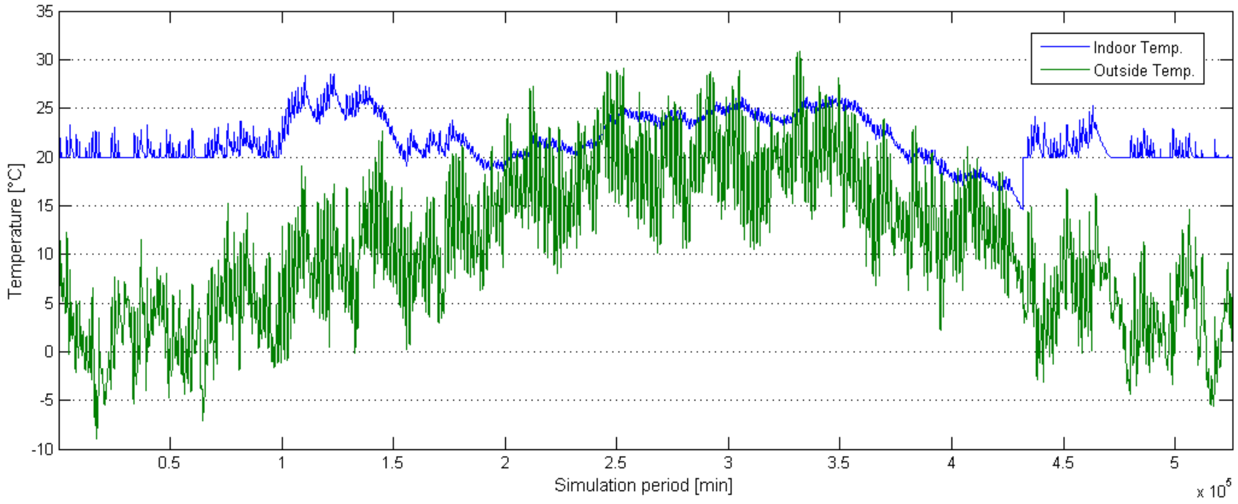


Figure 14. Temperatures variation for Scenario 6 (EC Predictive control)

Scenario 4 (low solar gain glazing with SHGC=0.12) exhibits an indoor temperature that for almost the entire winter season stays stable at around the set-point temperature of 20°C (**Figure 12**), while in the warmest days of the non-heating period the indoor temperature is never over 25°C. However, during some intermediate season days in spring and fall when heating is not required, internal air temperature falls at 18°C or lower. Again, this is due to permanent glazing characteristic of cutting-off most of potential solar gains from entering the room in days when they would have been beneficial for the conditioning of the space.

Cases 3, 5 and 6 appear to have comparable energy consumption but when compared against the internal temperature significant differences are observed. In scenario 3 (low solar gain glazing with SHGC=0.38) internal temperature at around 30°C is observed for about 75 days during the year. In the scenarios with the EC windows (5, 6; **Figure 13** & **Figure 14**), indoor temperature during non-heating season is at around 25°C, with the exception of some warm days during spring.

Figure 15 displays a qualitative approach comparing the internal temperatures distribution for each of the six proposed simulation scenarios. Scenarios 1 and 4 appear immediately as the extreme cases. Scenario 4 is the one having less dispersion with most of the values close to the median (20°C), keeping temperature steady throughout the year, in the expense of high energy consumption as we showed above.

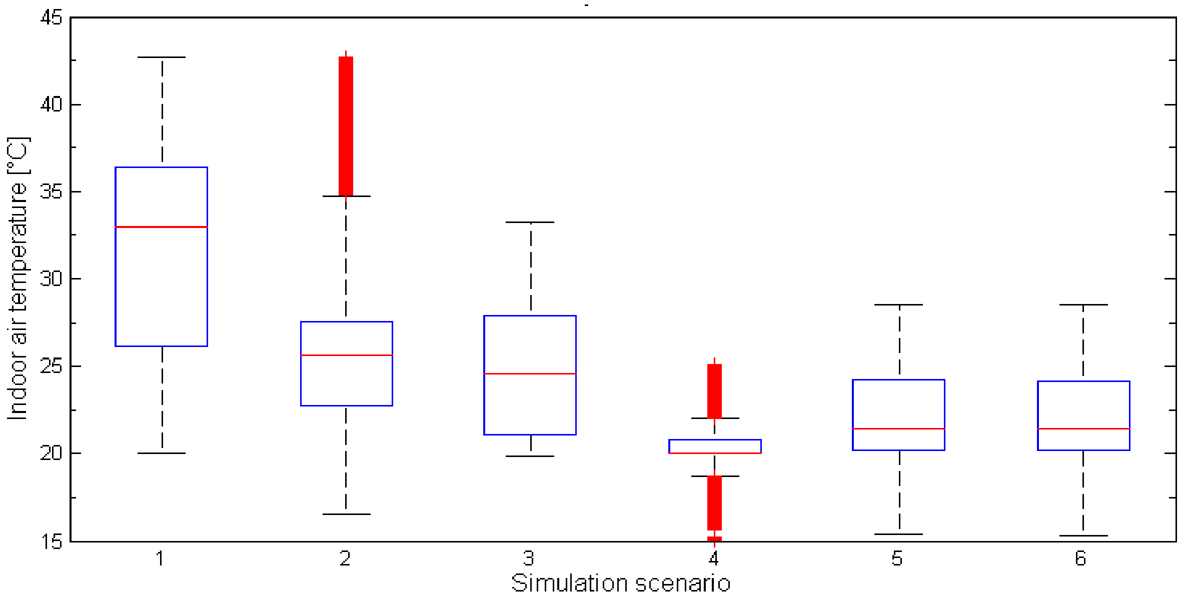


Figure 15. Distribution of indoor air temperature values for the six different simulation scenarios for a period of one year. The blue bottom and top of the box represent the 25th and 75th percentile respectively; the red mark inside the box is the 50th percentile (the median); whiskers represent the minimum and maximum of data points not considered outliers[5] (red points outside whiskers).

---

[5] Points are drawn as outliers if they are larger than q3 + w(q3 – q1) or smaller than q1 – w(q3 – q1), where q1 and q3 are the 25th and 75th percentiles, respectively. The value w=1.5 used here corresponds to approximately +/–2.7σ and 99.3 coverage if the data are normally distributed. The plotted whisker extends to the adjacent value, which is the most extreme data value that is not an outlier [13].

Scenario 1 is having a median at around 33°C and values inside the 25th and 75th percentiles in the area of 26.2 - 36.4°C. Scenario 2 has a reduced interquartile range (22.7-27.5 °C), but its median is rather high (overheat risk) and the whiskers extend far from this range, both over and under. The significance of these distributions becomes crucial next, when we calculate the Predicted Percentages of Dissatisfied (PPD).

The presence of many outliers is expected when there are so many data points (>0.5 million minutes per year with over of 0.1 million minutes inside working hours).

5.9.2. Predicted Percentages of Dissatisfied (PPD)

Thermal comfort was analyzed with the use of Fanger's model [21]. Using as input for every time step of the simulation the season, the radiant temperature in the room and the room's air temperature, the Predicted Percentages of Dissatisfied (PPD) were generated for every working hour in the year. The comfort parameters of air humidity, air velocity, clothing insulation and metabolic heat production were set according to standards and they appear on **Table 4**.

Parameter	Heating period	Non-heating period
Clothing [clo]	1.0	0.50
Operative temperature [°C]	19.2 - 23.8	23 - 26.3
Activity [met]	1.2	1.2
Air speed [m/s]	0.10	0.10
Relative humidity [%]	50.0	50.0

Table 4: Comfort parameters used in Fanger's model for a PPD<10%

The operative temperatures for the heating and the non-heating seasons were calculated as the limits within which the PPD remains below from the generally accepted standard for office rooms of 10% (-0.5<PMV<0.5 or 90% of thermally satisfied occupants). These comfort limits are proposed by the ISO 7730 standard [22]. Clothing insulation was set to 0.5 clo for the non-heating period and to 1 clo during the heating period (for the definition of "season" see paragraph 5.5). The metabolic heat production was set to 1.2 met (light desk work) in all simulations.

The estimation of the thermal comfort for the whole period (1 year) was conducted to evaluate the ability of the simulated case studies to keep the internal air temperature within the comfort limits specified by the said standards (**Table 4**). The percentage of the working time when the air temperature is outside the range defined by the comfort limits was determined for all the simulation scenarios and it can be seen on **Table 5** and **Figure 16**. Again, it should be noted that results should be put in perspective of the absence of cooling and of any form of ventilation. Hence, extreme temperatures and thermal discomfort are expected during mid-season and – most notably – during summer (i.e. non-heating periods).

Simulation scenario	Heating period [%]	Non-heating period [%]	Entire year [%]
1: Standard glazing	61.4	99.5	81
2: Standard glazing+Blinds	58.4	63.9	61.3
3: Low Solar gain glazing (0.38)	20.9	66.9	44.7
4: Low Solar gain glazing (0.12)	0	80.5	41.6
5: EC Simple control	15.6	50.7	33.7
6: EC Predictive control	15.6	50.6	33.6

Table 5: Percentage of working time during the simulation period where temperature is outside comfort limits and the PPD is over 10%, for each of the six considered simulation cases.

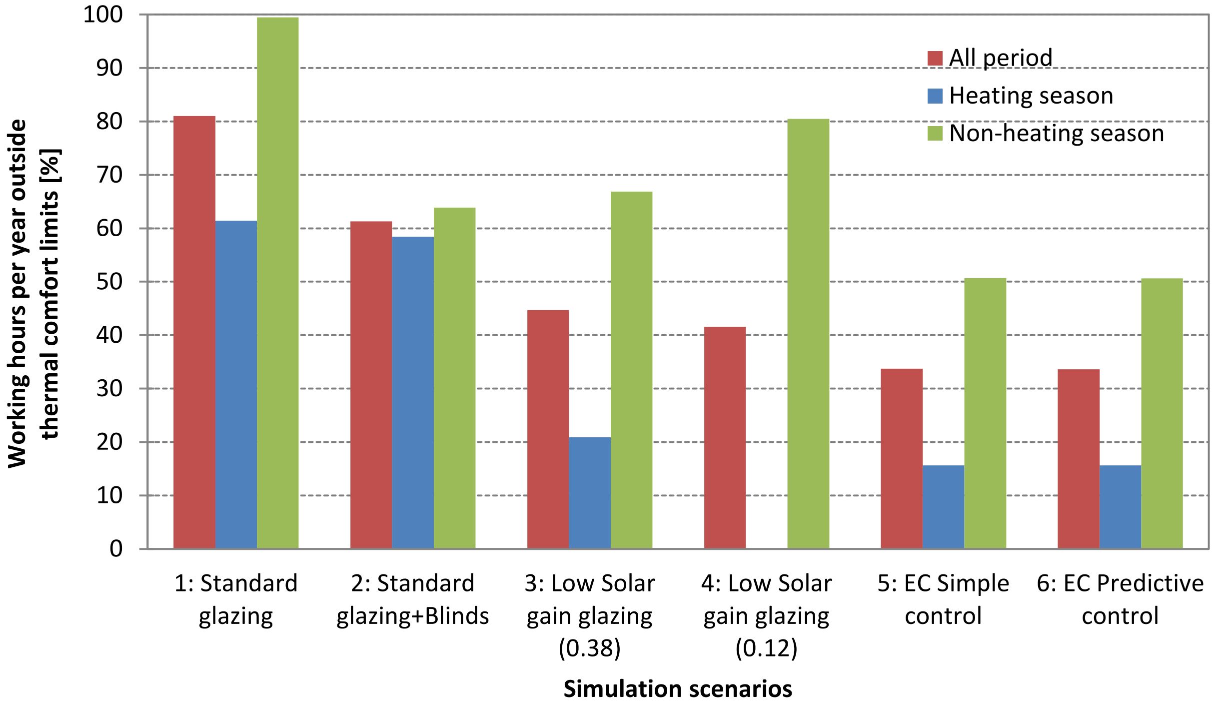


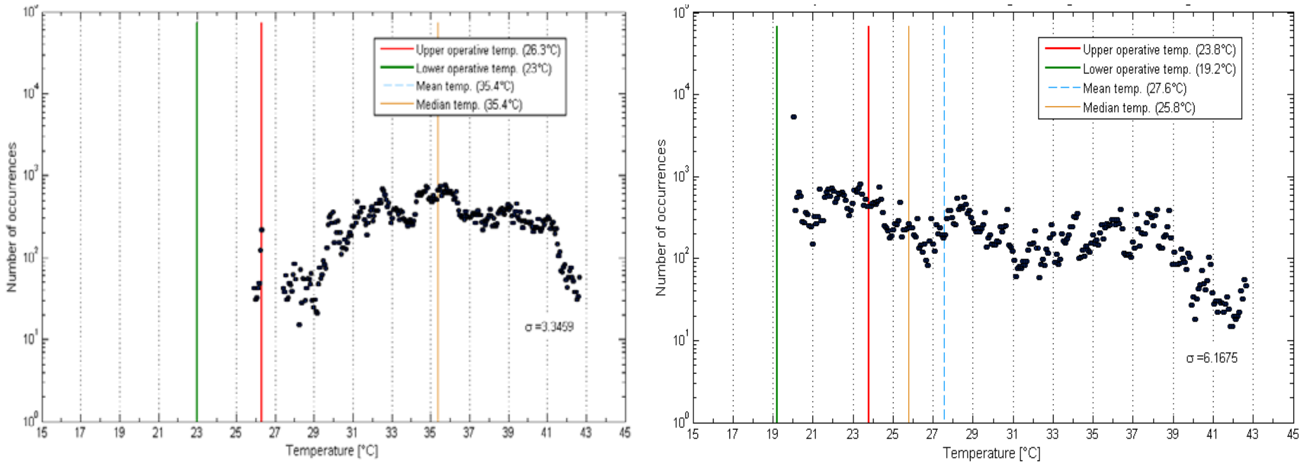
Figure 16. Percentage of working time during the simulation period where temperature is outside comfort limits and the PPD is over 10%, for each of the six considered simulation cases.

The comparison between all different scenarios shows clearly that automatically controlled EC windows (scenario 5 and 6) provide the best possible thermal comfort conditions with only a 15.6% of working time during the winter season found outside the thermal comfort limits. Scenario 3 also provides acceptable thermal comfort with 21% of working time during the winter season lying outside the thermal comfort limits. Standard glazing scenarios provide unacceptably high discomfort conditions. During winter, scenario 4 interestingly enough provides the “perfect” thermal comfort conditions with zero working time being outside comfort conditions. That is of course due to the excessive use of heating energy since almost all solar gains are rejected.

We kept separately the reports for the non-heating season on purpose. Since there is no active cooling system (and we chose not to implement night-cooling as well), temperatures during the “summer” days are more likely to fall outside thermal comfort criteria. But also in this case, EC windows scenarios are performing better than the others.

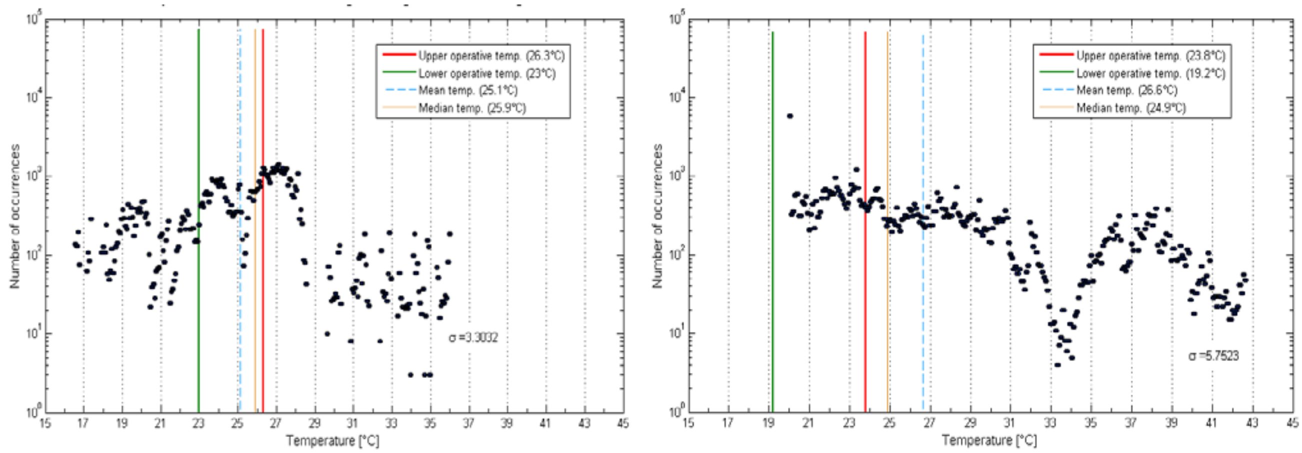
Figure 17 and **Figure 18** below complete the picture in thermal comfort providing some additional qualitative information about the indoor temperature during the simulation periods. In particular, the distribution of indoor temperature (values, median, mean and standard deviation) during working hours for both the non-heating and the heating period is displayed together with the limits of the operative temperatures (green and red lines) for all simulation scenarios.

5.9.3. Air temperature distributions during working hours



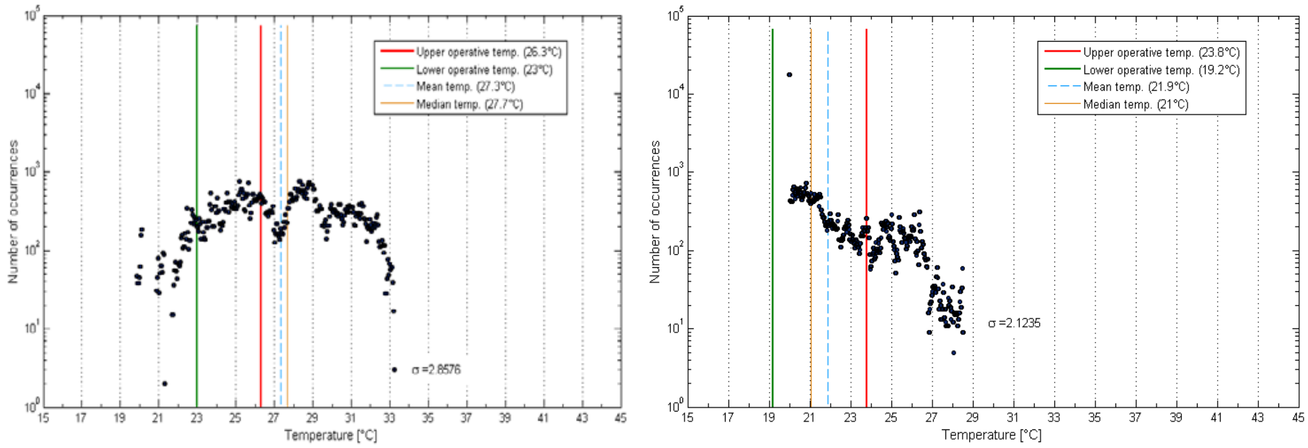
(Scenario 1a)

(Scenario 1b)



(Scenario 2a)

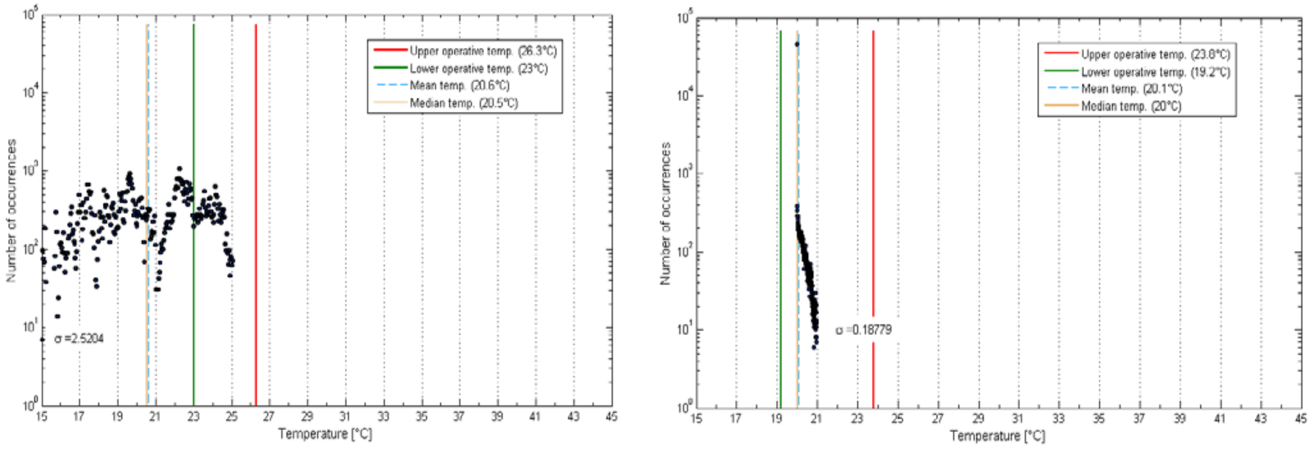
(Scenario 2b)



(Scenario 3a)

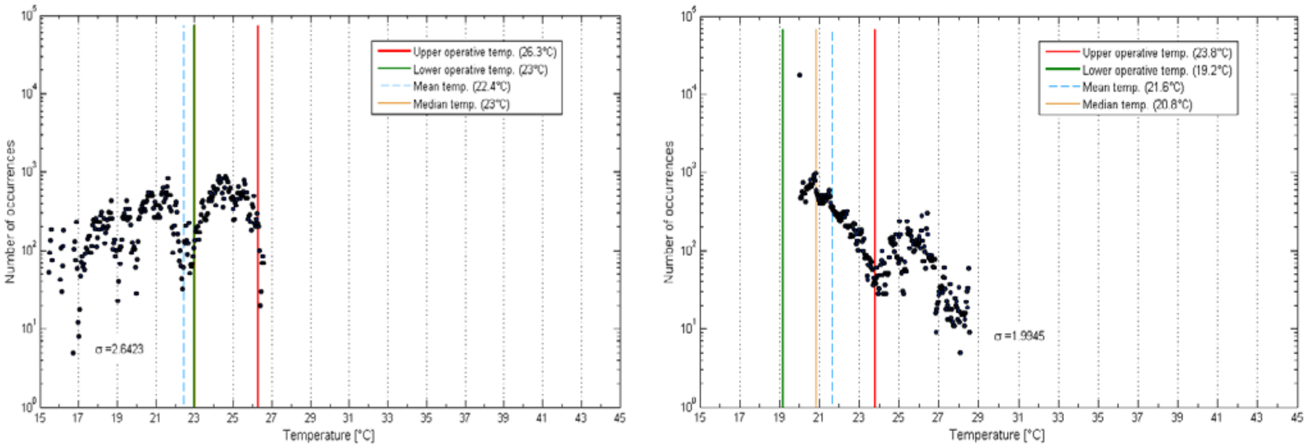
(Scenario 3b)

Figure 17. Indoor temperature values distribution during working hours in (a) non-heating and (b) heating period for simulation scenarios 1-3. Displayed are the values (dots), median (orange line), mean (light blue dashed line) and standard deviation together with the limits of the operative temperatures (green and red lines).



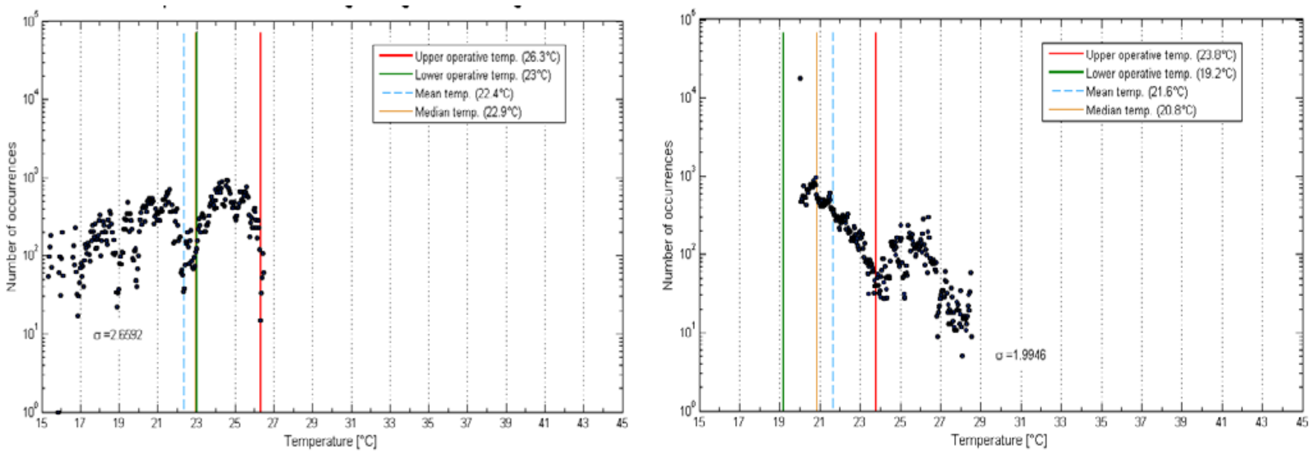
(Scenario 4a)

(Scenario 4b)



(Scenario 5a)

(Scenario 5b)



(Scenario 6a)

(Scenario 6b)

Figure 18. Indoor temperature values distribution during working hours in (a) non-heating and (b) heating period for simulation scenarios 4-6. Displayed are the values (dots), median (orange line), mean (light blue dashed line) and standard deviation together with the limits of the operative temperatures (green and red lines)

5.10. Visual comfort

For the estimation of visual comfort we use the work of Lindeloef realised in LESO regarding the Bayesian optimization of visual comfort [23]. Lindeloef calculates the user Visual Discomfort Probability (VisDP) as a function of the horizontal workplane illuminance (**Figure 19**). Based on his work, we list the illuminance limits for the VisDP as per **Table 6**:

Visual discomfort probability [-]	**Workplane illuminance** [lx]
< 0.30	400-500
< 0.35	300-720
< 0.40	250-1620
< 0.45	225-2000
< 0.50	210-2545
> 0.50	(outside above limits)

Table 6: Ranges of workplane illuminance and their probability to cause visual discomfort to space occupants.

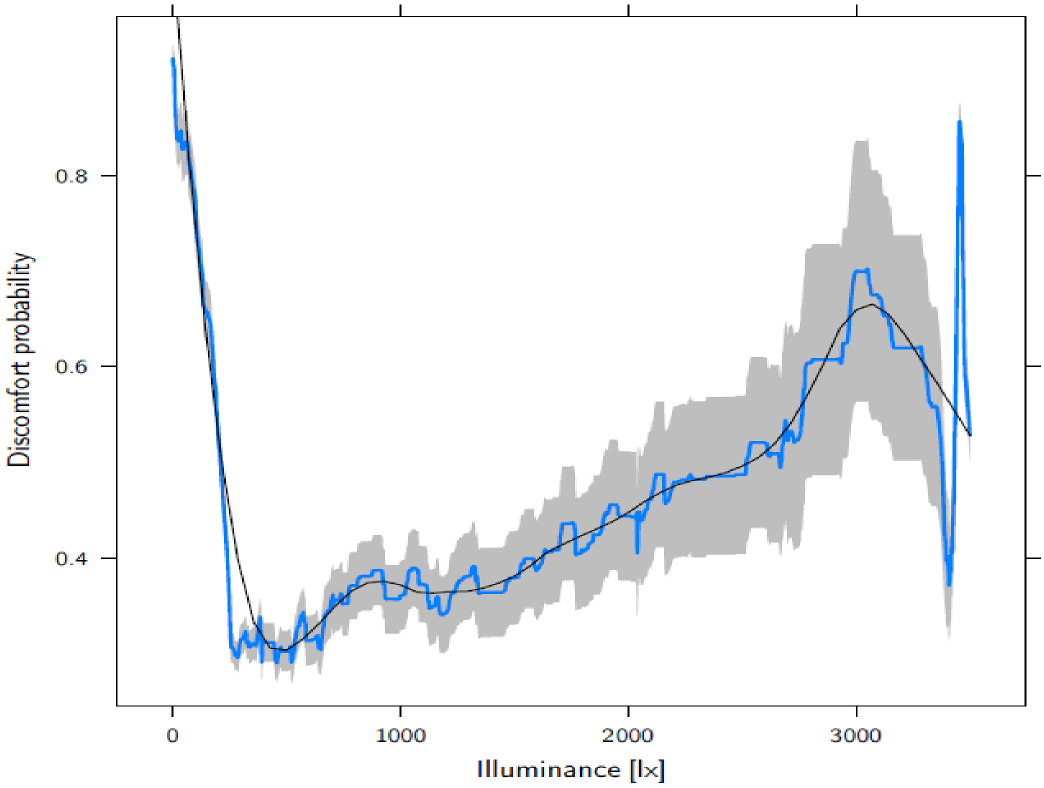


Figure 19. User discomfort probability as a function of horizontal workplane illuminance [23].

Using as input for every time step of the simulation the desktop (workplane) illuminance the VisDP was generated for every working hour in the year. The estimation of the visual comfort for the whole period (1 year) was conducted to evaluate the ability of the simulated case studies to keep the workplane illuminance within ranges (**Table 6**) which are less likely to cause discomfort to the occupants. The percentage of the working time when the VisDP is kept below certain values was determined for all the simulation scenarios and it is presented on **Table 7**. It should be noted that predicted visual discomfort only accounts for the illuminance intensity on the workplane and does not take into consideration at all the visual discomfort due to glare phenomena.

Simulation scenario	Working hours/year [%] with visual discomfort probability below:				
	<=0.3	<0.35	<0.4	<0.45	<0.5
1: Standard glazing	4.7	10	26.2	29.9	35.2
2: Standard glazing+Blinds	4.7	10.1	29.2	36.9	49.2
3: Low Solar gain glazing (0.38)	13.9	25.5	58.3	65.9	74.4
4: Low Solar gain glazing (0.12)	24.9	46.4	87	94.8	99.8
5: EC Simple control	14.2	26.3	70.8	83.3	93.7
6: EC Predictive control	14	26.1	70.7	83.7	93.7

Table 7: Percentage of working time during the simulation period where visual discomfort probability is kept below fixed values, for each of the six considered simulation cases.

The working hours per year where the workplane illuminance will cause visual discomfort in less than 30, 35, 40, 45 and 50% of the occupants is presented in **Figure 20**.

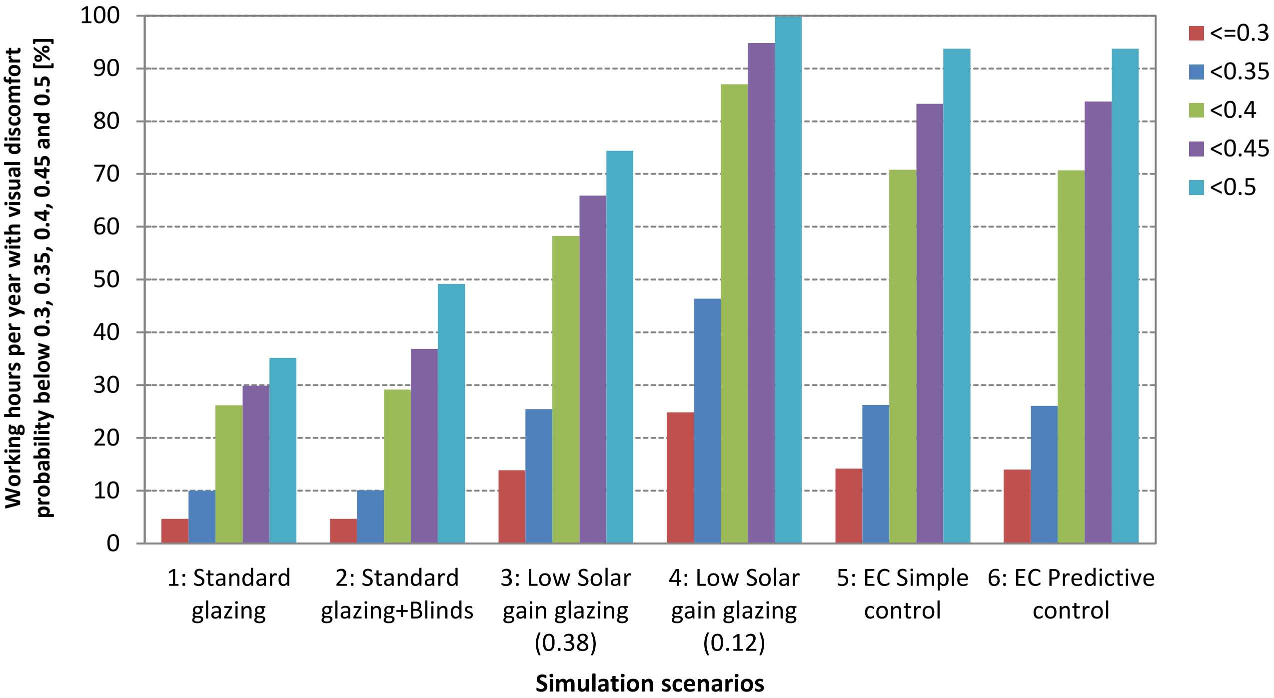


Figure 20. Percentage of working time during the simulation period where visual discomfort probability is kept below 30, 35, 40, 45 and 50%, for each of the six considered simulation cases.

Extreme-case scenario 4 demonstrated the best possible visual performance between the studied cases, followed closely by the EC windows scenarios (5 and 6) and scenario 3, although that is true only for the illuminance ranges corresponding to discomfort probability below 0.35. For the thresholds of VisDP above 0.35, scenario 3 performance deteriorates as there is some dispersion of illuminance towards higher values (**Figure 22** and **Figure 23**).

Scenarios 5 and 6 appear to achieve same levels of visual comfort in this analysis. Nevertheless, a close look to workplane illuminance values when comparing the 2 scenarios against the same weather conditions and time period (**Figure 21**), reveals that predictive control strategy (scenario 6) maintains workplane illuminance more stable compared to simple control (scenario 5). Workplane illuminance in non-predictive control tends to fluctuate in almost perfect agreement with external irradiance levels. This is especially true under constantly varying sky conditions where the switching-time inertia of the system is in the same order as the sky variations. Matching illuminance levels for the 2 scenarios occur when Vertical South Global Irradiance (IgvSouth) exceeds the upper cut-off limit of solar gains (300 W/m^2) and EC glazings keep in both cases a steady transmission value of Tv=15%.

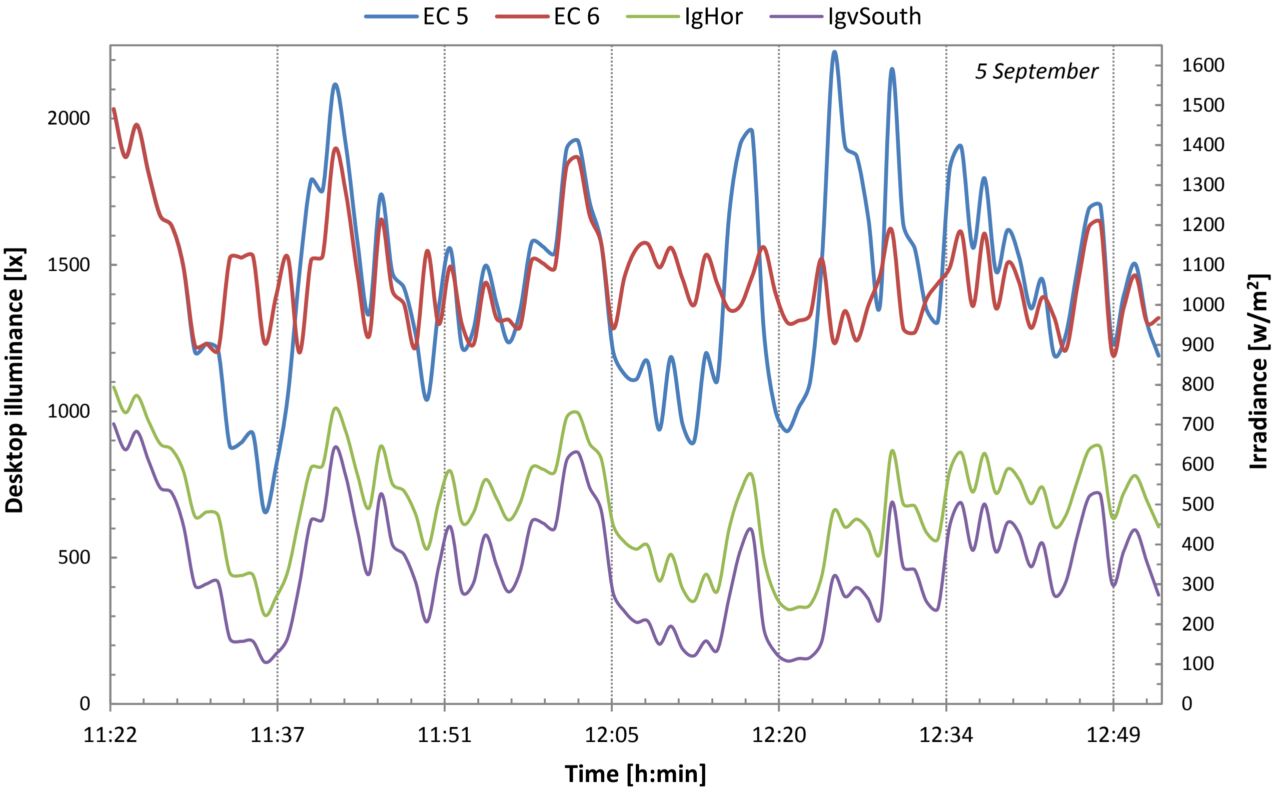


Figure 21. Desktop illuminance, Global Horizontal Irradiance (IgHor) and Vertical South Global Irradiance (IgvSouth) fluctuation around noon time on a day with intermediate sky conditions (September 5th; non heating period) for 2 different EC windows control strategies (Scenario 5 and 6).

Figure 22 compares the distribution of desktop illuminance values of the studied scenarios. As with the temperature values we observe the great dispersion and the high values of the standard glazing scenarios. On the other hand, scenario 4 appears “the perfect case” but we should consider that illuminances are kept to ideal only because a great deal of electric lighting is administered throughout the year. As in thermal comfort estimation, **Figure 23** provides additional qualitative and quantitative information about the workplane illuminance during the simulation periods. In particular, the distribution of illuminance during working hours for the entire period is displayed together with the range limits of the VisDP (**Table 6**) for each simulation scenario. Also noted on the figures are the percentages of working hours of the entire period measured inside the limits of each range.

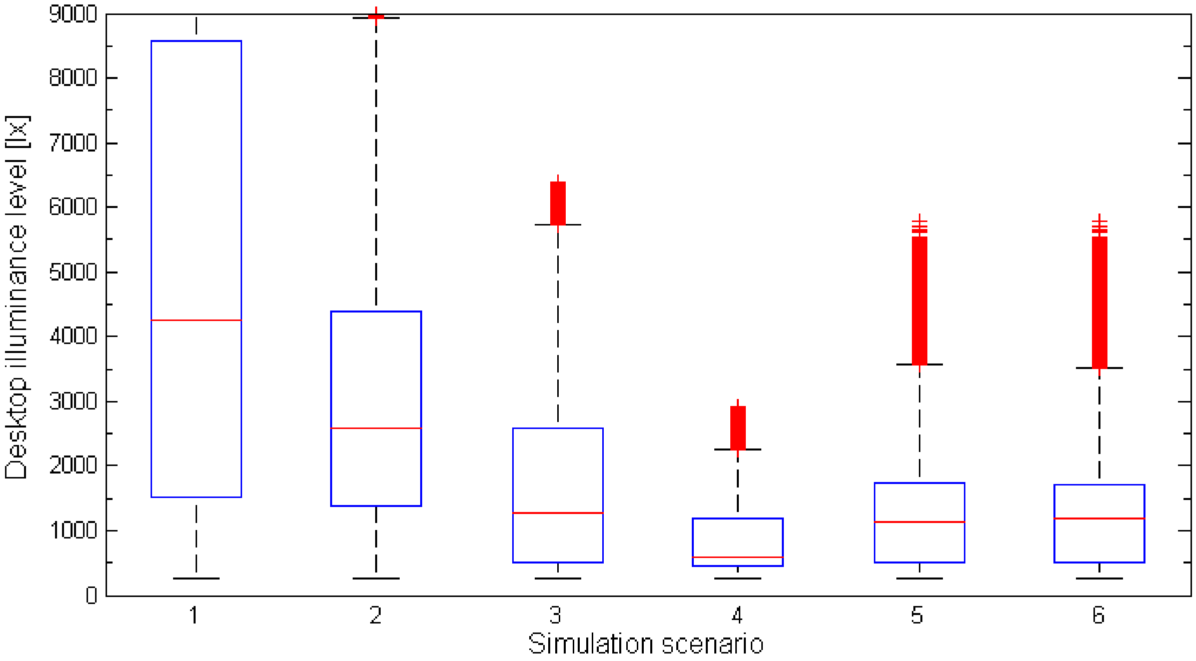
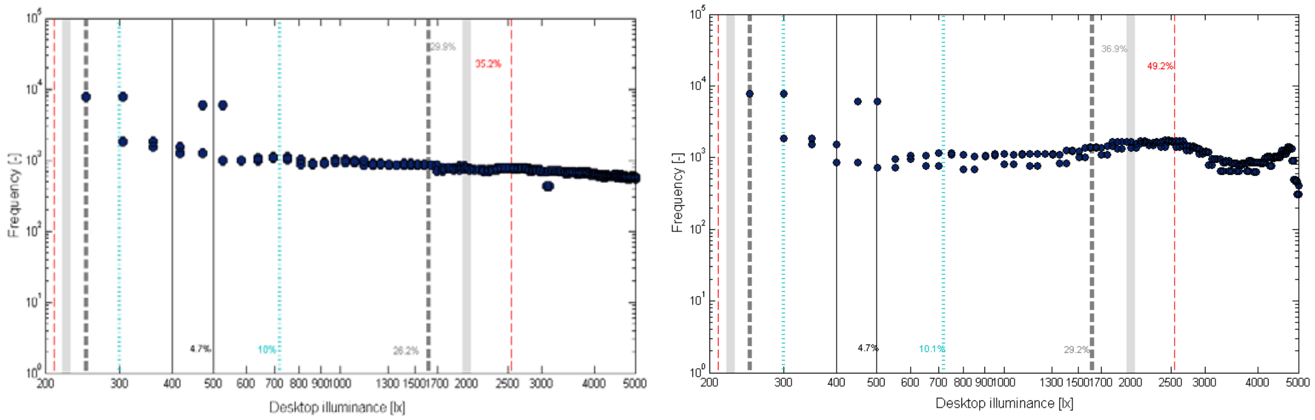


Figure 22. Distribution of desktop illuminance values for the six different simulation scenarios for a period of one year. The blue bottom and top of the box represent the 25th and 75th percentile respectively; the red mark inside the box is the 50th percentile (the median); whiskers represent the minimum and maximum of data points not considered outliers[6] (red points outside whiskers). Top whisker of Scenario ‘1’ is >9000 lx and it is not displayed here.

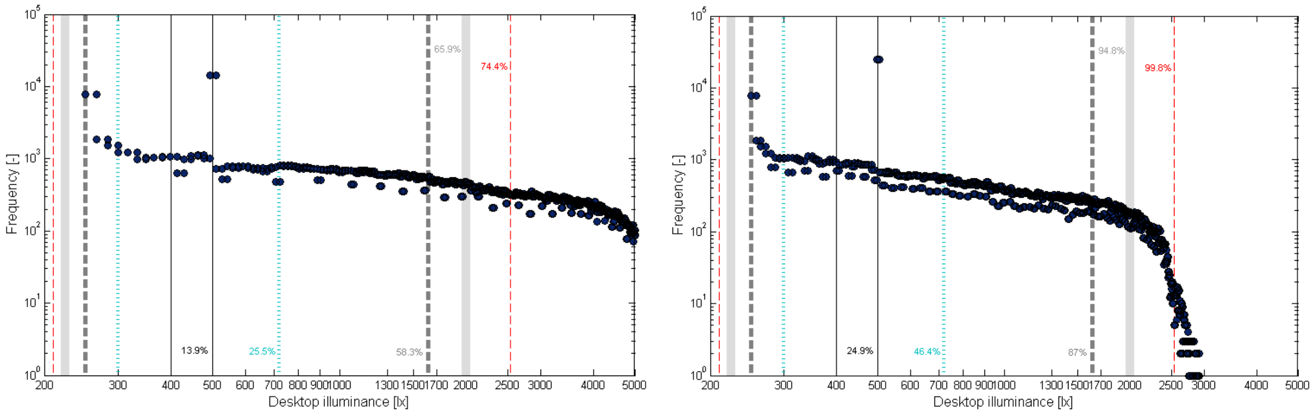
---

[6] Points are drawn as outliers if they are larger than q3 + w(q3 – q1) or smaller than q1 – w(q3 – q1), where q1 and q3 are the 25th and 75th percentiles, respectively. The value w=1.5 used here corresponds to approximately +/–2.7σ and 99.3 coverage if the data are normally distributed. The plotted whisker extends to the adjacent value, which is the most extreme data value that is not an outlier [13].

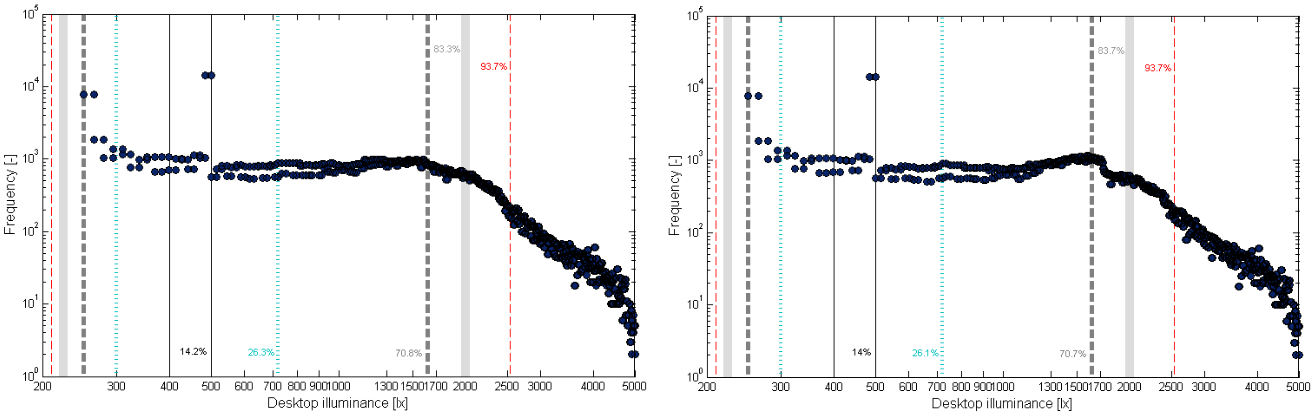
5.10.1. Desktop illuminance distributions during working hours



(Scenario 1) (Scenario 2)



(Scenario 3) (Scenario 4)



(Scenario 5) (Scenario 6)

Figure 23. Desktop illuminance values distribution during working hours for the entire simulation period and for all simulation scenarios. The illuminance limits for every range of the VisDP are marked with 2 identical vertical lines for every range. Displayed next to the limit lines with the same colour as them are the percentages of working hours of the entire period with illuminance inside the limits of each range.

6. CONCLUSIONS

Simulations showed that algorithms for the automatic control of EC windows can provide better thermal and visual comfort conditions when compared to standard glazing coupled with blinds and still exhibit acceptable levels of energy consumption for space heating and electric lighting. Permanently tinted windows (solar protection windows) with a SHGC=0.38 (the same as the clear state of EC windows) can offer competitive conditions as EC windows, exhibiting slightly worse thermal and visual behaviour, especially during days when solar gains are high (sunny days) which is expected since they cannot modify their transmission and block unwanted solar radiation.

As it became evident during the comprehensive parametric study, the developed sky prediction algorithm does not outperform a simpler closed-loop algorithm based on external irradiation when considering energy consumption aspects. In respect to visual comfort, the two control systems perform similarly when analysed for the Visual Discomfort Probability (VisDP). However, under varying intermediate sky conditions predictive control strategy minimizes workplane illuminance fluctuation when compared to simple control and thus, it provides a more stable luminous working environment.

Field survey showed that user acceptance of a daylight control system including EC windows is severely impaired by the unnatural colour rendering of the room and of the view when looking outside. Also, a bigger dynamic range of possible transmissions would be positively seen by most users. As it was expected, glare issues were mentioned by some users and blinds were employed in these occasions. However, most users are willing to oversee any inconveniences or disadvantages when comparing EC windows with a standard daylight control system such as blinds, mainly favouring the unobstructed view that EC windows offer at all times.

This project has confirmed that EC windows which are controlled automatically and are integrated into a holistic building control scheme (heating, cooling, electric lighting) create a comfortable visual and thermal environment and can be considered as a future replacement to standard window glazings with mobile solar shadings or to permanently tinted solar protection glazings.

Upon the completion of future field experimentation, the work performed in the framework of this project will be published in peer-reviewed scientific journal(s).

7. REFERENCES

[1]. **Lee, E.S., et al.** Advancement of Electrochromic Windows. *Lawrence Berkeley National Laboratory.* 2006. LBNL-59821.

[2]. **Baetens, R., Jelle, B.P. and Gustavsen, A.** Properties, requirements and possibilities of smart windows for dynamic daylight and solar energy control in buildings: A state-of-the-art review. *Solar Energy Materials and Solar Cells.* 2010, Vol. 94, 2, pp. 87-105.

[3]. **Lee, E.S. and DiBartolomeo, D.L.** Application issues for large-area electrochromic windows in commercial buildings. *Solar Energy Materials and Solar Cells.* 2002, Vol. 71, 4, pp. 465-491.

[4]. **Gonzalez, R.C., Woods, E. and Eddins, S.L.** *Digital image processing using MATLAB.* 2nd Edition. s.l. : Gatesmark Publishing, 2009. ISBN 978-0-9820854-0-0.

[5]. **Evans, A.N.** Cloud motion analysis using multichannel correlation-relaxation labeling. *Geoscience and Remote Sensing Letters, IEEE.* 2006, Vol. 3, 3, pp. 392-396.

[6]. **Reda, I., Andreas, A.** *Solar position algorithm for solar.* s.l. : National Renewable Energy Laboratory (NREL), 2003. Technical report NREL/TP-560-34302.

[7]. **Guillemin, A.** *Using genetic algorithms to take into account user wishes in an advanced building control system.* PhD thesis no. 2778, EPFL. 2003.

[8]. **Bauer, M., et al.** DELTA, a blind controller using fuzzy logic. *OFEN Final Report 50.943, Solar Energy and Building Physics Laboratory, EPFL, Lausanne.* 1996.

[9]. **Morel, N., et al.** Neurobat, a predictive and adaptive heating control system using artificial neural networks. *International journal of sustainable energy.* 2001, Vol. 21, 2, pp. 161-201.

[10]. **Courret, G., et al.** Design and assessment of an anidolic light-duct. *Energy and Buildings.* 1998, Vol. 28, 1, pp. 79-99.

[11]. **Scartezzini, J.-L. and Courret, G.** Anidolic daylighting systems. *Solar Energy.* 2002, Vol. 73, 2, pp. 123-135.

[12]. **Page, J., et al.** On-site performance of electrochromic glazings coupled to an anidolic daylighting system. *Solar Energy.* 2007, Vol. 81, 9, pp. 1166-1179.

[13]. MathWorks Inc. Official Website. [Online] http://www.mathworks.com/.

[14]. **Lee, E.S., DiBartolomeo, D.L. and Selkowitz, S.E.** Daylighting control performance of a thin-film ceramic electrochromic window: Field study results. *Energy and Buildings.* January 2006, Vol. 38, 1, pp. 30-44.

[15]. **Fasano, G., et al.** A detailed characterization of commercial electrochromic devices for building applications. *Proceedings of EUROSUN 2002, June 2002, Bologna, Italy.*

[16]. **Borisuit, A. and Scartezzini, J.-L.** Visual discomfort and glare rating assessment of integrated daylighting and electric lighting systems using HDR imaging techniques. *Architectural Science Review.* 2010, Vol. 53, 4, pp. 359-373.

[17]. Meteonorm official website. [Online] http://meteonorm.com/home/.

[18]. **Perez, R., et al.** Modeling daylight availability and irradiance components from direct and global irradiance. *Solar Energy.* 1990, Vol. 44, 5, pp. 271-289.

[19]. **Perez, R., Seals, R. and Michalsky, J.** All-weather model for sky luminance distribution - Preliminary configuration and validation. *Solar Energy.* 1993, Vol. 50, 3, pp. 235-245.

[20]. **Andrew, J.M.** RADIANCE and Daylight Factors. *Natural Frequency.* 11 2007, 004.

[21]. **Fanger, P.O.** *Thermal comfort analysis and applications in environmental engineering.* New York : McGraw-Hill, 1970.

[22]. **7730:2005, EN ISO.** *International standard: Ergonomics of the Thermal Environment-Analytical Determination of Thermal Comfort by Using Calculations of the PMV and PPD Indices and Local Thermal Comfort Criteria.* Geneva : International Standard Organization for Standardization, 2005.

[23]. **Lindeloef, D.** *Bayesian optimization of visual comfort.* PhD thesis no. 3918, EPFL. 2007.

[24]. **Clear, R.D., Inkarojrit, V. and Lee, E.S.** Subject responses to electrochromic windows. *Energy and Buildings.* July 2006, Vol. 38, 7, pp. 758-779.

[25]. **Klems, J.H.** Net energy performance measurements on electrochromic skylights. *Energy and Buildings.* 2001, Vol. 33, 2, pp. 93-102.

[26]. **Tenner, A.D. and Zonneveldt, L.** Switchable Facades and Visual Comfort. *Right Light Conference, Nice, France.* 29-31 May 2002.

[27]. **Zinzi, M.** Office worker preferences of electrochromic windows: a pilot study. *Building and Environment.* 2006, Vol. 41, 9, pp. 1262-1273.

[28]. **Barron, J.L., Fleet, D.J. and Beauchemin, S.S.** Performance of optical flow techniques. *International Journal of Computer Vision.* 1994, Vol. 12, 1, pp. 43-77.

[29]. **Zafarifar, B. and With, P.H.N.** Blue sky detection for picture quality enhancement. *Advanced Concepts for Intelligent Vision Systems.* 2006, Vol. 4179, pp. 522-532.

[30]. **Inanici, MN.** Evaluation of high dynamic range photography as a luminance data acquisition system. *Lighting Research and Technology.* 2006, Vol. 38, 2, pp. 123-134.

[31]. **Michel, L.** *Méthode expérimentale d'évaluation des performances lumineuses de bâtiments.* EPFL. 1999. PhD thesis no. 2042.

[32]. *EControl-Glas.* [Online] [Cited: 07 01 2011.] http://www.econtrol-glas.de.

[33]. **Jonsson, A. and Roos, A.** Evaluation of control strategies for different smart window combinations using computer simulations. *Solar Energy.* 2010, Vol. 84, 1, pp. 1-9.

[34]. **Assimakopoulos, M.N., et al.** Integrated energetic approach for a controlable electrochromic device. *Energy and Buildings.* 2004, Vol. 369, 5, pp. 415-422.

[35]. **Lee, E.S. and Tavil, A.** Energy and visual comfort performance of electrochromic windows with overhangs. *Building and Environment.* 2007, Vol. 42, 6, pp. 2439-2449.

[36]. **Macrelli, G.** Elecrrochromic windows. *Renewable Energy.* 1998, Vol. 15, 1-4, pp. 306-311.

[37]. **Assimakopoulos, M.N., et al.** Comparing the energy performance of an electrochromic window under various control strategies. *Building and Environment.* 2007, Vol. 42, 8, pp. 2829-2834.

[38]. **Karjalainen, S. and Lappalainen, V.** Integrated control and user interfaces for a space. *Building and Environment.* 2011, Vol. 46, 4, pp. 938-944.

[39]. **Spasojevic, B. and Mahdavi, A.** Sky luminance mapping for computational daylight modeling. *Ninth International IBPSA Conference, Montreal, Canada.* 15-18 August 2005.

[40]. **Thanachareonkit, A., Scartezzini, J.-L. and Andersen, M.** Comparing daylighting performance assessment of buildings in scale models and test modules. *Solar Energy.* 2005, Vol. 79, 2, pp. 168-182.

[41]. **Turiel, Isaac.** *Indoor Air Quality and Human Health.* s.l. : Stanford University Press, 1985. ISBN: 9780804712552.

[42]. Indoor Environments. *Environmental Law Institute.* [Online] [Cited: 23 11 2010.] http://www.eli.org/Program_Areas/indoor_environments.cfm.

[43]. **Fisk, W.J. and Rosenfeld, A.H.** Estimates of Improved Productivity and Health from Better Indoor Environments. *Indoor Air.* 1997, Vol. 7, 3, pp. 158-172.

[44]. **Olesen, B.W. and Parsons, K.C.** Introduction to thermal comfort standards and to the proposed new version of EN ISO 7730. *Energy and Buildings.* 2002, Vol. 34, 6, pp. 537-548.

[45]. **Knez, Igor.** Effects of indoor lighting on mood and cognition. *Journal of Environmental Psychology.* 1995, Vol. 15, 1, pp. 39-51.

[46]. **Li, D.H.W and Lam, J.C.** Evaluation of lighting performance in office buildings with daylighting controls. *Energy and Buildings.* 2001, Vol. 33, 8, pp. 793-803.

[47]. **Perez-Lombard, L., Ortiz, J. and Pout, C.** A review on buildings energy consumption information. *Energy and Buildings.* 2008, Vol. 40, 3, pp. 394-398.

[48]. **Goldberg, M.L.** Lighting in Commercial Buildings. *Report of U.S. Department of Energy, Energy Consumption Series.* 1992.

[49]. **Bodart, M. and De Herde, A.** Global energy savings in offices buildings by the use of daylighting. *Energy and Buildings.* 2002, Vol. 34, 5, pp. 421-429.

[50]. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings. *Official Journal of the European Union.* 18.6.2010, L 153/13.

[51]. **Lee, E.S., et al.** A Design Guide for Early-Market Electrochromic Windows. *Lawrence Berkeley National Laboratory.* 2006. LBNL-59950.

[52]. **Linhart, F.** *Energetic, visual and non-visual aspects of office lighting.* PhD thesis no. 4634, EPFL. 2010.

[53]. **Nygard F., A.M.** *Predictive thermal control of building systems.* PhD thesis no. 876, EPFL. 1990.

[54]. **Granqvist, C.G.** Electrochromic tungsten oxide films: Review of progress 1993–1998. *Solar Energy Materials and Solar Cells.* 2000, Vol. 60, 3, pp. 201-262.

[55]. **Czandernaa, A.W., et al.** Durability issues and service lifetime prediction of electrochromic windows for buildings applications. *Solar Energy Materials and Solar Cells.* 1999, Vol. 56, 3-4, pp. 419-436.

[56]. **Lee, E.S., et al.** Monitored Energy Performance of Electrochromic Windows Controlled for Daylight and Visual Comfort. *Lawrence Berkeley National Laboratory.* 2005. LBNL-58912.

[57]. **Fernandes, LL., Lee, E.S. and Ward, G.** Radiance-Mathematica optimization study of electrochromic window and daylighting control systems. *Advancement of Electrochromic Windows final report, Lawrence Berkeley National Laboratory. California Energy Commission, PIER Program.* 2006. CEC-500-2006-052-AT5.

[58]. **Piccolo, A. and Simone, F.** Effect of switchable glazing on discomfort glare from windows. *Building and Environment.* 2009, Vol. 44, 6, pp. 1171-1180.

[59]. **Sullivan, R., et al.** Effect of switching control strategies on the energy performance of electrochromic windows. *Proceedings SPIE.* 1994, Vol. 2255/443.

[60]. **Gugliermetti, F. and Bisegna, F.** Visual and energy management of electrochromic windows in Mediterranean climate. *Building and Environment.* 2003, Vol. 38, 3, pp. 479-492.

[61]. **Lalonde, J.-F., Narasimhan, S. and Efros, A.** What Do the Sun and the Sky Tell Us About the Camera? *International Journal of Computer Vision.* 2010, Vol. 88, 1, pp. 24-51.

[62]. **Scartezzini, J.-L., et al.** Intensive Use of Daylight in Buildings through Coupling of Electrochromic Glazings and Anidolic Daylighting Systems. *Final Report fo the VELUX Fondation, Solar Energy and Building Physics Laboratory, EPFL, Lausanne.* 2003.

8. APPENDICES

8.1. Nomenclature

EC	**E**lectro**c**hromic
HVAC	Heating, Ventilation and Air Conditioning
ADS	Anidolic Daylighting System(s)
LESO-PB	Solar Energy and Building Physics Laboratory
DC	Direct Current
Tv	Visible Transmittance
Igvs	Global vertical south solar radiation
Egh	Global Horizontal Illuminance
SHGC	Solar Heat Gain Coefficient
IGU	Insulating Glass Unit
PPD	Predicted Percentage of Dissatisfied
PMV	Predicted Mean Vote
VisDP	Visual Discomfort Probability
LC	Liquid Crystal
SP	Electrophoretic or Suspended-Particle

8.2. Communication Protocol for EControl-Glas glazings

(Translated from an EControl-Glas document, by Tobias Wesenberg)

1. General description

The EControl unit for an EControl glazing can be used either as standalone control for a single glazing (control unit with a manual control ESS/BT), or as integrated in an advanced automatic control system (control unit ESS without manual control capability, as a UP style unit), controlled by a EC-Group control unit (GSG). The GSG includes additionally an RS 485 serial interface, which can be connected either to a PC or to a EIB/KNX, LonWorks, or Ethernet network through an interface.

2. EC-Bus

A protocol with variable data length is used for the communication between GSG and ESS. The tables below describe the protocol, the adresses, and the coding of commands and errors. For data and adresses including more than 1 byte, the most significant byte (High-Byte) is transmitted first.

2.1 Protocol format on the EC-Bus

Address	Command	Length	Data	Checksum
1 byte	1 byte	1 byte	max 20 bytes	1 byte

Serial transmission protocol: 19200 bauds, no parity, 1 stop-bit

2.2 Addresses

Address	Function
0	Feedback to GSG
1-30	ESS
200	Broadcast
251-254	Not implemented
255	Device not addressed (delivery status)

2.3 Commands

Remark: the commands 1 and 2 can be sent as broadcast, since these commands are checked periodically by the GSG. For that, the periodic sending (command 13) must be activated !

Number	Length	Description	Broadcast	Single	Answer
1	0 bytes	Glazing initialization	X	X	
2	1 byte	Start glazing transmission setting in % (18 … 64)	X	X	
3	0 byte	Request short info		X	60
4	0 byte	Request measured values for current glazing temperature and current glazing transmission		X	61
7	1 byte	Request error list (0 … 4)		X	60/63
8	0 byte	Request HW and SWstatus		X	60/64
9	0 byte	Request number of cycles		X	60/65
13	1 byte	Cyclic request of all ESS on EC-bus by the GSG: 0 = not active (reading of the individual ESS or ESS/BT by the GSG) 1 = active (default)			
30	7 bytes	Set clock: byte 1 = seconds (0 … 59) byte 2 = minutes (0 … 59) byte 3 = hours (0 … 23) byte 4 = day of the month (1 … 31) byte 5 = day of the week (0 …6, 0 = Sunday) byte 6 = month (1 … 12) byte 7 = year (0 … 99)		X	60
31	0 byte	Read system time		X	60/69

2.4 Feedback

All feedback data take place at address 0 (GSG).

Number	Length	Description	Broadcast	Single	Answer
60	1 byte	<u>General feedback</u> negative --> error code			

		positive: 0 = ready, 1= currently changing, 2 = init cycle Feedback "cyclic request" negative --> error code positive: 30 = not active, 31 = active Feedback "set clock" negative --> error code positive: 40 = clock set			
61	20 bytes	Feedback from command "request measured values": glazing temperature (hi-byte 14, low-byte 15) glazing transmission (byte 18)			
63	10 bytes	Feedback from command "request error list" last 5 errors with time stamp: error number (0-4), error code (1), cycle number (3, see below), timestamp (5 bytes, see below)			
64	4 bytes	Feedback from command "request HW and SW status": bytes 1and 2 --> hardware status xxxx bytes 3 and 4 --> software status yy.yy			
65	3 bytes	Feedback from current cycle number (3 bytes: lo, hi, LO) ???			
69	7 bytes	Feedback from command "request current system time", coded BCD: byte 1 = seconds (0 ... 59) byte 2 = minutes (0 ... 59) byte 3 = hours (0 ... 23) byte 4 = day of the month (1 ... 31) byte 5 = day of the week (0 ...6, 0 = Sunday) byte 6 = month (1 ... 12) byte 7 = year (0 ... 99)			

Remark: the temperature is a 16-bit number with sign ???

2.5 Error codes

Error number	Description
-15	checksum error EC-bus
-16	checksum error building bus
-30	temperature sensor broken or not connected
-31	temperature sensor broken or short-circuited
-38	glazing temperature too high (transmission coefficient adjustment stopped until T < Tmax - hysterese)
-39	glazing temperature too low (transmission coefficient adjustment stopped until T > Tmin

Explanation "feeback to": errors that stop the adjustment of transmission coefficient are stored in the error memory of the EEPROMs. The errors can be retrieved by the command "request short info" through the bus, until a reset takes place. Errors whose cause is a bus access (checksum errors, status errors) are directly fedback.

When errors with other codes take place, please contact EControl-Glas !

2.6 Error memory organization

(BCD coding)

byte 1	error code
byte 2	cycle number low byte
byte 3	cycle number mid-byte ???
byte 4	cycle number high byte
byte 5	year
byte 6	month
byte 7	day of the month
byte 8	hour
byte 9	minute

2.7 Error request by GSG

The GSG polls cyclically every ESS on the EC-bus. By command number 3 ("request short info"), the current status (ready, currently adjusting transmission coefficient, initialized, or error code when an error happens) is provided.

3. Interface for an automatic control system

The RS485 interface of the GSG can be connected to a building bus through an additional interface, or to a PC. The telegrams on the EC-bus are directly transmitted to the RS485 interface, without any change of protocol.

4. Control of glazing transmission coefficient

The transmission coefficient of the glazing can be adjusted between 18 % (dark) and 64 % (clear).

5. Example: request short info from controller #2

1. De-activate cyclic sending:

Address	Command	Length	Data	Checksum
0	13	1	0	14

2. Wait answer from GSG:

Address	Command	Length	Data	Checksum
0	60	1	30	91

3. Request short info from controller #2:

Address	Command	Length	Data	Checksum

2	3	0	-	5

4. Answer controller #2:

Address	Command	Length	Data	Checksum
0	60	1	1	62

5. Re-activate cylic sending:

Address	Command	Length	Data	Checksum
0	13	1	1	15

6. Answer from GSG:

Address	Command	Length	Data	Checksum
0	60	1	31	92

8.3. Switching time curves table

Measurements were taken place with EC reported temperature at about 26°C.

8.3.1. From clear to tinted state

Time [min]	Tv EC [%]	Tv IGU [%]	SHGC [%]
0	64	50	38
1	58.8	46.3265	35.7613
2	53.2	42.1472	32.8584
3	48.2	38.4185	30.2567
4	43.7	35.0488	27.8736
5	39.7	32.0465	25.7265
6	36.1	29.32	23.7328
7	33	26.9777	22.0099
8	30.3	24.928	20.4752
9	28	23.1793	19.1461
10	26	21.64	17.94
11	24.3	20.3185	16.8743
12	23	19.3232	16.0664
13	21.9	18.4625	15.3337
14	21	17.7448	14.6936
15	20.3	17.1785	14.1635
16	19.8	16.772	13.7608
17	19.5	16.5337	13.5029
18	19.2	16.272	13.2072
19	19.1	16.1953	13.0911
20	19	16.112	12.972
21	18.9	16.0305	12.8673
22	18.8	15.9592	12.7944

23	18.7	15.9065	12.7707
24	18.5	15.7808	12.7136
25	18.3	15.6905	12.7405
26	18	15	12

8.3.2. From fully tinted to clear

Time [min]	**Tv EC [%]**	**Tv IGU [%]**	**SHGC [%]**
0	18.037	15	12
1	19.3517	16.379892	13.382
2	20.4476	17.465136	14.5168
3	21.5017	18.428884	15.4342
4	22.6622	19.419288	16.2866
5	24.0485	20.5557	17.1976
6	25.7512	21.928672	18.262
7	27.8321	23.599956	19.5458
8	30.3242	25.602504	21.0862
9	33.2317	27.940468	22.8916
10	36.53	30.5892	24.9416
11	40.1657	33.495252	27.187
12	44.0566	36.576376	29.5498
13	48.0917	39.721524	31.9232
14	52.1312	42.790848	34.1716
15	56.0065	45.6157	36.1306
16	59.5202	47.998632	37.607
17	62.4461	49.713396	37.9
18	64	50	38

8.4. Short survey questionnaire

Electrochromic Windows short survey (LESO, Office LE003)

Time required: ~ 10min

Part A: Background information

Date: ……………………………

Start time: …………………   End Time: …………………

A1. What is your gender?

○ Male

○ Female

A2. How old are you?

○ Under 30

○ 30-39

○ 40-49

○ 50-59

○ 60 and over

A3. Are you color blind?

○ No

○ Yes: Red/Green; Blue/Yellow (please underline one pair)

○ I am not sure

A4. On a scale from 1 to 5, how familiar you would say you are with the Electrochromic (EC) Windows applications in buildings? [1=Not at all, 5=Very familiar]

☐

Part B: Survey

1. During this session, what percentage of your time was spent on each of the following tasks:

   a. Reading (from paper) : %

   b. Computer: %

   c. Writing by hand: %

   d. Other: %, please specify: ………………………………………………………………

2. During this session, what percent of your time were you facing the following directions:

   a. Side wall : %

   b. Windows: %

   c. Back wall/Door: %

   e. Other: %, please specify: ………………………………………………………………

3. Please assign **a rating of 1,2,3,4 or 5** with **all** the following lighting/thermal conditions during the time you spent in the test office.

   a. Room Temperature [1=Too cold, 3=Just right, 5=Too hot]: ………

   b. Light level [1=Too dark, 3=Just right, 5=Too bright]: ………

   c. Light distribution [1=Very bad, 5=Excellent]: ………

   d. Room colours [1=Very unnatural, 5=Natural]: ………

   e. Colours when looking outside [1=Very unnatural, 5=Natural]: ………

   f. Glare sensation [1=None, 3=Acceptable, 5=Intolerable]: ………

4. Please **rate** with **1,2,3,4 or 5 your satisfaction** regarding **all** of the following aspects of the Electrochromic (EC) Windows during the time you spent in the test office. [1=Very Dissatisfied, 5=Very Satisfied]

   a. Ease of use of EC windows manual control panels: ………

   b. Time to switch to desired transmission level (lighten/darken): ………

   c. Other (Please specify):____ ………

5. During your stay in this office, did you use the blinds?

○ No

○ Yes, for the following reason(s): [Choose as many as appropriate]

- ☐ To deal with overheating issues
- ☐ To deal with glare issues
- ☐ To reduce illuminance levels
- ☐ EC windows were difficult to adjust to desired levels of light transmission
- ☐ EC windows took a lot of time to change their light transmission levels
- ☐ Privacy
- ☐ Other (Please specify):____

6. During your stay in this office, did you use the electric lighting?

○ No

○ Yes, for the following reason(s): [Choose as many as appropriate]

- ☐ To increase lighting level
- ☐ Other (Please specify):____

7. Regarding the natural light conditions, what did you appreciate during the time you spent working in this office? (e.g. you can compare with your usual workplace in LESO)

8. Regarding the natural light conditions, what did you not like during the time you spent working in this office? (e.g. you can compare with your usual workplace in LESO)

9. Please freely add below any additional remarks, comments or suggestions you may have regarding the time you spent working in this office.

   Also, in the view of a thorough survey we are planning for the future on the subject of users' satisfaction with an advanced automatic control system of Electrochromic Windows, you're also kindly asked to comment on the survey itself and help us improve the questionnaire and research protocol.