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Optimal control and performance of photovoltachromic switchable glazing for building integration in temperate climates

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HIGHLIGHTS

- The features and properties of photovoltachromic switchable glazing are presented.
- The different possible control strategies for the switchable glazing are presented.
- Thermal and daylight performance are co-simulated for rule-based and optimal control.
- A novel building performance simulation framework is developed for this aim.
- Switchable glazing performance is compared for different controls and climates.

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ABSTRACT

The development of adaptive building envelope technologies, and particularly of switchable glazing, can make significant contributions to decarbonisation targets. It is therefore essential to quantify their effect on building energy use and indoor environmental quality when integrated into buildings. The evaluation of their performance presents new challenges when compared to conventional "static" building envelope systems, as they require design and control aspects to be evaluated together, which are also mutually interrelated across thermal and visual physical domains.

This paper addresses these challenges by presenting a novel simulation framework for the performance evaluation of responsive building envelope technologies and, particularly, of switchable glazing. This is achieved by integrating a building energy simulation tool and a lighting simulation one, in a control optimisation framework to simulate advanced control of adaptive building envelopes. The performance of a photovoltachromic glazing is evaluated according to building energy use, Useful Daylight Illuminance, glare risk and load profile matching indicators for a sun oriented office building in different temperate climates. The original architecture of photovoltachromic cell provides an automatic control of its transparency as a function of incoming solar irradiance. However, to fully explore the building integration potential of photovoltachromic technology, different control strategies are evaluated, from passive and simple rule based controls, to optimised rule based and predictive controls.

The results show that the control strategy has a significant impact on the performance of the photovoltachromic switchable glazing, and of switchable glazing technologies in general. More specifically, simpler control strategies are generally unable to optimise contrasting requirements, while more advanced ones can increase energy saving potential without compromising visual comfort. In cooling dominated scenarios reactive control can be as effective as predictive for a switchable glazing, differently than heating dominated scenarios where predictive control strategies yield higher energy saving potential. Introducing glare as a control parameter can significantly decrease the energy efficiency of some control strategies, especially in heating dominated climates.

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Nomenclature

α	absorption coefficient (–)	Q	Load (kW/m^2)
ε	emissivity (–)	RBC	Rule Based Control
η	efficiency (–)	RHC	Receding Horizon Control
ρ	reflection coefficient (–)	SE	Site Energy (kW h/m^{2}y)
σ	standard deviation (–)	THM	Thermal History Management
τ	transmission coefficient (–)	U	Thermal transmittance (W/m^2 K)
τ_n	transmissivity (–)	UDI	Useful Daylight Illuminance (%)
ω	solid angle (sr)	WWR	Window to Wall Ratio (%)
CDD	Cooling Degree Day (°C)		
DGP	Discomfort Glare Probability (%)	*Subscripts*	
E	illuminance (lux)	h	horizontal
f_{load}	load profile matching index (%)	a	autonomous
f_{grid}	grid interaction index (%)	e	excess
g-value	total solar heat gain coefficient (–)	f	fell short
HDD	Heating Degree Day (°C)	s	supplementary
MPC	Model Predictive Control	t	time
NSE	Net Site Energy (kW h/m^{2}y)	sol	solar
P	Guth position index (–)	vis	visible
PVCC	Photovoltachromic cell	v	vertical (eye level)
PVC-G	Photovoltachromic glazing		

1. Introduction

The stringent CO_2 emission targets imposed on the building sector (more than 90% less CO2 emission compared to 1990 levels by 2050 [1,2]) has boosted the development of innovative technologies for reducing energy demand and lowering CO_2 emissions in buildings, while maintaining high level of indoor environmental quality [3], and improving the match between on-site renewable energy production and building energy use [4]. The building envelope plays a key role in regulating the heat and mass transfer between the outdoor and indoor environment. In particular, building envelope technologies that can modulate their thermo-optical properties and operating strategies according to transient boundary conditions and performance requirements could significantly improve the (i) energy efficiency, (ii) environmental quality, and (iii) energy flexibility of buildings [5–7]. These innovative technologies are commonly referred to as responsive or adaptive building envelope systems. Among these, adaptive (or so-called smart, intelligent, switchable, dynamic) glazing technologies have undergone significant developments in the last two decades [8]. The potential of adaptive glazing technologies to be exploited for building applications is due to their ability to modulate their thermo-optical properties in response to external *stimuli*, enabling the modulation of the amount of solar radiation entering the indoor environment. At a technological level this is achieved by reversibly controlling the thermo-optical properties of a chromogenic material between other functional layers (i.e. electrodes and glass layers) integrated into an insulated glazing unit [9]. By controlling an adaptive glazing, different objectives, i.e. privacy, view to the outside, visual comfort, thermal comfort, reduction of energy use, could be achieved either independently or simultaneously. In order to correctly respond to changing objectives, a smart glazing needs to be controlled accordingly [10], as an adaptive behaviour itself is not always leading to effective operations [11]. Besides the capability of switchable glazing technologies to actively manage the solar radiation entering the built environment, it is their control strategy that finally determines which performance objective is improved and to which extent.

1.1. Adaptive glazing control

The control of an adaptive glazing can be either a self-triggered mechanism, in which case the technology is said to have a passive or smart behaviour, or it can be triggered by an external *stimulus*, whereby the technology is said to be active or intelligent. Passive technologies include thermo-chromic TC [9], thermo-tropic TT [12,13] and photo-chromic PC glazing [14], in these technologies a change in the internal energy of the chromogenic layer triggers the variation of physical properties of the adaptive material/system. Active technologies such as electro-chromic EC, suspended particle devices SPD, and liquid crystal devices LCD, require a variation in the electrical potential to trigger a variation in thermo-optical properties of the chromogenic material [15].

During building operations, an adaptive glazing must meet multiple (and sometimes conflicting) performance requirements, across multiple physical domain, such as visual and thermal comfort, as well as energy efficiency related requirements. For example, glare risk can conflict with solar energy exploitation for heating purposes during the winter season or with increasing daylight availability. Designing and controlling an adaptive glazing (either in a smart/passive or intelligent/active way) for effective building operations is a non-trivial task. This is even more so, as design and control aspects are often mutually interrelated for adaptive systems because of the dynamic interactions between the adaptive material, the outdoor environment, the building services, the indoor environment and the building occupants [16]. The design of optimal control strategies for smart glazing technologies, and in general of adaptive building envelopes, according to their context of application is still a significant challenge, strongly influencing their building integration [17].

Most control strategies for switchable glazing found in literature adopt simple control rules based on: (a) work-plane illuminance [18–21]; (b) external illuminance [19,22]; (c) vertical solar irradiance [10,18,21–27] (with different threshold, 95 to 315 W/m^2 in [24]; 100 to 850 W/m^2 in [23] depending on the WWR and orientation; 150 W/m^2 in [26,27]; 189, 315 or 630 W/m^2 in [21] depending on the WWR; i.e. 200 W/m^2 in [10,22]; 250 W/m^2

in [25]; 350 W/m^2 [18,28]); (d) occupancy [10,18]; (e) occurrence of heating or cooling [10,21]; (f) room air temperature [22]; (g) outdoor air temperature [19]; (h) seasonal variation [19,29]. A small number of studies [18,28] tested more advanced control strategies, such as a proportional-integrative-derivative control based on work-plane illuminance and an adaptive neuro-fuzzy inference control system. The latter was based on work-plane illuminance, average window luminance, vertical solar irradiance and room temperature sensors, based on experiments in which the switchable glazing system was controlled by experts [28] or occupants [18].

Many researchers investigated few aspects (mainly related to energy performance) of the influence of the control strategies (either smart or intelligent) on the performance of adaptive glazing technologies. Only very few analysed the influence of control on both energy and visual comfort performance [23,24,30]. The performance of a system integrating adaptive materials is very sensitive on the control logic for facade adaptation during operation [5]. References [10,18,23,24,28,31] show how the switching settings of EC windows can dramatically change indoor comfort levels and energy use of buildings. For example, the authors in [18] tested different control logics based on indoor lighting levels, time-schedule control and more complex fuzzy logics under the same boundary conditions. Energy consumption variations resulted in considerable deviations of 24% for winter heating, 39% for summer cooling, 20% for winter electricity and 63% for summer electricity, depending on the control strategy. Warwick et al. [32] investigated the influence of switching parameters of a passive smart glazing, i.e. thermochromic, on energy use of an office building. They showed how the energy saving achieved in different climates, compared to a conventional "static" glazing, is highly dependent on the transition temperature triggering thermo-chromic bleaching phenomenon, and therefore high performance deviations are influenced by the control strategy of the passive glazing.

When multiple performance requirements need to be achieved the choice of the most effective control strategy is even more challenging, as one control strategy of the smart glazing could improve the energy performance while decreasing visual and/or thermal comfort. For example, Loonen et al. [30] showed the effect of different simple control strategies on multiple performance parameters of an innovative switchable glazing technology. As far as energy saving are concerned, a variation of 30% (+10% to −20%) is observed in the results for the same case study, while 40% and 70% deviations are observed in the results for daylight availability and thermal comfort, respectively.

The choice of the more appropriate control strategy for smart glazing building integration is of foremost importance when selecting between different building envelope alternatives to be integrated into a building at a design stage, or when optimising the design of a specific innovative adaptive glazing technology for multiple building scenarios. In these situations, building modelling and performance simulation can bring insights into the mutual influence between design and control aspects of switchable glazing, and can therefore strongly contribute to their integration into buildings and to the achievement of the afore-mentioned decarbonisation targets. However, current building energy simulation tools have restricted capabilities to simulate adaptive facades and adaptive glazing technologies [33]. In fact, they are not capable of evaluating the environmental performance of adaptive building envelope technologies across different physical domains. For example within a single building performance simulation (BPS) tool it is not possible to account for the mutual influence between thermal and daylight aspects on the control of a switchable glazing, due to absence of accurate daylight prediction modules [34] or to the inability of integrating advanced control of the adaptive glazing with the artificial lighting system. Moreover, with current BPS tools only simple dynamic façade operations can be modelled, while control strategies aiming to minimise total building loads or total energy use, cannot be evaluated.

For these reasons in order to evaluate the effect of innovative switchable glazing technologies and advanced operations some researchers either adopted different building performance simulation tools without realising a complete coupling [19], or developed reduced scale models [35], or adopted model simplifications within a single BPS tool [36]. Reduced scale models, although enabling the simulation of more advanced control strategies in the design phase [35] and their implementation during operations [37], are often limited in scope: most of the time a single thermal zone (or few of them) can be simulated; only one or few validated models of building technologies are integrated; only one physical domain is considered; complex heat, radiation and mass transfer phenomena are simplified [38]. While adopting model simplifications could invalidate the results of the analysis if a proper validation of the modelling approximations is not provided.

1.2. Research objectives and layout of the paper

The aim of this work is to present a novel simulation framework that can be used to evaluate the performance of innovative adaptive glazing technologies across multiple physical domains adopting optimised control strategies using current validated building performance simulation tools. The use of the novel simulation framework, which is developed on the basis of previous work [39], is demonstrated by evaluating the performance of an innovative switchable glazing technology that can be operated in a smart or intelligent way, namely PhotoVoltaChromic (PVC) glazing technology, integrated in the operating strategy of an office building in different climates. The focus of this paper is the comparison of different control strategies of the PVC glazing (from passive, to active and active optimised control). In particular, the simulation strategy is designed in such a way that it is possible to evaluate the highest performance achievable by means of an optimally controlled adaptive glazing according to multiple requirements. The performance of this optimally controlled switchable glazing could be used as a reference to evaluate effective operations in a smart/passive mode or with simpler control strategies.

In the second section of the paper the properties and control features of the PVC glazing technology are described. In the third section, the methodology for the performance assessment of different PVC operating strategies is detailed by describing: (a) the performance objective and indicators adopted; (b) the reference building models and climates of analysis and (c) the control strategies tested. In the fourth section, the integrated simulation strategy developed is detailed. In the remaining of the paper, the results from the evaluation are presented and discussed.

2. PVCC technology characteristics and operations

Photoelectrochromic cells (PECCs) [40], a special kind of self-powered switchable transparent functional layer for glazing integration, represent a very promising category of smart chromogenic devices. PECCs are generally photoelectrochemical cells consisting of two electrodes separated by a redox electrolyte. The photoanode is coated with a layer of dye-sensitized mesoporous TiO_2 (on a transparent conductive oxide), whereas a cathodic electrochromic material is deposited on the counter electrode (generally WO_3). Several architectures have been proposed for these devices, which are all characterized by a self-generated coloration process with no need of external voltage, which depends on the available irradiance [41–43]. Wu et al. [44] developed a novel device, namely a photovoltachromic cell (PVCC), composed of a patterned WO_3/Platinum

(Pt) electrochromic counter electrode and a dye-sensitized TiO_2 photoanode. For the first time they successfully integrated dye-sensitized solar cells (DSSCs) [45] and photoelectrochromic (PEC) technologies, within a unique multifunctional device. Nevertheless, this first demonstration of the PVCC did not permit the photovoltaic conversion to be managed separately from the chromogenic functionality. A complete separation was subsequently proposed by Cannavale et al. [46], for the two areas of the counter electrode, devoted to coloration (WO_3) and to photovoltaic conversion (Pt) respectively, realising a devices consisting of three electrodes [47]: a titania (TiO_2) photoelectrode, a platinum counter electrode and, on the same substrate of the latter, but electrically separated, a WO_3 electrode. With this design, adopted for the present work, three independent operation strategies are possible for the PVC cell: (a) in the so-called DSSC mode, only the Pt is connected to the photoanode via the external circuitry, with the device acting as a photovoltaic cell only; (b) in the PEC mode, the electrochromic portion of the counter electrode is connected to the photoanode and the whole amount of electrons generated by the photoanode is used to activate, autonomously, the adaptive modulation of visual and infrared transmittance (passive control); (c) in the Active mode, the modulation under sun irradiance (short circuit conditions) can be manually controlled by means of variable resistors in series, as reported by Yang et al. [48] (active control). When both of the afore-mentioned circuits are connected (Pt and TiO_2 circuit, WO_3 and TiO_2 circuit), the device is operating in the PVCC mode (passive control (b) and active control (c)), in which the cell shows a chromic transition and will also produce energy, when illuminated, to an extent corresponding to the available irradiance. The disadvantages of this version of the device is that the region covered by the Pt catalyst could not undergo a chromic modulation, and the uniformity and kinetics of the coloration process was affected by the distance from the platinum layer. In order to address this issue, a new PVCC architecture was developed by exploiting a full area bifunctional counter electrode [49], in which the catalytic and electrochromic regions are arranged to form an interdigitated array of micro-sized stripes, totally overlapped to a partially transparent dye-sensitized photoelectrode fabricated on the front-side glass of the "sandwich" device.

Table 1 summarizes the integral optical characteristics and the photovoltaic efficiency of the PVCC device adopted for the subsequent analysis, as experimentally characterized in [46], and the thermo-optical characteristics of the Double Glazing Unit integrating the PVCC. Fig. 1 shows the PVCC device in its most opaque (left, 1 Sun) and transparent state (right, 0 Sun), and Fig. 2 shows the spectral variation of the PVCC device transmittance function of perpendicular solar radiation (0 to 1 Sun).

3. Methodology

This paper quantifies the environmental performance of a building integrated Photo-Volta-Chromic Glazing (PVC-G) technology, adopting different advanced control strategies, by means of an innovative integrated simulation strategy. The methodology adopts building performance simulation to evaluate and compare different building performance indicators for several representative case studies. It follows the steps indicated by Loonen et al. [30], who mapped out the different fundamental stages for simulation based support for product development of adaptive building technologies. In particular, the resulting stages detailed in the following sub-sections are: (i) defining the performance objectives and indicators (Section 3.1); (ii) defining the test case models and the climates of analysis (Section 3.2); (iii) defining the variables in the parametric analysis (control, Section 3.3); (iv) elaborate an appropriate simulation strategy (Section 4); and (v) present and discuss the results (Section 5).

3.1. Performance objectives and indicators

The control of the PVC glazing can influence building performance in different ways. Modulating the amount of visible and total solar radiation entering in a space can reduce cooling energy use in summer and mid-season, and contribute to heating demand in winter. A low visible transmission of the most opaque state (cf. 1 SUN in Table 1) can prevent glare discomfort, while a high visible transmission of the most transparent state (cf. 0 SUN in Table 1) can enhance indoor daylight availability, reducing lighting energy use. Additionally, when renewable energy is produced on site by the PVC glazing, demand management strategies could be actuated. The solar energy entering through the glazing can be modulated to increase the portion of renewable energy that is used by the building, provided that the thermal comfort of occupants is always ensured by the heating, ventilation and air conditioning system.

The aim of this study is to quantify the capability of the PVC switchable glazing to improve the following building performance objectives by means of smart (passive) and intelligent (active) control strategies:

1. ***Low building energy use***. The **total specific yearly Site Energy (SE)** is used as performance indicator, measuring the total specific amount of energy which is delivered to the building[1], and used for heating, cooling and lighting purposes, as in Refs. [50,51];

$$\mathrm{SE} = E_{heating} + E_{cooling} + E_{lighting}\ [\mathrm{kW\,h/m^2\,y}] \tag{1}$$

2. ***High self-consumption of on-site renewable energy***. Different performance indicators are herewith adopted to quantify: (i) the amount of renewable energy offsetting the yearly energy consumption of the building, using the **Net total specific yearly Site Energy (NSE),** yearly difference between energy use and on-site harvested energy from renewable energy sources[2] (**$E_{PVC\text{-}G}$**); (ii) the yearly mean of the amount of renewable energy that is used by the building itself to offset, on an hourly basis, its energy use, and not exported to the electrical grid, using the **Load profile matching index (f_{load})**, a higher value indicates a higher self-consumption of on-site harvested renewable energy [4]; (iii) the yearly variation of the exported energy from the building to the electrical grid, **Grid interaction index (f_{grid})**, a higher value indicates a higher un-balance of the electrical grid introduced by the building energy use [4].

$$\mathrm{NSE} = E_{heating} + E_{cooling} + E_{lighting} + E_{PVC-G}\ [\mathrm{kW\,h/m^2\,y}] \tag{2}$$

$$\overline{f_{load}} = \frac{1}{8760}\sum_{i=1}^{8760}\left(\min\left(1, \frac{E_{PVC-G,i}}{\mathrm{SE}_i}\right)\right)\ [\%] \tag{3}$$

$$\sigma(f_{grid}) = \sqrt{\frac{1}{8760}\sum_{i=1}^{8760}\left[\left(\frac{\mathrm{NSE}_i}{\max|\mathrm{NSE}_i|}\right) - \frac{1}{8760}\sum_{i=1}^{8760}\left(\frac{\mathrm{NSE}_i}{\max|\mathrm{NSE}_i|}\right)\right]}\ [\%] \tag{4}$$

[1] The delivered energy (excluding site to source conversion factors) is adopted instead of the primary energy, as this is depending on the national context. But in order to sum together the different contributions to the SE, all the energy uses in the building are considered electric as described in Section 3.2.

[2] It is assumed that the solar energy transformed by the PVC-G (with the efficiencies detailed in Table 1), when actively controlled, is sold to the electrical energy grid, offsetting on a yearly basis the building energy use. 14% energy losses are assumed for the system converting and exchanging the electrical energy from the PVC-G to the electrical grid.

Table 1
Thermo-optical properties of (a) PVC Cell and (b) PVC-Glazing (adopting the PVCC as outer layer).

	(a) PVC Cell						(b) PVC Glazing[a]			
	τ_{sol} (–)	ρ_{sol} (–)	τ_{vis} (–)	ρ_{vis} (–)	$\varepsilon_{1,2}$ (–)	η_{PVC} (–)	τ_{VIS} (–)	g-value (–)	τ_n (–)	States
Bleached	0.499	0.074	0.658	0.080	0.84	–	0.595	0.508	0.6486	1
0.2 SUN	0.356	0.074	0.538	0.080	0.84	–	0.446	0.396	0.4863	2
0.4 SUN	0.267	0.074	0.377	0.080	0.84	4.30%	0.341	0.325	0.3719	3
0.7 SUN	0.169	0.074	0.281	0.080	0.84	4.90%	–	–	–	
1 SUN	0.156	0.074	0.263	0.080	0.84	4.13%	0.238	0.238	0.2596	4

[a] Double Glazing Unit thermo-optical properties: the DGU is composed of an external glass layer with the properties of the PVCC, 10 cm cavity filled with Argon, an internal glass layer Clear low-E (τ_{sol} = 0.782, ρ_{sol} = 0.066, τ_{vis} = 0.899, ρ_{vis} = 0.069, ε = 0.3). The *U*-value of the DGU is 2.0 W/m^2 K. 0.7 SUN state is not included in the control of the PVC-G in order to have equally spaced PVC-G states in terms of τvis/g-value intervals.

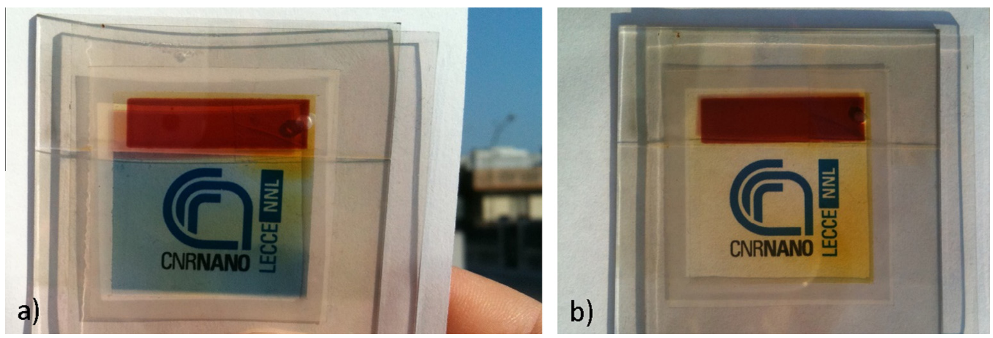

Fig. 1. Picture of PVCC in the opaque state (a. 1 SUN) and bleached state (b. 0 SUN).

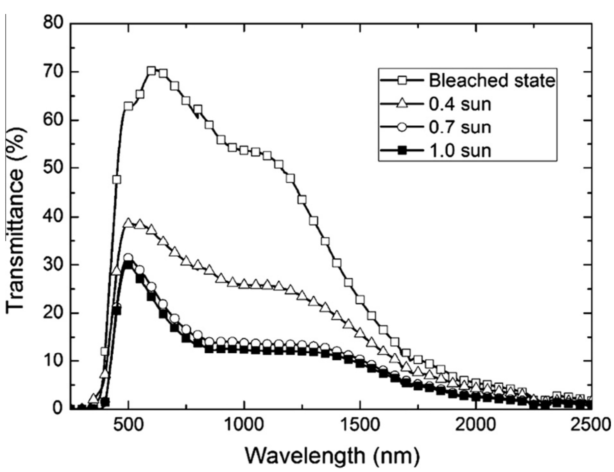

Fig. 2. τ versus wavelength for 300 nm PVCC thickness for different amount of perpendicular solar radiation.

3. ***High useful daylight availability in the indoor environment***. The **Useful Daylight Illuminance index (UDI)**, developed by Nabil and Mardalevic [52], is used to describe the percentage of time, throughout the year, the illuminance of a certain portion of space (Ill_X) falls between certain illuminance thresholds, derived from human comfort studies. In particular four classes are identified, in which the two classes positively contributing to reduce artificial lighting use and occupant discomfort at the same time are UDI_S (Supplementary artificial lighting is required, percentage of time 100 lux $\leqslant Ill_X <$ 320 lux) and UDI_A (Autonomous, sufficient daylight for visual comfort, percentage of time 320 lux $\leqslant Ill_X <$ 3000 lux). Values of Ill_X higher than 3000 lux increase the probability of occurrence of glare, and lower than 100 lux do not have a significant contribution to daylight comfort and are therefore not considered as having a positive effect on occupant visual comfort [53]. Therefore the indicator adopted for daylight availability is the sum of UDI_s and UDI_a:

$$UDI = UDI_S + UDI_A = \left.\frac{\sum_{i=1}^{8760} t(100 \leqslant E_H \leqslant 3000)}{\sum_{i=1}^{8760} i}\right|_{occupied} \quad [\%] \tag{5}$$

4. ***Low occurrence of glare discomfort***. The **Discomfort Glare Probability (DGP)** indicator is adopted [54] as it quantifies the probability of the occurrence of glare due to direct solar radiation and/or high contrast in the field of view. According to Mardaljevic et al. [53], three classes of environment can be defined according to the value of DGP: Class A, "imperceptible" glare (DGP < 0.35 for 95% of the occupied time); Class B, "perceptible" glare (DGP < 0.40 for 95% of the occupied time); Class C, "disturbing" (DGP < 0.45 for 95% of the occupied time). For this study only the percentage of time in the best class (Class A) is considered:

$$DGP = 5.87 \times 10^{-5} E_v + 9.18 \times 10^{-2} \log\left(1 + \sum_j \frac{L_{s,j}^2 \omega_{s,j}}{E_V^{1.87} P_j^2}\right) \quad [-] \tag{6}$$

$$DGP_A = \left.\frac{\sum_{i=1}^{8760} t(DGP \geqslant 0.35)}{\sum_{i=1}^{8760} i}\right|_{occupied} \quad [\%] \tag{7}$$

3.2. Test case models, climates and simulation parameters

The virtual test case building is an office room (4 m wide × 8 m deep × 3.5 m high), with a Window-to-Wall-Ratio of 60% on the sun-oriented façade (South for the Northern Hemisphere and North for the Southern one), which is showed in Fig. 3. The benchmark case test room adopts a building envelope with thermo-optical properties complying with the minimum require-

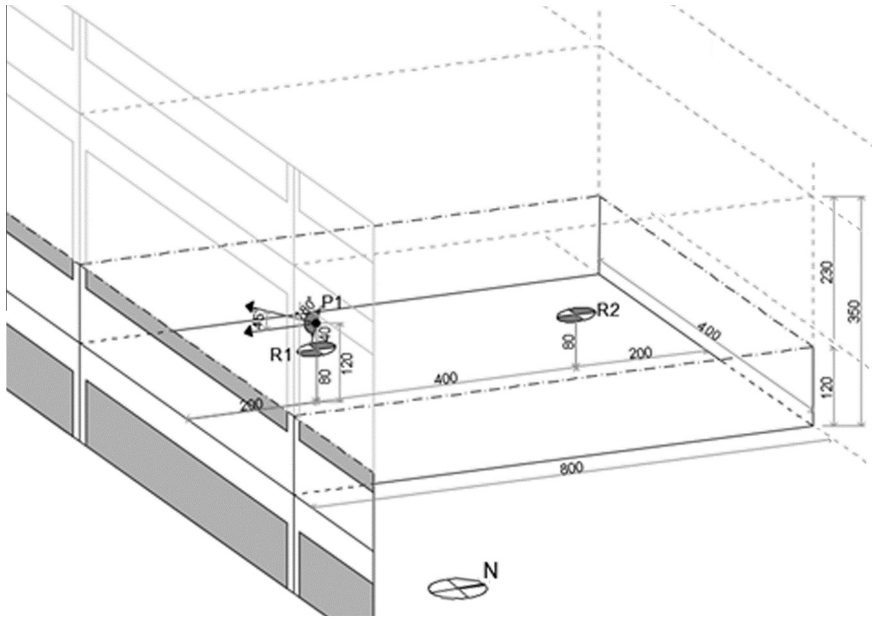

Fig. 3. Office test room model (measurements in cm).

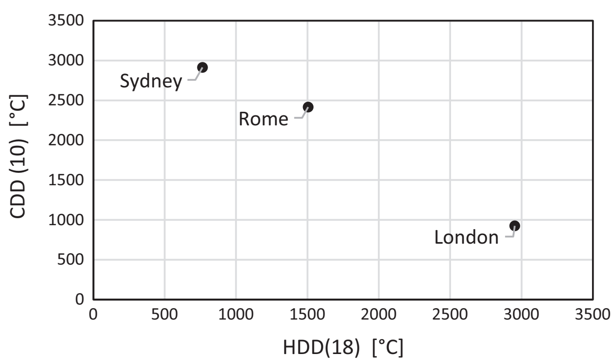

Fig. 4. HDD(18) and CDD(10) of the different temperate climate analysed, according to [58].

Table 3
Construction characteristics, calculated according to [83].

Construction	Unit	Curtain wall	Concrete slab
Internal thermal capacity[a]	(kJ/m^2 K)	21.7	67.8
External thermal capacity[a]	(kJ/m^2 K)	23.2	29.3
Superficial mass	(kg/m^2)	54	675
Time lag	(h)	1.63	10.61

[a] Valid for all partitions other than the ceiling, wherein the internal and external thermal capacity are inverted.

ments of local regulations [55–57]. Two different simulation models are built to evaluate the performance of the PVC-G, a thermal model and a daylight one, with identical characteristics. The performance of the benchmark office is compared with the one of the test room adopting the PVC-G with different operating strategies, as detailed in Section 3.3, and in different climates. In order to provide a full picture of the performance of the PVC-G technology in temperate climate scenarios, three different climates are analysed, i.e. in Sydney, Rome and London. The Heating Degree and Cooling Degree days are shown for the three locations in Fig. 4, according to the baseline of 18 and 10 respectively [58], and summarised in Table 2.

EnergyPlus version 8.3.3 is adopted for the thermal model and to perform the energy simulations [59]. The simulation algorithms in EnergyPlus have been chosen to achieve a balance between accuracy and a reasonable computational time of a single simulation run (solar calculations 15 days, conduction transfer function method with a 10-min time step, adaptive convection algorithm, initialization period 25 days).

The characteristics of the opaque and glazed parts of the façade meet the minimum requirements set in the national standards and are summarized in Table 2. The opaque portion of the façade is a typical curtain wall construction, while a concrete slab is adopted for the horizontal partitions (Table 3). As far as the transparent portion of the sun oriented façade a LowE Double Glazing Unit (DGU) is adopted (*U*-value of 2.0 W/m^2 K) with the thermo-optical properties described in Table 1 (PVC Glazing). The evaluation of the overall thermo-optical properties of the PVC DGU was performed using the software tool WINDOW 6.3 [60]. The test office room is flanked by identical offices on two sides on the same floor and on the floor immediately above and below, while the third side on the same floor is adjacent to a corridor space, with identical characteristics to the office rooms. Indoor comfort relative to the air temperature, ventilation and lighting requirements is always maintained within acceptable limits by a combination of PVC glazing control and the building services. The indoor

Table 2
Reference building data according to local building standards (Sydney [57], Rome [55], London [56]).

Climate	Köppen-Geiger classification	HDD(18) (°C)	CDD(10) (°C)	U_{wall} (W/m^2 K)	$U_{glazing}$ (W/m^2 K)	*g*-value (–)	τ_{vis} (–)
Sydney	Cfa	764	2912	0.36	2.00	cf. Table 4	cf. Table 4
Rome	Csa	1505	2415	0.29			
London	Cfb	2953	926	0.27			

comfort requirements are: indoor temperature set-points for heating and cooling (20 °C and 26 °C respectively) with a nocturnal set-back (12 °C and 40 °C respectively); primary air ventilation rate is set to 1.4 l/sm^2 when the office is occupied; threshold of 320 lux is considered for the minimum illumination level, as suggested by Mardaljevic et al. [53], to be maintained by a combination of daylight and dimmable artificial lighting system (at desk level, 0.8 m high, at 1.5, R1, and 3.5 m, R2, far from the façade). Schedules and peak loads for the building services, lighting, equipment and occupation are defined according to the ASHRAE standard 90.1 [61]. The lighting power density is set to 12.75 W/m^2, the equipment power density is 13.45 W/m^2, while the room is occupied by 2 people. A reversible heat pump is considered to provide heating and cooling to the office building, with an average seasonal COP of 3.5 for the winter and Seasonal Energy Efficiency Ratio of 2.5 for the summer. Given that all energy use (heating, cooling and lighting) and the energy harvested from renewable energy sources is electrical, no conversion to primary energy is done, and the site building energy is considered as a performance indicator, as described in Section 3.1.

In EnergyPlus the EMS tool [62] was adopted to model the adaptive behaviour of the PVC glazing according to different control strategies (cf. Sections 2 and 3.3). In particular the "Construction State" enables to vary the glazing thermo-optical properties according to a user designed control strategy, as described in [34].

EnergyPlus model can be considered validated as the software undergoes two major types of validation tests [63]: analytical tests, according to ASHRAE Research Projects 865 and 1052, and comparative tests, according to ANSI/ASHRAE 140 [64] and IEA SHC Task34/Annex43 BESTest method. Additionally, the use of the EMS "Construction State" actuator to simulate a switchable glazing was validated against experimental data and validated models in [65], and results showed that the error are comparable to validated glazing models as in [66].

Daysim 4.0 is adopted for the daylight simulations. It is a Radiance based simulation software and its validation is documented in Reinhart and Walkenhorst [67] and Tian et al. [34]. The latter concluded that, compared to experimental data, Radiance has a higher accuracy than EnergyPlus daylight module to predict the visual environment in a side-lit office with a controllable venetian blind in different sky conditions. In Daysim, 4 different models of the room equipped with the 4 different PVC glazing state detailed in Table 2 were defined and the results combined with the thermal analysis adopting the ad-hoc developed simulation strategy detailed in Section 4.

The materials' reflectivity adopted for the different building constructions are: 0.5 for walls and partitions, 0.8 for ceiling, 0.2 for floor and for the external ground. The transmissivity (i.e. transmission of the light at normal incidence) of a transparent material (τ_n) is calculated according to Eq. (8), as provided in [68], and it is detailed in Table 1 for the different glazing states. In the Daysim model a greyscale scene is generated and, therefore, materials' reflectivity and transmissivity assume the same values for red, green and blue bandwidths. Specularity and roughness of 0 are adopted for all opaque materials, as they are modelled as perfectly diffusive.

$$\tau_n = \frac{\left(\sqrt{0.8402528435 + 0.0072522239 \cdot \tau_{vis}^2}\right) - 0.9166530661}{0.0036261119 \cdot \tau_{vis}} \quad (8)$$

For the calculation of the UDI and the DGP the position of the desk and the occupants in the office room is considered. The UDI is calculated for the entire room averaging the values at the sensor positions R1 and R2 in Fig. 3. The DGP is calculated for point P1, with a wide view angle of 180°, directing to the South West direction (North West in the Southern hemisphere).

In order to provide a good accuracy of the daylight modelling results, the influence of the ambient bounces on the illuminance level at desk plane and on the DGP was investigated by means of a parametric study, based on which the following parameters were adopted for the daylight simulation: ambient bounces (-ab) of 5, ambient division (-ad) of 1024, ambient accuracy (-aa) of 0.1, ambient supersamples (-as) of 16 and ambient resolution (-ar) of 256, according to the definitions given in [69], as done by the authors in [70].

3.3. Control strategies

The performance of the PVC glazing is evaluated under different control strategies, the performance of two conventional "static" glazing (corresponding to the transparent and opaque state of the PVC glazing) are compared to the controlled ones (either in a passive/smart or active/intelligent way). These control strategies range from the simplest passive and Rule Based Control (RBC) to the more advanced predictive Receding Horizon Control strategies. The control time frame of the smart glazing is one hour, i.e. one control action can be performed on the actuator (PVC-G state between the four in Table 1) per hour.

3.3.1. Rule based and receding horizon control strategies

Rule Based Control (RBC) depicts a control strategy defined by a set of rules, which are based on measurement of the current and/or past states of the building system (i.e. incident solar radiation, difference between indoor and outdoor temperature, heating or cooling demand etc.). It relies on an external decision making system consisting of sensors, control algorithms and actuators. This is by far the most adopted control option in the market [37], and many studies used this kind of control to test the performance of smart glazing technologies and shading devices [10,19,20,30,71].

A Receding Horizon Control (RHC) strategy relies not only on the measurement of current and past states of the building system (temperatures, loads etc.), but on the prediction of the effect of the control action on future building states as well (i.e. energy use and/or indoor comfort levels over a certain evaluation period). In particular, RHC is a feedback non-linear control technique, which solves an optimization problem at each time step to determine the control sequence (sequence of optimal adaptive building envelope properties) over a certain time horizon (planning horizon), by minimizing a user defined cost function (i.e. building performance indicator) over a cost horizon. This comprises the planning horizon and a future time horizon (in respect to the planning horizon), which for adaptive façade control is required to predict and measure the effect of varying material properties at a certain time, on current and future building energy balance. In Fig. 5 the logic of RHC is represented: at time step "n" the control of the present and future time steps is optimised, therefore the effect of the control (i.e. energy use) is evaluated over the cost horizon (including the present time horizon and a prediction one). Once the optimised control is found, it is implemented at time-step "n" in sequence with previously optimised control (in the simulation and in Fig. 5 this is called pre-conditioning horizon, cf. Section 4), and the simulation/operation time is shifted one time step forward ("$n + 1$") together with the planning and cost horizons and the optimisation process is repeated.

RHC is also referred to as Model Predictive Control (MPC), as a model of the building is needed in order to make predictions and optimise the control. It is claimed that this control technique is well suited for optimising the control and the performance of nearly/net zero energy buildings [72]. Although the implementation

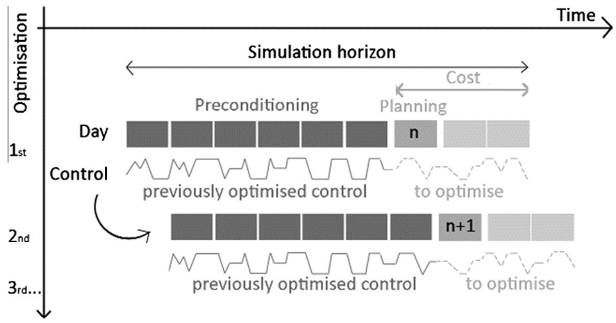

Fig. 5. Optimisation horizons management.

of RHC during actual building operations requires additional resources compared to RBC techniques, such as the adoption of a building model calibrated on the actual building controlled and forecasts of weather and endogenous loads. The operational performance of RHC depends on the forecasts accuracy (weather and endogenous loads) and on the method to account for it in the optimisation [73]. The most adopted RHC strategy on the market is currently "deterministic", in which the forecasts are assumed to have zero uncertainty. Deterministic RHC represents a performance bound (highest performance achievable) of an active/intelligent control, and could be used as a performance reference to: (i) measure the additional advantages of implementing a predictive control strategy compared to rule based ones for real-world facades; (ii) design a more advanced RBC strategy, not requiring on-line optimisation, which improves building performance beyond current simple RBC options [74,75].

The only study considering the effect of RHC on the control of adaptive facades, and specifically switchable glazing, is the one by Dussault et al. [35]. They adopt a reduced scale building model to perform control optimisation, which has the afore-mentioned limitations (cf. Section 1.1), and consider only the effect of the control of the switchable glazing on the thermal domain (heating and cooling energy use), while neglecting the effect on lighting energy use, occupant visual comfort, and the mutual influence between visual comfort and energy use.

3.3.2. Control strategies for the PVC switchable glazing

Nine different reference, rule based (passive and active) and optimised (active) control options are evaluated, which are described below: two reference controls, adopting two conventional static glazing (R1 and R4); one passive control strategy (3); one active RBC (Rule Based Control, cf. Section 3.3.1) based on glare discomfort reduction (4); two optimised RBC strategies (5 and 6); three RHC (Receding Horizon Control, cf. Section 3.3.1) strategies (7, 8 and 9). The implementation of control options 5 to 9, where the solution of an optimisation problem is required, cannot be done in the current version of the BPS tools adopted, but it was enabled by the simulation framework presented in Section 4. In order to illustrate the different objective functions optimised for control options 5 to 9, a typical load curve of the office room adopting the PVC-G, for a typical summer day in Sydney (2nd January, R1 glazing configuration) is shown in Fig. 6, this represents the total building loads SE_{total}/dt (sum of heating, cooling and lighting), the converted solar power E_{PVCG}/dt and the net total building load NSE/dt (difference between building loads and converted solar power).

R1. and R4. Reference 1 and 4: the DGU adopts a conventional static glazing with the thermo-optical properties of the PVC-G most transparent (cf. Table 1, state 1, Bleached) and most opaque state respectively (cf. Table 1, state 4, 1 SUN). In this design option the PVC-G is not controlled (either passively or actively), but only one state of the glazing is adopted for the whole simulation. These two control options represent two reference conventional static glazing cases. It has to be highlighted that the conventional glazing corresponding to the PVC-G with control R1 (most transparent state) and R4 (most opaque state) are compliant with the national building regulation in the climate of Rome [55] and London [56], while only control R4 (most opaque state) is compliant with the local regulation in the climatic context of Sydney for a sun oriented office with 60% WWR [57].

3. **RBC – Passive:** the PVGC is controlled in a passive/smart manner, i.e. the darkening of the glazing is proportional to the amount of incident solar radiation as shown in Table 1. This control option would be the simplest one, as it does not require any sensor or actuator. Similarly to this control case, most of the

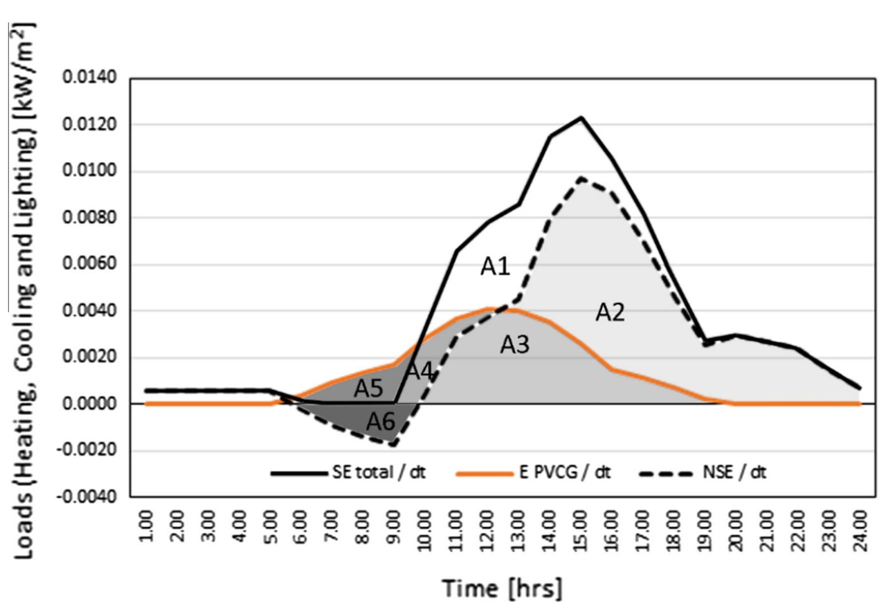

Fig. 6. Total specific daily loads (heating, cooling and lighting) of the office room with PVC glazing.

studies available in literature [10,18,23,24,28,30] adopt an active/intelligent control which is based on the amount of perpendicular solar radiation on the façade, therefore control option 3 can be considered a particular case of active control as well based on the incident solar radiation on the glazing.

4. **RBC – Glare A:** the PVGC is controlled actively to maintain an acceptable visual comfort level for the occupants at all times, in particular the glazing always assume the clearest state which is ensuring a glare class A [76].
5. **RBC – Opt Hourly:** the PVGC adopts a state, at 1-h intervals, which minimizes the total building loads (sum of heating, cooling and lighting loads). This control option is the best performance achievable by means of a RBC controller aiming at minimizing energy use based on current and past measurements. In order to implement this controller an optimisation problem needs to be solved for each hour of the simulation. The algorithm implemented in the controller to evaluate the optimal PVC-G state minimizing the total building loads (SE_{total}/dt in Fig. 6) is as follows:

$$\min\begin{cases} f(X) = \dot{Q} = \dot{Q}_{heat} + \dot{Q}_{cool} + \dot{Q}_{ligh}\ \left[\frac{\text{kW}}{\text{m}^2\ \text{y}}\right] & \text{(a)} \\ X(t) = (g\text{-value}(t)\ [-],\ \tau_{vis}(t)\ [-]) & \text{(b)} \end{cases} \quad (9)$$

6. **RBC – Glare A – Opt Hourly:** a constraint on the DGP is introduced in control 5, to ensure an acceptable glare discomfort probability (level A) and to simultaneously minimise the total building loads. The comparison with control 5 quantify the influence of glare risk on the energy saving performance of the PVC-G RBC strategy. The algorithm implemented in the controller to evaluate the PVC-G state is as follows:

$$\min\begin{cases} \textit{if}\ \text{DGP} < 0.35,\ f(X) = \dot{Q} = \dot{Q}_{heat} + \dot{Q}_{cool} + \dot{Q}_{ligh}\ \left[\frac{\text{kW}}{\text{m}^2\ \text{y}}\right] & \text{(c)} \\ \textit{if}\ \text{DGP} \geqslant 0.35,\ f(X) = \dot{Q} + Z = \dot{Q} + \frac{\text{DGP}_i}{\text{Glare A}}\ \left[\frac{\text{kW h}}{\text{m}^2\ \text{y}}\right] & \text{(d)} \\ X(t) = (g\text{-value}(t)\ [-],\ \tau_{vis}(t)\ [-]) & \text{(b)} \end{cases} \quad (10)$$

7. **RHC:** the PVC-G is actively controlled such that the sequence of PVC-G states minimizes the total site energy use of the building over a certain time horizon. In particular, the purpose of RHC control is to minimise the total area A1 + A2 + A3 + A4 below the load curve SE_{total}/dt in Fig. 6, which represents the site total building energy use for a certain day. The implementation of this controller relies on the solution of the following optimisation problem:

$$\min\begin{cases} f(X) = \text{SE} = \text{SE}_{heat} + \text{SE}_{cool} + \text{SE}_{ligh}\ \left[\frac{\text{kW h}}{\text{m}^2\ \text{y}}\right] & \text{(e)} \\ X(t) = (g\text{-value}(t)\ [-],\ \tau_{vis}(t)\ [-]) & \text{(b)} \end{cases} \quad (11)$$

8. **RHC – Glare A:** the PVC-G is controlled according to the RHC strategy, with the additional constraint that the PVC-G state adopted must produce a DGP lower than 0.35, whenever possible. The difference between RHC and RHC – Glare A strategies assess whether the objective of reducing glare discomfort affects energy efficiency of an optimally active controlled smart glazing in an office environment. The optimisation problem in Eq. (11) can be re-formulated as follows to include the glare constraint:

$$\min\begin{cases} \textit{if}\ \text{DGP} \leqslant 0.35,\ f(X) = \text{SE} = \text{SE}_{heat} + \text{SE}_{cool} + \text{SE}_{ligh}\ \left[\frac{\text{kW h}}{\text{m}^2\ \text{y}}\right] & \text{(f)} \\ \textit{if}\ \text{DGP} > 0.35,\ f(X) = \text{SE} + Z = \text{SE} + \frac{\sum_{i=1}^{t}\text{DGP}_i}{\text{Glare A}}\ \left[\frac{\text{kW h}}{\text{m}^2\ \text{y}}\right] & \text{(g)} \\ X(t) = (g\text{-value}(t)\ [-],\ \tau_{vis}(t)\ [-]) & \text{(b)} \end{cases} \quad (12)$$

9. **RHC – Glare A – NSE:** the PVC-G is controlled according to the RHC – Glare A strategy, with the only difference that the objective function is the net total specific yearly site energy, NSE, (difference between site energy, SE, and PVC-G solar harvested energy, $E_{\text{PVC-G}}$) over the cost horizon. This control strategy aims to improving self-consumption of renewable energy transformed on site by means of the PVC glazing (cf. Section 2, Table 1 and Section 3.1), without increasing the energy use of the building. In particular it aims to minimise the total area A2 + A3 + A6 below the load curve NSE_{total}/dt in Fig. 6. No difference between control strategies 8 and 9 indicates that the area A5 (=A6) is zero, which means that either insufficient energy is transformed on site to be exported or that shifting environmental loads to promote self-consumption is not effective to improve energy efficiency. The optimisation problem in Eq. (12) can be re-written as:

$$\min\begin{cases} \textit{if}\ \text{DGP} \leqslant 0.35,\ f(X) = \text{NSE} = \text{SE} - E_{PV}\ \left[\frac{\text{kW h}}{\text{m}^2\ \text{y}}\right] & \text{(h)} \\ \textit{if}\ \text{DGP} > 0.35,\ f(X) = \text{NSE} + Z = \text{NSE} + \frac{\sum_{i=1}^{t}\text{DGP}_i}{\text{Glare A}}\ \left[\frac{\text{kW h}}{\text{m}^2\ \text{y}}\right] & \text{(i)} \\ X(t) = (g\text{-value}(t)\ [-],\ \tau_{vis}(t)[-]) & \text{(b)} \end{cases} \quad (13)$$

4. Integrated simulation strategy

Performance evaluation of adaptive building envelope technologies is a non-trivial task for multiple reasons including [33]: (a) unavailability of models for innovative and non-established adaptive; (b) modelling the dynamic operation of adaptive material/system adaptation integrated with building services; and (c) co-simulating interrelated physical domain [77]. In the present case, all the above mentioned challenges are present: (a) unavailability of PVC material model enabling modulation of thermo-optical properties proportionally to incident solar radiation; (b) unavailability of advanced control strategies for adaptive building envelope technologies, such as optimised RBC and RHC, which can enable the evaluation of the maximum performance achievable by means of the actively controlled switchable glazing, requiring optimisation during simulation run-time; (c) requirements for co-simulation of thermal and visual physical domains, as the control of the PVC switchable glazing not only influences both energy efficiency and visual comfort objectives, but the control in the thermal domain is influenced by the results of the visual one [78].

These functionalities, which are required to simulate the behaviour of the PVC glazing, and in general of other switchable glazing and adaptive facades, could not be achieved with a single BPS tool, as assessed by the authors in [33]. For these reasons, a novel simulation strategy was designed to evaluate the PVC glazing performance, which can be easily extended to the evaluation of other adaptive building envelope technologies, for example shading devices, adaptive insulation, double skin façade and others. This simulation strategy was adapted from previous work carried out to evaluate the optimal thermo-optical properties of an ideal adaptive glazing and its energy saving potential [39]. Compared to [39] the features implemented in the present simulation framework are the co-simulation between thermal and visual physical domain, the possibility to optimise the control of the switchable glazing on an hourly basis according to difference performance requirements, the integration of the control of the smart glazing with the artificial lighting system in EnergyPlus.

4.1. Overall architecture and functionalities

The novel simulation strategy integrates multiple levels/software: a coordination layer/software, an optimisation layer/software, and one evaluation layer/software (one or more BPS tools on which the evaluations are based on). The overall architecture and tasks of the simulation strategy are summarised in Fig. 7 (from bottom to top): (a) EnergyPlus [59] and the Radiance-based

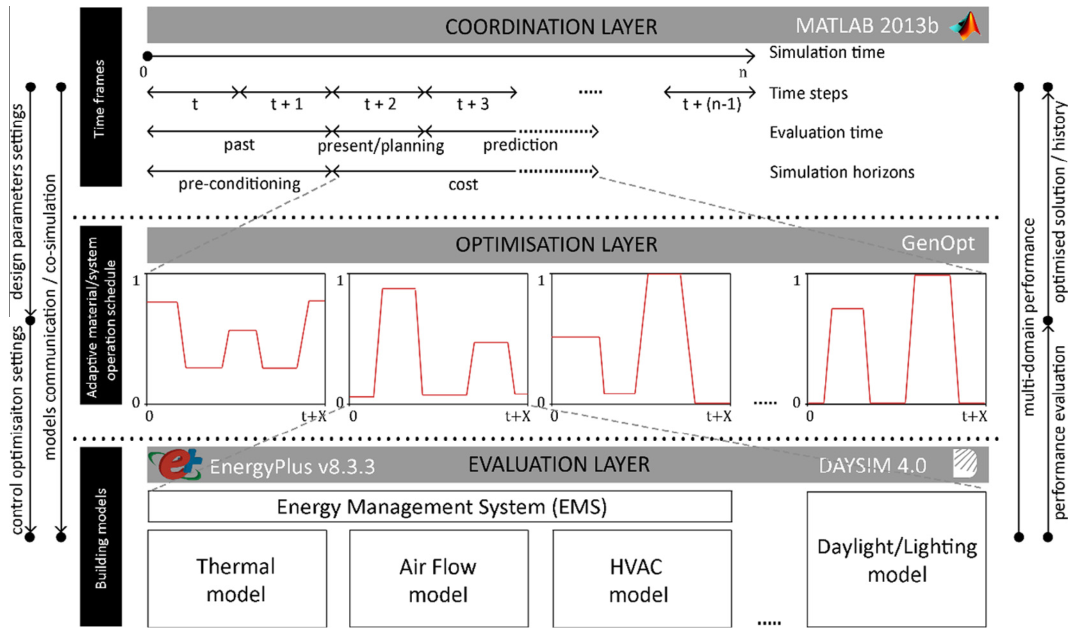

Fig. 7. Integrated simulation strategy architecture enabling multi-domain and advanced control building performance evaluation.

daylight simulation tool Daysim [79] are adopted in the evaluation layer for calculating building performance indicators (e.g. SE, NSE, UDI, DGP, cf. Section 3.1); (b) GenOpt [80] is adopted in the optimisation layer if there is a need to optimise the control sequence of adaptive thermo-optical properties, minimising the cost functions described in Section 3.3; (c) Matlab is adopted as coordination layer to manage the simulation runtime, the time horizons of the optimisation layer and the exchange of information between the different building models (thermal and daylight).

The evaluation layer based on EnergyPlus is capable of simulating different dynamic materials and technologies, by means of the embedded Energy Management System (EMS) [62]. This is employed for the following tasks: (a) varying the thermo-optical properties of the switchable glazing (or of the adaptive façade in general) during simulation runtime according to a pre-determined control strategy; (b) computing the variables used for building services integration (i.e. illuminance levels and glare according to predefined control) from EnergyPlus outputs or from importable look-up tables (results from Daysim); (c) controlling the building services and the artificial lighting system, according to the control of the adaptive façade, to maintain the required indoor comfort conditions (i.e. constant illuminance on a certain surface, glare free environment, indoor temperatures within human comfort limits, etc.); (d) computing the objective functions and the constraints used by the optimisation layer from EnergyPlus outputs (i.e. NE, NSE, UDI, DGP etc., cf. Section 3.1); (e) enabling the update of the thermal history of the building system (state update) according to previous control actions performed by the adaptive façade. The Thermal History Management (THM) method is adapted from [38] for task (e) within the EMS, this is required to set the initial boundary conditions of the building for each optimisation horizon, according to the ending boundary conditions of the previous optimisation (state update). Because explicit state update in EnergyPlus is not possible by means of this method, before each control optimisation, the building is re-simulated for a certain period (pre-conditioning horizon in Fig. 5), preceding the current optimisation horizon (cost horizon). In the pre-conditioning horizon the adaptive façade (PVC glazing in this case) is controlled according to the previously optimised control strategy, until the beginning of the planning horizon of the specific optimisation.

In the optimisation layer, based on GenOpt [80], different optimisation algorithms are available including Generalised Pattern Search (GPS), Particle Swarm Optimisation (PSO) [80], Genetic Algorithms (GA), and hybrid optimisation algorithms (GA + GPS, PSO + GPS). The hybrid optimisation algorithm (GPSPSOCCHJ) was adopted for the optimisation [80], as it offers the best trade-off between computational time and optimality of the results when compared with alternative algorithms. In fact it couples a global stochastic population-based optimisation algorithm (PSOCC) with a local one (GPSHJ), ensuring that a result close to the global minimum is found with the first algorithm, which is then improved by the local search [81]. Optimisation parameters were adopted according to the optimal value suggested by GenOpt manual [80] and according to a parametric evaluation on the effect of optimisation parameters on the optimality of the solution and on computational efficiency (population size of 150 individuals, 10 generations, 8000 maximum iterations).

In the coordination layer, performed by MATLAB [82], the inputs of the optimisation and evaluation layers are defined. These include: building envelope adaptive properties; their modulation ranges and modulation time (thermo-optical properties of the PVC-G); the definition of the cost functions to be optimised; the length of the planning, cost and pre-conditioning horizons; the optimisation algorithm and optimisation parameters; the seeding strategy for the optimisation, whereas known solutions (i.e. simpler control strategies or previously optimised controls) are introduced in the initial population for the optimisation.

4.2. Simulation workflow

The simulation process of the bespoke tool is shown in Fig. 8. Continuous arrows indicate the model/input flow, while dashed arrows indicate results/outputs flow between the layers. In this simulation framework, in order to simulate controls in which the solution of an optimisation problem is required (control option 5. to 9.), two simulation loops are performed: an inner one, control optimisation loop (cf. Table 4, points (C) to (G)), and an outer one, simulation and time management loop (cf. Table 4, points (C) to (J)). In the inner loop, involving the optimisation and evaluation layers, the control strategy for the adaptive material/

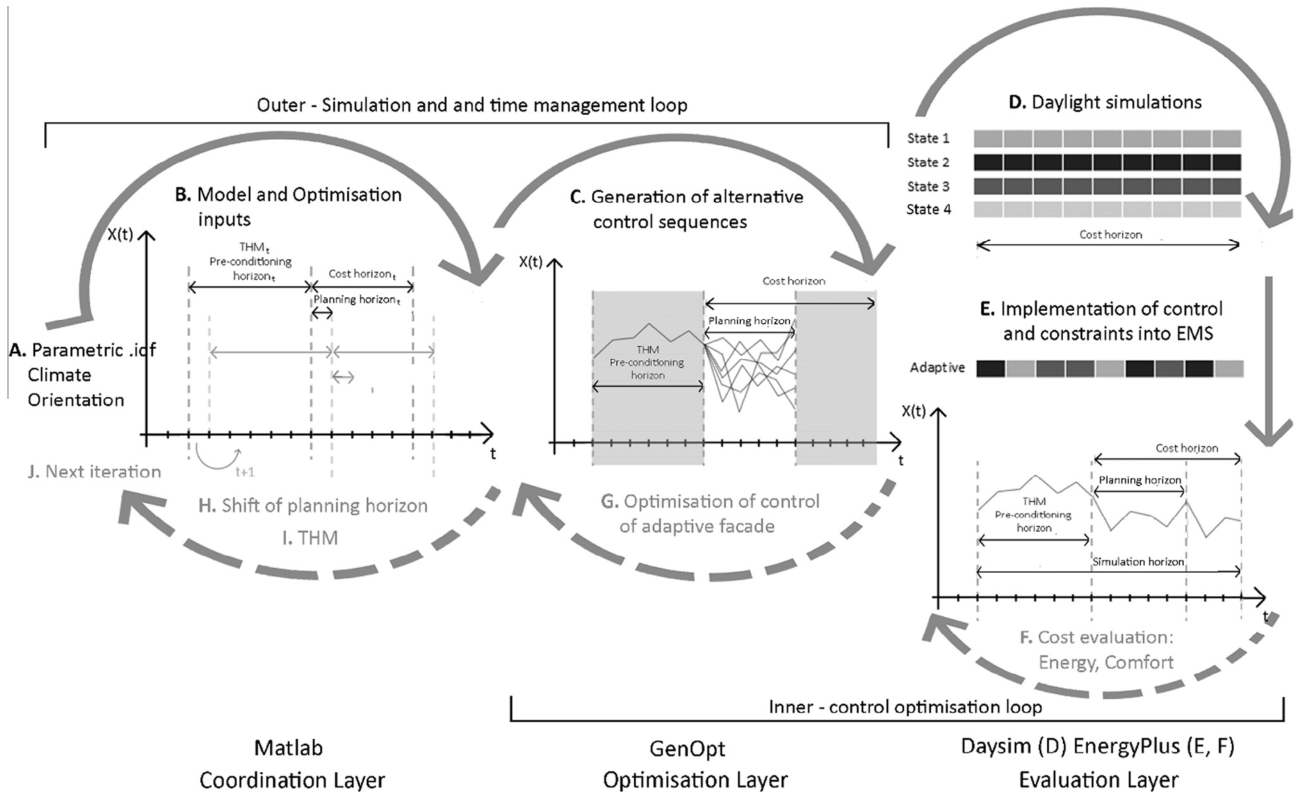

Fig. 8. Simulation strategy workflow: the arrows represents the flow of inputs/models (continuous line) and of outputs/results (dashed line).

technology is optimised for a user-defined cost horizon. The outer loop is used to shift the cost horizon and the simulation forward in time (of one control step, 1 h in this case), re-simulating previous optimised control and coordinating the results from different building models. A step forward in the outer loop is not performed until the inner optimisation loop for the specific cost horizon is completed. In particular for control options 5. and 6. (RBC strategies) planning and cost horizon coincide (i.e. 1 h, cf. Fig. 5), while for control options 7., 8. and 9. (RHC strategies) a planning horizon of 1 day and a cost horizon of 3 days are considered, in order to account for building dynamics (time constant of the building system, weekend occupation and variable set-points), as suggested

Table 4
Workflow of the simulation with the novel simulation framework (cf. Fig. 8).

Non automated simulation process		
		(A) Two parametric building models (i.e. EnergyPlus and Radiance models) with variable orientation, climate, WWR, material properties and control strategy are created
		(B) The coordination layer (Matlab) is used to set the different parameters of the models, the simulation and optimisation parameters and to start the simulation from the user-defined starting date
Automated simulation process		
Simulation and time management loop (outer loop, (C) to (J))	Control optimisation loop (inner loop, (C) to (G))	(C) The parametric models and the seeds for the optimisation algorithm are automatically fed to the optimisation layer (GenOpt), which generates alternative control sequences for the adaptive properties of the façade to be evaluated for the first cost horizon
		(D) Independent Radiance simulations are performed for the length of the cost horizon for each possible adaptive façade configuration, the results are post processed and stored by the coordination layer to provide useful metrics and schedules to EnergyPlus
		(E) Each specific control sequence for the adaptive façade system (from the optimisation layer) and the post-processed results, schedules and constraints (from the complementary BPS tool, Radiance) are implemented into the EMS system of EnergyPlus. In particular the EMS will manage the results of the daylight evaluations, the schedules and the constraints according to the control sequence generated by the optimisation layer
		(F) An evaluation is performed for the specific cost horizon in EnergyPlus, and the user-defined objective functions are computed in the EMS based on outputs from the models (i.e. EnergyPlus and Radiance)
		(G) The results from each evaluation are returned to the optimisation layer in an iterative way until convergence of the optimisation is reached for that specific cost horizon, enabling the optimisation layer to define the optimal control strategy, sequence of optimal adaptive façade properties. At this point the inner control optimisation loop is completed and the results stored and passed to the coordination layer
		(H) The simulation time is shifted forward in time by the coordination layer, for a period equal to a control time-step
		(I) THM simulation is performed in the thermal evaluation layer (EnergyPlus), this simulation is performed adopting the optimised control sequence found in (G) for the precedent control optimisation time frames, for the duration of the pre-conditioning horizon
		(J) steps (C) to (I) are repeated until the optimisation horizon reaches the end of the simulation period, defined by the user in point B, and finally all yearly building performance results are returned, post-processed and stored

by Corbin et al. [38]. The length of the pre-conditioning horizon was set to one month in order to minimise the effect of the adaptive façade control on the first day of the optimisation. For the remaining control options (3. and 4.) the evaluation can be carried out by means of the sole evaluation layer (using both EnergyPlus and Radiance), as no optimisation is required.

The first part of the simulation workflow, (A) and (B) in Fig. 8, is performed at the beginning of the simulation only, as it requires one or more models (depending on the co-simulation requirements) to be built in each BPS tool and the definition of the optimisation and simulation parameters. While the second part, steps (C) to (L), consisting of the two simulation loops afore-mentioned, is iterative and automated and it is performed until the end of the user-defined simulation period is reached. The steps of the simulation workflow are summarized in Table 4 and are represented in Fig. 8.

Parallel computing was enabled for the simulation in EnergyPlus and Daysim to reduce the computational time. Each yearly simulation run takes approximately 48 h (8 to 10 min to simulate/optimise each day of the simulation, in the inner control optimisation loop, repeated 365 times), with 64 parallel evaluation processes, running on a 2.5 GHz clock per processor, with 192 GB RAM.

5. Results

5.1. Influence of PVC switchable glazing control on building performance

The performance of the PVC glazing in the sun-oriented office reference room, according to the performance indicators (listed in Section 3.1) is significantly sensitive to the control strategy adopted and to the climatic zone. The results from the simulations are presented in form of tables and figures for each climate: Fig. 9 and Table 5 for Sydney, Fig. 10 and Table 6 for Rome and Fig. 11 and Table 7 for London. In each Table and Figure the different control alternatives are identified by a letter indicating the climate (S. for Sydney, R. for Rome and L. for London) and one number indicating the control strategy according to Section 3.3.2 (from R1 and R4, to 9).

In Sydney both yearly energy use and visual comfort are highly sensitive to the characteristics of the transparent portion of the façade. In such a climate zone, if a conventional glazing is adopted, the less transparent the glazing is, the higher the building performance. In fact if a conventional glazing corresponding to the darkest state of the PVC-G is adopted throughout the year compared to the most transparent one (R4 compared to R1, in Fig. 9 and Table 5), Site Energy (SE) is decreased by nearly 60% (cooling energy use halves its value); useful daylight availability (UDI) increases by 11% and probability of glare discomfort (DGP_A) decreases from 22% to 0%, due to the lower magnitude of horizontal illuminance in the working space during the occupied period. A passive/smart control of the PVC-G according to incident solar radiation (cf. S.3, Fig. 9) increases the useful daylight availability and reduces glare discomfort (only 6%), to the expenses of Site Energy use (SE, +5% compared to R4). In contrast a control based on glare reduction (S.4), although reducing to the lowest extent glare discomfort, it increases energy use accordingly. The adoption of optimised rule based control, which minimizes building loads (cf. S.5 and S.6, Fig. 9 and Table 5), can improve the energy saving achievable by controlling the PVC-G in an intelligent/active way, without compromising glare discomfort and daylight availability. If the control strategy is designed to minimise total building energy use, predictive control strategies (S.7 to S.8, Fig. 9 and Table 5), 5% energy use reduction can be achieved compared to the best static solution (S.R4) (mainly in heating and lighting energy use), UDI is maximised and glare discomfort can be reduced to imperceptible (<0.35) at all times.

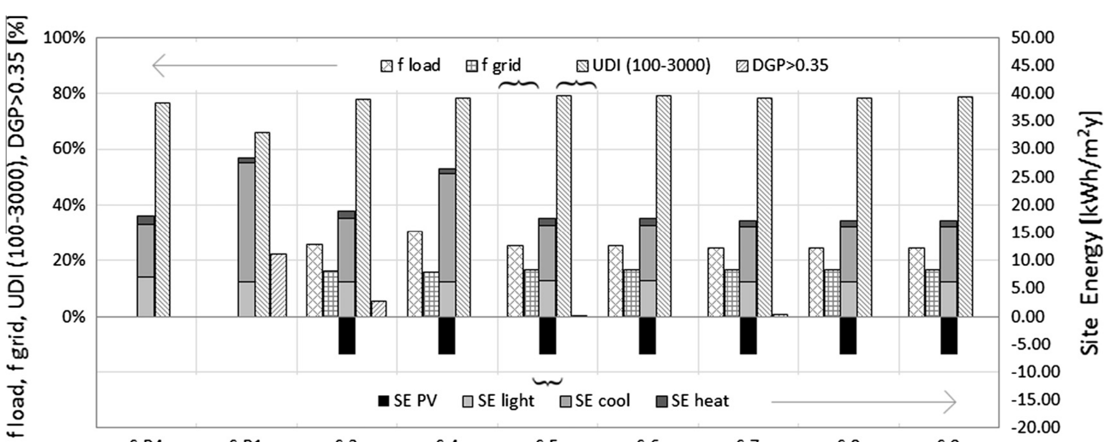

Fig. 9. Performance of North oriented office building equipped with the PVC glazing, in Sydney climate.

Table 5
Performance of North oriented office building equipped with the PVC glazing, in Sydney climate.

#	SE heat (kW h/m^2 y)	SE cool (kW h/m^2 y)	SE light (kW h/m^2 y)	SE (kW h/m^2 y)	SE PV (kW h/m^2 y)	NSE (kW h/m^2 y)	f_{load} (%)	$\sigma(f_{grid})$ (%)	UDI (%)	DGP_A (%)
S.R4	1.54	9.29	7.14	17.98	0	17.98			77	0
S.R1	0.84	21.42	6.10	28.37	0	28.37			66	22
S.3	1.30	11.49	6.10	18.89	−6.82	5.26	26	16	78	6
S.4	0.85	19.51	6.10	26.46	−6.82	12.83	31	16	78	0
S.5	1.25	9.93	6.44	17.63	−6.82	4.00	25	17	79	0
S.6	1.25	9.93	6.44	17.63	−6.82	3.99	25	17	79	0
S.7	1.13	9.85	6.18	17.16	−6.82	3.53	24	17	78	1
S.8	1.13	9.85	6.18	17.16	−6.82	3.53	24	17	78	0
S.9	1.13	9.85	6.18	17.16	−6.82	3.53	25	17	79	0

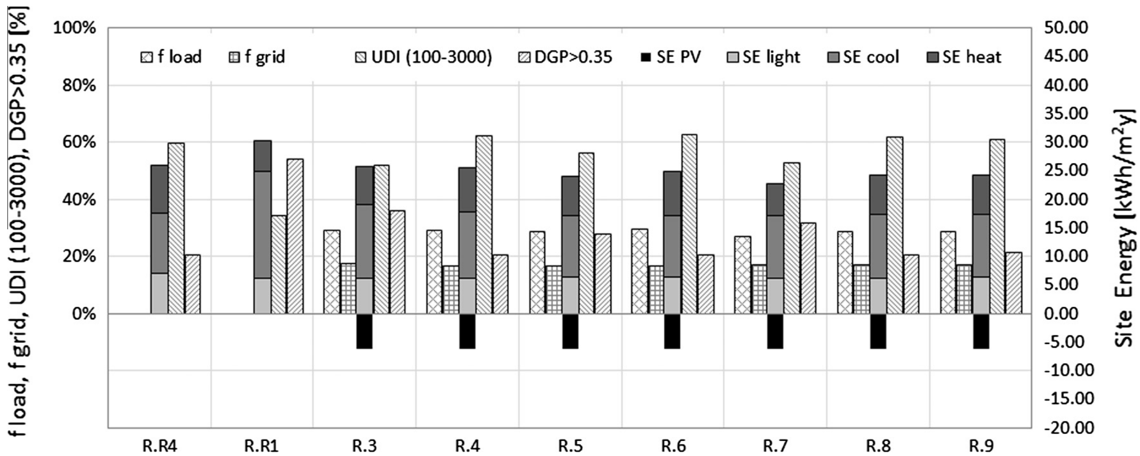

Fig. 10. Performance of South oriented office building equipped with the PVC glazing, in Rome climate.

Table 6
Performance of South oriented office building equipped with the PVC glazing, in Rome climate.

#	SE heat (kW h/m^2 y)	SE cool (kW h/m^2 y)	SE light (kW h/m^2 y)	SE (kW h/m^2 y)	SE PV (kW h/m^2 y)	NSE (kW h/m^2 y)	f_{load} (%)	$\sigma(f_{grid})$ (%)	UDI (%)	DGP$_A$ (%)
R.R4	8.24	10.58	7.07	25.89	0	25.89			60	21
R.R1	5.32	18.78	6.12	30.22	0	30.22			34	54
R.3	6.81	12.86	6.17	25.84	−6.37	13.09	29	18	52	36
R.4	7.82	11.60	6.12	25.55	−6.37	12.80	29	17	62	21
R.5	6.75	10.86	6.36	23.97	−6.37	11.22	29	17	56	28
R.6	7.88	10.76	6.36	25.01	−6.37	12.26	29	17	63	21
R.7	5.74	10.87	6.18	22.80	−6.37	10.05	27	17	53	32
R.8	6.89	11.06	6.21	24.15	−6.37	11.40	29	17	62	21
R.9	6.91	10.92	6.36	24.19	−6.37	11.44	29	17	61	21

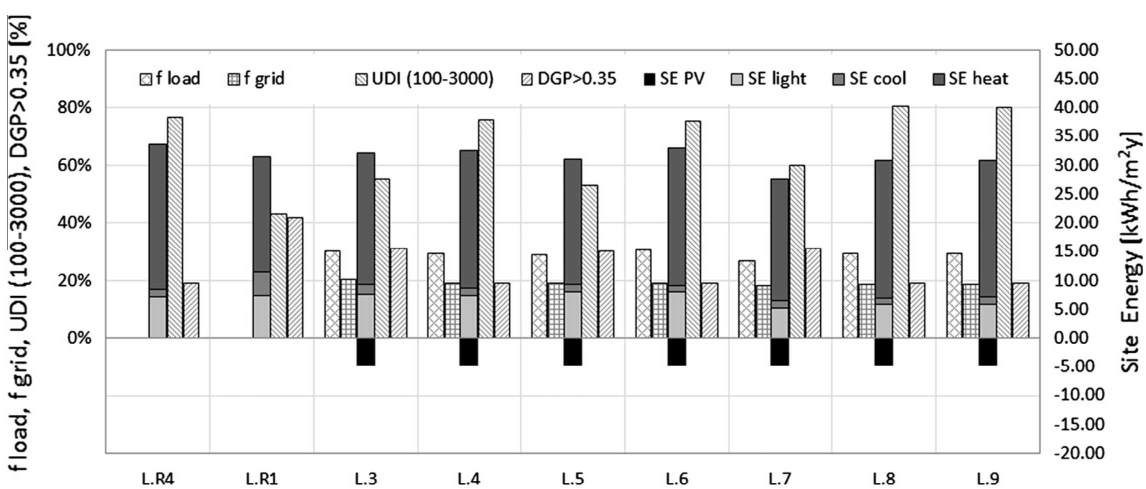

Fig. 11. Performance of South oriented office building equipped with the PVC glazing, in London climate.

Table 7
Performance of South oriented office building equipped with the PVC glazing, in London climate.

#	SE heat (kW h/m^2 y)	SE cool (kW h/m^2 y)	SE light (kW h/m^2 y)	SE (kW h/m^2 y)	SE PV (kW h/m^2 y)	NSE (kW h/m^2 y)	f_{load} (%)	$\sigma(f_{grid})$ (%)	UDI (%)	DGP$_A$ (%)
L.R4	25.27	1.18	7.14	33.60	0.00	33.60			77	19
L.R1	20.07	3.98	7.41	31.46	0.00	31.46			43	42
L.3	22.77	1.64	7.59	32.01	−4.80	22.41	30	20	55	31
L.4	23.78	1.27	7.41	32.45	−4.80	22.85	29	19	76	19
L.5	21.81	1.29	7.94	31.04	−4.80	21.44	29	19	53	30
L.6	23.88	1.20	7.90	32.98	−4.80	23.38	30	19	76	19
L.7	21.14	1.24	5.29	27.66	−4.80	18.06	27	18	60	31
L.8	23.73	1.22	5.76	30.71	−4.80	21.11	29	18	80	19
L.9	23.69	1.24	5.87	30.80	−4.80	21.20	29	18	80	19

To decrease the building-grid interaction self-consumption need to be promoted by the control strategy (S.9), as a result total energy use, and in particular cooling energy use, is increased. In fact the only strategy available to reduce grid interaction (increasing f_{self} and decreasing f_{grid}), by means of controlling the PVC-G, is to modulate the amount of solar radiation entering the room, which yields limited capability to shift cooling or heating energy needs towards period of available solar converted energy on the sun oriented façade. Although the façade converted solar energy is able to offset, on a yearly basis, one third on the office energy use, contributing to a reduction of the NSE without compromising façade transparency.

Concluding in a cooling dominated temperate climate like Sydney, energy use is very sensitive to the control strategy adopted, as this could determine whether an adaptive glazing solution could outperform or be outperformed by alternative conventional static options. On the contrary visual comfort in a room equipped with a switchable glazing, in a climate like Sydney, is less sensitive to the choice of the control strategy. In fact the lower latitude and the low building heating energy demand in Sydney, decreases the simultaneity of solar loads requirements with occurrence of glare discomfort, and provided the large amount of solar radiation available it ensures a high daylight availability during the occupied period.

In Rome the building energy performance of an office building in less sensitive the characteristics of the transparent part of the building envelope, on the contrary of useful daylight availability and glare discomfort. In fact the difference in site energy use (SE) between the two reference conventional static glazing cases is only is only 17%, as the increase in cooling energy use is balanced by a reduction in heating needs), but UDI is decreased by 36% and in DGP_A is increased by 33%, if we compare the darkest (R.R4, which is the best performing according to all yearly building performance metrics) and the bleached state (R.R1) of the PVC-G. This is reflected by the building performance indicators relative to passive, rule based and predictive control strategies. All PVC-G control strategies yield a lower energy use than their static references although the visual comfort performance is more sensitive to the choice of the control strategy, unlike what was observed for Sydney. When smart/passive or RBC – DGP_A control is adopted (cf. R.3 and 4, respectively, Fig. 10 and Table 6) SE is only marginally reduced, while with a passive control the building performance according to visual comfort is decreased (UDI −8%, DGP_A +15% compared to R.R4) and differently rule based glare control (R.4) improves daylight availability and glare risk to the maximum extent. Optimising total building loads (R.5 and R.6) results in further total energy savings, although there is a significant difference between the two in terms of glare probability and useful daylight. In fact in a temperate climate like Rome, a higher amount of heating energy use can be saved by means of the entering sun light from a clearer PVC-G state, although this contrast with the higher glare probability during winter months due to lower solar angles. This difference is maximised for predictive control strategies (R.7 and R.8), in which the minimisation of total energy use, by means of a significant reduction in heating needs, is penalized by an increased glare occurrence and hence lower useful daylight availability for the working space. As a result of introducing glare constraints to the predictive control strategy (R.8), the energy saving potential of the PVC-G solution is halved. Compared to Sydney climate, the PVC-G converted solar energy is able to offset, on a yearly basis, only one forth (nearly 25%) of the office energy use, and this is not able to contribute to the improvement of building grid interaction metrics.

In a temperate climate in which heating and cooling energy uses are of the same magnitude, the energy performance of an adaptive glazing is less sensitive to the control strategy chosen, if simple control strategies are adopted, although higher energy savings could be achieved with more advanced ones to the detriment of the visual comfort. In this climate the two building performance objectives (energy use and visual comfort) can be contrasting for large part of the year and a trade-off is often needed.

The trend of the results from the two precedent climates are confirmed by the ones from London, where the building energy use difference between the two conventional static glazing references (L.R1 and L.R4 in Fig. 11 and Table 7) is reduced even more, although the variability in visual comfort performance is not as high as the more temperate climate of Rome. The potential of the PVC-G control strategy to reduce total building energy use relies on its capability to minimise heating needs, which are the predominant in this colder temperate climate. This is even more penalized by the contemporaneity of occupied period, building heating loads and low solar angles, which increase glare occurrence reducing useful daylight availability. As a result adding a glare constraint to any control strategy (from the more simple rule base one, L.4, to the more advanced rule based, L.6, and predictive, L.8) significantly reduces the energy saving potential of each control strategy.

In a heating dominated climate, with a latitude comparable to London, due to the higher relative importance of heating and lighting demand, the requirements for visual comfort and low energy use are even more contrasting, compared to lower latitudes and hotter climates, like Rome and Sydney. Hence it is more difficult to implement control strategies which are able to increase the performance of a transparent adaptive façade as far as all building performance objectives are concerned.

One of the biggest potential of a switchable glazing technology, in this case of the PVC-G, is the capability to respond to changing performance requirements, with the possibility to achieve the best performance as far as multiple aspects are concerned, compared to different conventional static alternatives. Although these changing performance requirements can be contrasting at a certain moment in time and therefore a trade-off, as pointed out in the previous section.

In general the reduction of glare discomfort (DGP_A) and the improvement of useful daylight illuminance (UDI) are concordant performance objectives, in fact it is unlikely that a glare risk free environment has horizontal illuminance values higher than 3000 lux. Therefore in Fig. 12 only Site Energy use (SE) and occurrence of glare discomfort (DGP_A) are adopted to compare the results of the different controlled PVC glazing alternatives across different climates. The capability of improving both performance requirements can be measured in terms of the distance of each data point from the origin of axis in Fig. 12, each data point identifies a different PVC-G control strategy (with a number corresponding to entries in Tables 5–7) and the corresponding UDI values. Due to the limited variability of the self-consumption and grid interaction indicators, these are not represented in Fig. 12. From this representation the following observations can be drawn:

- conventional static glazing have limited capability of maximising the performance as far as more than one performance aspect is concerned (light grey bigger data points, S.R1 and S.R4, R.R1 and R.R4, L.R1 and L.R4): for heating dominated climates whenever visual comfort is improved (low DGP and low UDI) energy use is reduced (low SE and high UDI); in cooling dominated climates whenever DGP and energy use is reduced, UDI is reduced as well;
- switchable glazing solutions, depending on the climate context, can yield better performance than conventional glazing as far as multiple performance aspects are concerned (distance from the origin of axis), but this is significantly sensitive to the control strategy. In fact, simpler control strategy, only based on incident solar radiation (3. Passive) or glare (4. Glare A) occurrence, may

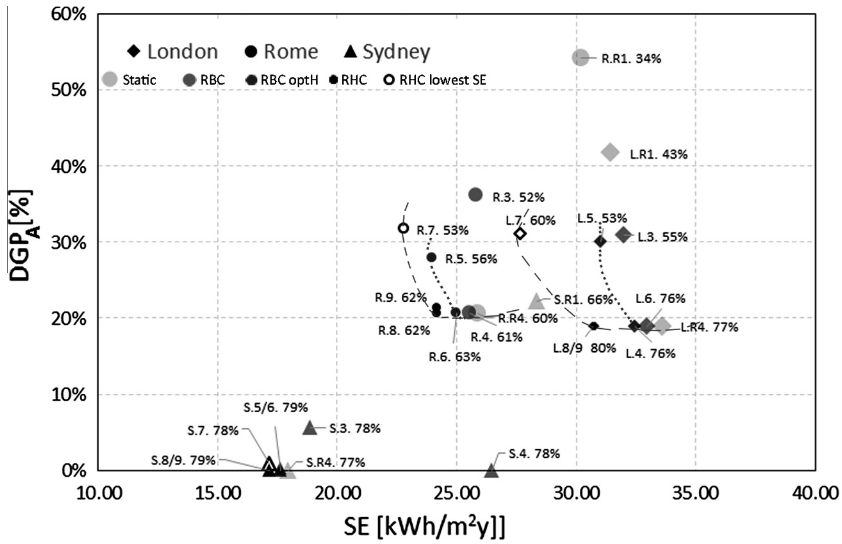

Fig. 12. Site energy against discomfort glare probability and UDI, for the three climates.

be able to only reduce energy use or improve visual quality. More advanced control strategies are required to improve energy efficiency and visual comfort at the same time, such as those minimizing building loads (reactive, 5. RBC and 6. RBC + Glare A) or building energy (predictive, 7. RHC, 8. RHC + Glare A and 9. RHC + Glare A + NSE), even though this could be still far from the highest achievable performance as far as each specific building performance objective is concerned;

- in a cooling dominated climate the objectives of low energy use and high visual comfort can coincide when controlling a switchable glazing, differently than in a heating dominated climate (with latitudes comparable with Rome and London) in which the introduction in the control strategy of glare constraints (6. RBC + Glare A and 8. RHC + Glare A) can strongly affect the energy saving potential of an actively controlled switchable glazing;
- adopting a switchable glazing, with the characteristics of the PVC-G, compared to its conventional static references, yields only marginal improvements as far as single performance objectives are concerned. In fact energy use can be reduced up to no more than 12% (with 7. RHC), while visual comfort cannot be improved more than the performance of the conventional static glazing corresponding to the PVC-G darkest state (6. RBC + Glare A, 8. RHC + Glare A and 9. RHC + Glare A + NSE). Therefore the choice of the control strategy is fundamental, as in most cases "smart" itself does not necessarily correspond to "better". This margin could be maximised only if advanced control options are adopted (5. to 9.);
- predictive control strategies (7., 8. and 9.) are the best performing one for the control of switchable glazing with the purpose of decreasing total building energy use, which is minimised by 7. RHC, although their energy saving potential compared to reactive ones depends on climate boundary conditions and on the glare constraints. This difference is visible in Fig. 12 as the difference between dashed and dotted lines, representing the maximum performance achievable with RHC and RBC strategies, respectively, for the PVC-G technology analysed.

5.2. Passive/smart compared to active/intelligent PVC-G control

The main feature of the PVC architecture, as pointed out in Section 2, in contrast to previously developed PVC and PEC layers, is that different independent control configurations are possible: (a) only photovoltaic (DSSC mode); (b) passive (self-modulating smart control) (PEC mode) and (c) active (manual supervisory control) (SC mode). The architecture of this switchable glazing technology is aimed at an automatic control to facilitate its building integration [46]. In order to quantify the potential of the PVC glazing to be used with passive self-modulating control strategy in buildings, the performance difference compared to an optimally controlled PVC are evaluated. In particular, RHC controls (RHC and RHC + Glare A) are used as a reference, as they are the best performing ones, as pointed out previously. The daily cumulative differences for the whole year are calculated in terms of both Site Energy use (SE, Fig. 13a) and probability of glare discomfort (DGP, Fig. 13b), for the three climates. The slope of the curves indicates that magnitude of the difference arising for the corresponding days. As far as energy use is concerned, in London climate the higher differences are measured during the winter period, in which the RHC control of the PVC could be able to better optimise the energy use of the building compared to a passive control, as pointed out in the previous paragraph. In the climates of Sydney and Rome, higher differences between passive and optimal control are present during the summer months instead, as far as energy efficiency is concerned. These differences are due to the relationship between incident solar radiation and the coloration process exhibited during winter months (most of the time opposite to energy efficiency requirements) and of the minimum solar and visible transmission achievable by the PVC glazing during summer (when entering solar radiation can cause additional cooling loads). For climates where glare risk is an issue, like London and Rome, lower differences in terms of energy use arises between passive and RHC + Glare A control, given the higher energy use of the latter. Counter intuitively the higher differences between passive and optimal active control, as far as glare risk is concerned, are present during summer months in all climates, when glare risk should be a less important issue. Although DGP is still high in winter for climates like Rome and London, there are no substantial performance differences between passive and optimal active control, as they are equally unable to provide a glare free indoor environment due to the high visible transmission threshold of the PVC glazing (darkest state of the PVC-G, cf. 1 SUN in Table 1, R4 in Section 3.3.2). In the summer months, the increasing performance difference in glare risk between passive and optimally active controls could be due to both a high minimum value of visible transmission and a solar radiation-colouration curve of the PVC glazing that is not tuned to the climates studied. Unsurprisingly, larger differences arise whenever glare control is added to the optimal active control

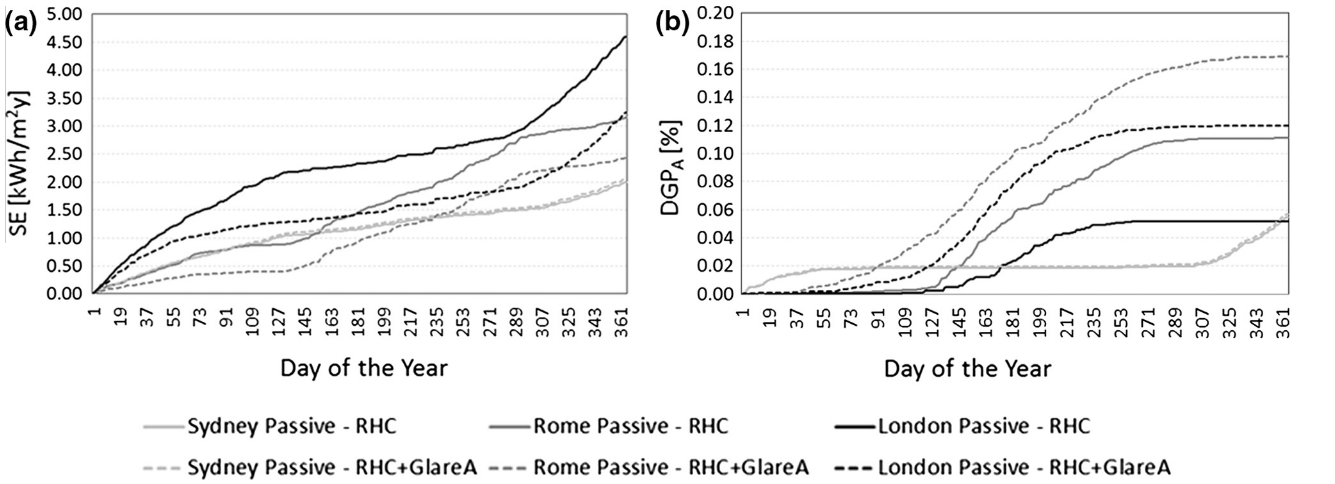

Fig. 13. Cumulative differences between RBC – Passive and RHC control, according to building performance in terms of (a) site energy SE and (b) DGP_A, for different climates.

strategies, except for Sydney climate, where glare risk is not an important issue. Although the PVC technology is aimed for automatic passive control, there are non-negligible differences between passive and optimal active control (RHC and RHC + Glare A) in terms of both performance and in terms of PVC glazing control. Overall, passive control is identical with optimally active control strategies for the PVC glazing for only 30% of the time, depending on the season and on the climate: 30% for Sydney, 25 or 35% for Rome and London (depending on the optimal control reference, RHC or RHC + Glare A, respectively).

5.3. Active/intelligent PVC-G control performance and boundary conditions

An adaptive glazing has the ability to modulate its thermo-optical properties according to transient boundary conditions, such as external temperature and the solar radiation. The performance of the control of switchable glazing depends on climatic boundary conditions as well, and it is therefore important to understand their influence on the optimal control of the PVC glazing.

As shown in Fig. 12, Predictive control (7.RHC) always provides the highest performance achievable in terms of energy use, moreover the higher the heating energy use the higher the energy saving achievable by means of the predictive control (in Fig. 12, distance between 7.RHC and 5.RBC is growing if comparing Sydney, Rome and London). Analogously larger heating requirements lead to larger influence of glare on the control strategy of the switchable glazing (in Fig. 12, distance between 7.RHC and 8.RHC + Glare A, or 5.RBC and 6.RBC + Glare A, is growing if comparing Sydney, Rome and London). In heating or cooling dominated climates, London and Sydney respectively, simpler control strategies (passive control according to solar radiation, 3.RBC – Passive, or based on glare only, 4.RBC – Glare A) have higher energy use compared to alternative conventional glazing systems (R1 and R4). While if heating and cooling energy uses are comparable instead (like in Rome), simpler control strategies can result in reduced energy use compared to the static alternatives. As far as the DGP is concerned, the best control option would always be adopting the darkest state of the smart glazing throughout the year (R4), to the detriment of energy efficiency. RHC alone is not able to provide a the lowest occurrence of glare discomfort among the controls analysed, unless in cooling dominated climates (or seasons), in which glare and cooling load reduction are both achieved by reducing the amount of solar radiation entering the indoor environment, or unless a glare constraint is introduced in the control strategy (6.RBC + Glare A, 8.RHC + Glare A), to the detriment of heating energy saving.

As already highlighted predictive control techniques (RHC) have a better performance, as far as energy use is concerned, than the best possible reactive ones (RBC – OptH), as the former minimizes total building energy use, while the latter total building loads. Even though this is true on a yearly basis, while restricting the analysis to smaller time frames can help to understand the relationship between climatic conditions and the energy saving potential of different control strategies and to quantify the advantages in different seasons and/or climates. Moreover the operational performance of "deterministic" RHC strategies can be much lower than the predicted one [73], as it depends on other factors like model and predictions uncertainties, hence a lower difference between RHC and RBC control can constitute a high risk of adopting a predictive control (for which significantly higher costs are required).

In Fig. 14 the Energy Saving Index (ESI) of the RHC strategy, compared to the RBC – OptH one, is plotted against an indicator

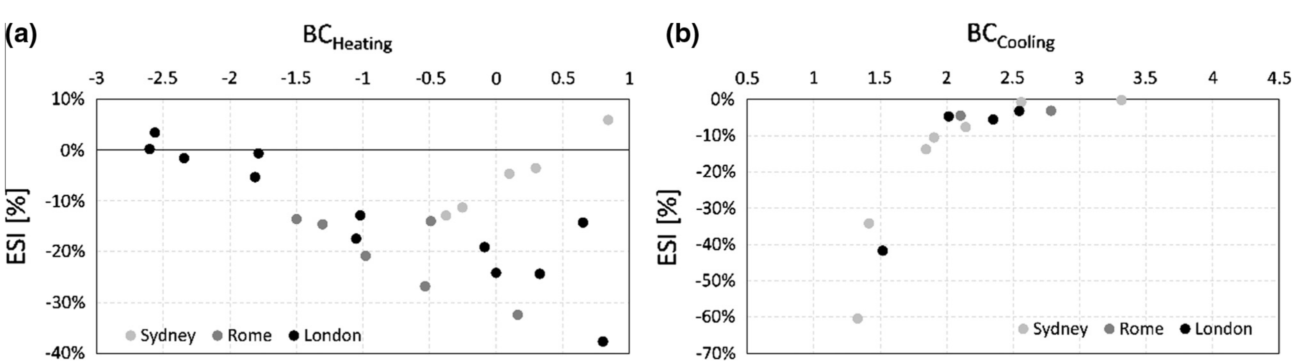

Fig. 14. Energy saving of RBC strategies compared to RHC strategy against boundary conditions during heating season (left) and cooling season (right).

of climatic boundary conditions (BC). The ESI is the relative reduction of energy use with the RBC – OptH strategy compared to the RHC one, which is considered as a reference because it has always the lowest energy use on a yearly basis. The indicator of the climatic boundary conditions (BC) is a measure of the severity of the climate and it is calculated as the normalized[3] sum of heating (negative) or cooling degree days (positive) and daily horizontal total solar radiation for a certain month. The results are analysed on a monthly basis: in fact the monthly energy use of the RHC strategy is expected to be always lower than other controls, hence the Energy Saving Index of the other control strategy compared to the RHC would always be negative. This is because RHC minimizes long term energy uses, therefore the building energy use in a single hour or in a single day may be higher for the RHC compared to other control strategies. Fig. 14(a) shows the results for the three climates for the heating season (sum of heating and lighting energy use is considered for the ESI), while Fig. 14(b) presents the results for the cooling season (sum of cooling and lighting energy use is considered for the ESI).

It is noticeable how there is a clear correlation between energy saving potential of the RHC and the climatic boundary conditions for both seasons. This correlation appears to be independent of the climate. The more extreme the boundary conditions (low temperature and low solar radiation in winter, or high temperature and high solar radiation in summer), the lower the energy saving potential of the predictive control compared to the best rule based one. For switchable glazing, in extreme climatic conditions, there is no advantage in predicting the thermal response of the building and the rule based control strategies (based only on present and past measurement of the building states) can be as good as the predictive ones. In contrast in more temperate climatic conditions (low temperature and high solar radiation, or high temperature and low solar radiation) the improvement of adopting a predictive control compared to the best rule based one can be up to 40–50%. Moreover it has to be highlighted that in the heating season the energy saving potential of RHC strategy is steadily reducing with an increase of the climate severity. In contrast in the cooling season even higher energy savings could be achieved by controlling switchable glazing in a predictive way for low to average climate boundary conditions (i.e. mid-season), while for average to extreme climate boundary conditions the benefits of adopting a predictive control compared to a reactive one suddenly drop below 10%.

Concluding PVC-G switchable glazing controlled by means of predictive strategies (RHC) can yield better performance as far as energy efficiency is concerned in climates where either heating and cooling energy use are balanced, or in heating dominated climates with enough solar energy available. While RHC can be substituted by reactive rule based control to minimise cooling energy use and for cooling dominated climates. This is due to the main strategy adopted by the switchable glazing to control the building internal environment, which is the ability to modulate the amount of solar radiation that can be admitted and stored in the internal space. During the heating season, when the admission and storage of solar energy in the building is beneficial to reduce heating and lighting energy use, prediction has larger benefits as it enables to evaluate the effect of the controlled action and the changing boundary conditions on the thermal response of the building over the next hours or days. Differently in the cooling season the control strategies aim to prevent a large part of the solar radiation available from entering the building, in order to maximise energy saving and visual comfort. Therefore the benefits of the prediction of the effect of the switchable glazing control action on the building energy balance are lower, as a smaller delay occurs between the controlled action and the building thermal response.

6. Conclusions

The present work investigated the influence of control on the performance of a photovoltachromic switchable glazing device when building integrated in different temperate climates, by means of simulation. This switchable glazing technology could be controlled in either a passive/smart or an active/intelligent way. Different active controls were tested and compared to a passive one, focusing on the difference between reactive and predictive control strategies, to optimise different performance objectives such as building energy use, energy grid interaction, useful daylight availability and probability of glare discomfort. A typical commercial reference room was analysed on a sun-exposed orientation, equipped with continuous dimming daylight control.

It is shown how “smart” or switchable does not necessarily produce lower energy use or higher visual comfort, but the design of the control strategy plays a fundamental role in the performance of an adaptive glazing. Passively controlled PVC glazing does not always mean a better performance than the best static solution in terms of both energy use and visual comfort. In fact in heating or cooling dominated climates, control strategies based only on solar radiation or glare control may result in higher energy use and/or lower visual comfort than a conventional static glazing alternative.

Active is preferable to passive control for most of the time and in all climates according to both energy efficiency and glare control requirements. Active control strategies, depending on the climate, can yield between 2% and 12% energy saving compared to static alternatives, maintaining a lower occurrence of glare risk, even though this is highly dependent on the kind of active control strategy implemented and the climate under analysis. Amongst the active control strategies predictive (receding horizon) control yields the highest energy saving potential, to reduce heating and lighting energy use. Optimised reactive (rule based) control is as performing as the predictive one in more extreme climatic conditions, such as winter with low temperature and solar radiation and summer with high temperature and solar radiation. Predictive control strategies can help reducing the gap between contrasting performance objectives, i.e. maintaining a 5–12% energy savings compared to the best static conventional glazing and the highest performance in terms of glare risk.

In temperate climates, whereas heating and cooling energy uses are of comparable magnitude, the energy efficiency of a solution is less sensitive to the control strategy and switchable glazing may have a better performance of their static alternatives with most of the control strategies analysed in this paper. Although in climates were heating energy use is higher than cooling, glare control is a key issue, as it becomes detrimental to the energy efficiency of the control solution. While in cooling dominated climates glare control and energy efficiency objectives can be coincident.

The results presented in this work, specific of the PVCC device analysed, can be an useful feedback to re-design the architecture of the device (electrolyte formulation, selection of the most suitable chromogenic materials, their properties and thickness, energy levels within the device architecture) in order to fulfil specific performance requirements. In fact the capability of the PVC-G to reduce energy use and increase visual comfort is limited by the range of thermo-optical properties of the PVC cell.

It is fundamental to evaluate the effect of the control strategy on the performance of adaptive glazing technologies, as this can inform the design of the control system but also the design of

[3] The normalization between heating or cooling degree days and the horizontal total solar radiation is calculated on the average conditions across the three climates, in order to represent all the results in the same graph.

the building integrated adaptive technology. By means of the simulation framework developed and presented in this paper it is possible to evaluate the effect of advanced control strategies in the design phase, and the influence between different physical domains involved in the adaptive mechanisms. The adoption of this simulation method takes the advantage of relying on validated building performance simulation tools, but requires a high user expertise and high computational time. Although future work will aim to develop its interface to improve usability.

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