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

Subscripts

h	horizontal
a	autonomous
e	excess
f	fell short
s	supplementary
t	time
sol	solar
vis	visible
v	vertical (eye level)

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

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