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Reduced energy consumption and enhanced comfort with smart windows: Comparison between quasi-optimal, predictive and rule-based control strategies

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ABSTRACT

Smart windows are used to reduce energy consumption and improve thermal and visual comfort mainly by controlling the solar flux entering into a building. This article presents a simulation study in which the impact of the applied control strategy on the overall energy consumption (heating, cooling and lighting) is investigated. A commercial building located in Montreal (Canada) with south-oriented integrated electrochromic windows is modeled. The hour-by-hour state of the smart windows required to minimize overall energy consumption while respecting constraints related to thermal and visual comfort is determined through an optimization strategy based on genetic algorithms (GA). Then, this quasi-optimal control is compared to other approaches that could be applied in real-time applications: (i) two types of rule-based controls (RBC), i.e. RBC1 and RBC2 and (ii) a model predictive control (MPC). The impacts of thermal mass and installed light power density are also analyzed. Results show that the four control strategies under study presented similar energy consumption with differences in total energy consumption ranging from 4% to 10%. While more complex controllers such as MPC could potentially lead to improved performances considering more design variables, complex models and extensive commissioning, this study illustrates that simpler control strategies such as RBC2 can also lead to satisfying results.

1. Introduction

A tradeoff between energy performance and visual comfort has to be made when selecting the window type, position and size in a building. Ochoa et al. [1] state that introducing solar shading technologies considerably enlarge the search space in this field of research. Moreover, if solar shading control strategies are considered, it further increases the complexity of such an optimal design exercise.

When investigating the potential of smart window technologies [2], i.e. glazing technologies offering controllable optical properties, the determination of the control strategy is often recognized as a crucial factor in achieving the required performance [3]. Nowadays, the flexibility (large dynamic range [4]) of existing smart window technologies offers great control opportunities and challenges. Selkowitz et al. [5] present the challenges and opportunities related to dynamic control of smart windows that are judged as essential considerations in the application of smart façade technologies. The SW state influences illuminance levels, electricity consumption for artificial lighting and solar and lighting thermal loads in the building zone. These aspects should all be taken into account in order to properly assess the impact of control strategies on energy savings and on the visual and thermal comfort of occupants.

Several authors showed that the effect of smart window control strategies on energy consumption is largely influenced by the type of building zones and control strategy parameters used. Often daylight optimization strategies are applied to control smart windows. In a field study, Lee et al. [6] monitored a lighting energy reduction of 26% ± 15% and a cooling load reduction of 7 ± 4% with electrochromic windows controlled in various ways so as to optimize daylight while avoiding glare compared to a spectrally selective low-e window. Lee [7] analyzed among other parameters the effect of control strategies based on vertical plane incident solar radiation and work plane natural illuminance control, and identified illuminance and glare based strategies as the best to decrease annual energy consumption. Shehabi et al. [8] concluded that dynamic

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Nomenclature

A	Surface area, m^2
C	Thermal capacity, J/K
CLT	Cross laminated timber floor
Cr	Concrete floor
DC	Discomfort cost, Kh
F	Weighting factor
Fu	Utilization factor
GA	Genetic algorithm
GDF	Global depreciation factor
H_c	Control horizon
H_p	Prediction horizon
IGDB	International glazing database
LDD	Luminaire dirt depreciation
LED	Artificial lighting system with LEDs
LLD	Lumen lamp depreciation
LPD	Light power density, W/m^2
MPC	Model predictive control
n	Number of capacitances
Q	Load, W
r	Control setpoint
R	Thermal resistance, K/W
RBC	Rule-based control
SW	Smart window
T	Temperature, K
T8	Artificial lighting system with T8 lamps
U	Inputs
U-value	Thermal conductance, W/m^2K
WP	Work plane
x	Building states, K
$\hat{x}$	Building states estimation, K
Y	Building output temperatures, K

Subscripts

1	Interior surface of the exterior glass pane
2	Exterior surface of the interior glass pane
air	Zone air
abs	Absorbed energy
airchange	Outdoor air ventilation flow rate requirement
c	Control
cl	Center location of the layer
conv	Convective heat transfer
cool	Cooling
d	Disturbances
diff	Diffuse component of solar radiation
direct	Direct component of solar radiation
ew	Exterior wall layer of the exterior building wall (concrete)
ew1	Thermal node between the exterior and middle wall layers
fl	Floor
gains	Internal gains
gap	Insulated glazing unit argon gap
glass	Window glass panes
heat	Heating
i	Interior walls and zone air thermal node
in	Indoor
iw	Interior wall layer of the exterior building wall (gypse)
iw2	Thermal node between the middle and interior wall layers
k	k^{th} time step in MPC control
light	Artificial lighting system
mw	Middle wall layer of the exterior building wall (insulation)
o	Over maximum temperature setpoint
out	Outdoor
p	p^{th} prediction time step
rad	Radiative heat transfer
SW	Smart window glazing
SW1	Exterior glass pane of the smart window glazing
SW2	Interior glass pane of the smart window glazing
t	t^{th} time step in ideal modulating control (Appendix A)
u	Under minimum temperature setpoint
w	Exterior wall of the building zone
state	State of transparency
sol	Solar

prismatic optical element window coatings controlled to maximize performance and energy savings available from daylighting controls could increase lighting energy savings by 85% compared to conventional daylight controls.

Assimakopoulos et al. presented a novel advanced control strategy based on an adaptive neuro-fuzzy inference system [9]. Results of that study revealed that the developed control strategy, although presenting a good performance, needed a higher range of possible SHGC values for it to fully take advantage of the complexity of the strategy. Nowadays, the advances in smart window technologies [10] could potentially justify the integration of such advanced control strategy in smart window control systems.

The various studies dedicated to improving smart window control strategies brought up to light the main challenges for a large-scale integration of smart window in current buildings. Among others, the main challenges in the development of efficient controllers are the occupancy type and the occupant's acceptance [11], the transient effects of unanticipated energy demand fluctuations, the radiative thermal load shift due to building thermal mass [12], the influence of the climate and façade orientations [13] and the HVAC parameters such as part-load performance or time delays introduced by air distribution systems [12]. Furthermore, intrinsic properties of the different smart window technologies [13] such as the required switching time between possible states or the variation of the spectral distribution of the visible transmittance [14] should be added up in the considered parameters for enhanced smart window controls.

In this paper, a building model with predefined geometry and material properties was used to explore the effect of different state-of-the-art control strategies on energy consumption for heating, cooling and lighting and on thermal discomfort, while taking into account the effect of the smart window state on the natural illuminance on the work plane. The intent of this work is to assess the performance of viable control solutions for real-time control of smart windows. The most promising rule-based controllers [15] and a model based predictive controller [16] are proposed as applicable real-time control strategies and compared to a quasi-optimal reference case based on genetic algorithms.

2. Building model

2.1. Building location, geometry and construction

A typical commercial building was considered in the present work. A 100 m^2 office zone of the building was modeled (6-sided box model of 10 m by 10 m by 3 m), with one exterior south-facing wall. The exterior building façade is composed of an electrochromic