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A Review of Control Methodologies for Dynamic Glazing

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Abstract

With adaptive building façade technologies, a building envelope can provide a comfortable indoor environment under varying external conditions with minimal additional heating or cooling. The control strategy applied to the adaptation of the façade is a key determining factor in the successful integration of these technologies into a building. The building envelope plays a key role in regulating light, heat and mass transfer from the outdoor environment to the indoor. Dynamic glazing can be used to adjust the amount of solar radiation entering a building. The control strategies that ultimately determine the success of these switchable technologies to affect a building's energy performance and occupant comfort are reviewed in this paper.

Introduction

Directive 2010/31/EU (EPBD recast) states that from January 2019, all new public buildings in the European Union (EU) will have to be designed to Nearly Zero Energy Building (NZEB) standards and all other new buildings will have to comply with NZEB from January 2021. An NZEB is a building that has a very high energy performance with a very significant amount of its energy requirement met by renewable sources [1]. The expectations for EU member states in "Zone 4 - Oceanic climates", which includes Ireland, is as follows:

- Offices: 40-55 kWh/(m^2.y) of net primary energy with, typically, 85-100 kWh/(m^2.y) of primary energy use covered by 45 kWh/(m^2.y) of on-site renewable sources;
- New single family house: 15-30 kWh/(m^2.y) of net primary energy with, typically, 50-65 kWh/(m^2.y) of primary energy use covered by 35 kWh/(m^2.y) of on-site renewable sources; [2]

Specific building design requirements will vary according to function, site, climate, façade orientation and regulatory/code specifications. The choice of glazing has a significant impact on overall building energy performance [3]. Buildings located in heating-dominated climates will want to maximise solar gains, thereby reducing artificial heating requirements. Those located in cooling-dominated climates will want to reduce cooling loads by minimising solar gains. These relatively simplistic requirements are complicated by the need to consider occupant comfort, changing occupancy, diurnal changes in weather and heat stored in the building fabric. Introducing glare as a design consideration can significantly reduce energy efficiency in heating dominated climates [4]. Air quality requirement and acoustic comfort must be fulfilled when considering the building and the operation of all mechanical and electrical services in an holistic manner. Some of these considerations are measurable; such as daylight illuminance and temperature, however the quality of the view of the outside environment is more difficult to quantify. Optimising windows for visual comfort can lead to high energy consumption, whereas windows optimised for energy efficiency do not always meet general visual acceptance criteria [5]. These multiple design requirements make choosing an appropriate control strategy for window systems that can change their thermal and optical characteristics even more challenging [4]. Liu et al. [6], found that the use of dynamic glazing enables an increase in Glazing Ratio (GR), without compromising building performance; even with a GR of 100%, the dynamic glazing outperformed a static façade with a GR of 20%.

As it is difficult to optimise windows for visual or thermal comfort and at the same time minimise building energy use [5], a compromise is required when choosing the size, type and location of the glazing. A significant difficulty in determining the best control strategy is the need for an adaptive façade to address multiple conflicting performance requirements often across differing physical domains such as visual comfort, thermal comfort and energy efficiency [4]. A simple example is the conflict between minimising glare risk while maximising solar gains. Control strategies have attempted to optimise visual and thermal comfort while simultaneously achieving low energy consumption targets. [7]. To truly maximise the use of dynamic glazing, controlled external shading may be required [5], [6],[8]. The need to control such shading adds a further level of complexity to any potential control strategy.

Types of Control Strategies

Self-triggered passive/dynamic glazings include Thermochromic (TC), Thermotropic (TT) and Photochromic (PC). Glazings that can be triggered by an external stimulus are categorised as active/intelligent. They include Electrochromic (EC), Suspended Particle Devices (SPD) and Liquid Crystal Devices (LCD) [4]. Their characteristics are included in Table 1.

Table 1: Characteristics of Dynamic Glazing

		Power Supply	Voltage Req.	Power Req.	Change Time	No. of States	VLT	VLT	SHGC	SHGC	U-Value W/m^2/K^{-1}
Type							Max	Min	Max	Min	
	EC	5VDC	To Switch	0.5W/m^2	3-7 min	5	.409	.006	.309	.108	1.834
	SPD	35-100 VAC	Constant	3.5-15.5 W/m^2	1-3s	∞	.650	.040	.570	.050	-
	PDLC	75 VAC	Constant	<10 W/m^2	0.1s	2	.800	.620	-	-	-
	TC	N/A	N/A	N/A	20-30 mins	5	.493	.094	.337	.196	2.666
	TT	N/A	N/A	N/A	-	2	.690	.350	-	-	5.740
	PC	N/A	N/A	N/A	2 min	2	.640	.230	-	-	-

Advanced control strategies can lead to significant improvements in building energy performance without compromising visual comfort [7],[9]. Current control strategies for glazing's are either (i) Rule-Based Control (RBC), (ii) Model-Predictive Control (MPC) also referred to as Receding-Horizon Control (RHC), or (iii) Genetic Algorithms (GA). The majority of studies have examined a relatively simple rule based control [4],[9],[10]. These strategies are generally unable to optimise contrasting requirements, such as the optimisation of solar gain contrasted with the desire to reduce summer cooling loads. Notwithstanding this, they frequently outperform some of the more complex alternatives [4].

(i) Rule Based Control

A RBC strategy is defined by a set of rules that rely on measurements of the current or past states of the building (i.e. lighting levels, temperature, building energy demand). It uses an external decision making system of sensors, control algorithms and actuators [4]. A number of different RBC's have been tested for control of dynamic glazing [11]. RBC control strategies use one or more pre-determined instructions acting on measured or pre-set data values [11]. Dussaullt et al. [9] used two RBC control strategies in their study, RBC1 and RBC2. Both were designed to maximise daylight without exceeding 500 lx. If this threshold was exceeded the glazing switched to the next darkest state that would keep the daylight level below 500 lx. The difference between the two strategies was the operation of the glazing during the hours when the building was said to be unoccupied. RBC1 switched to its clearest state, thereby maximising solar gain and RBC2 switched to its darkest state, minimising cooling requirement. Of the two strategies, RBC2 performed better even outperforming some of the more complex GA and MPC strategies. It was noted, that the use of energy efficient artificial lighting systems has a significant impact on the effectiveness of the control strategies. Using on–off switches where the switch is triggered by the level of indoor illuminance or global solar radiation, Assimakopoulos et al. [7] achieved similar results within ≈ 2%, with their RBC to those achieved using a more complex fuzzy logic control. This study however, (i) did not compare results with a standard glazing (ii) only relates to lighting, heating and cooling energy consumption and (iii) does not present data on daylighting or glare comfort. In a simulation study, Fernandes et al. [8] used target indoor illuminance and luminance levels as the design parameters for determining the performance of a split pane EC window used in conjunction with automatic roller blinds to reduce lighting energy consumption. Their control strategy used a least-squares algorithm with linear inequality constraints. This work did not attempt to compare control strategies but rather utilised this particular method of control to compare the performance of an EC window with a standard reference glazing. They found that if the blinds are operated once per day at the first instance of visual discomfort, the annual lighting energy consumption was reduced by 37% – 48%. Favoino et al. [4] found that although RBC strategies could outperform more complex strategies for a single performance requirement, they were generally unable to optimise multiple performance objectives. Importantly, this study did show that a RBC strategy could outperform the best static glazing option. A simulation carried out by Tavares et al. [12], used a simple control strategy based only on incident solar radiation applied to south, east and west facades in a Mediterranean climate but did not consider the effect of glare on occupant comfort. They concluded that this type of strategy resulted in energy savings compared to a standard single or double glazing.

(ii) Model Predictive Control

Model Predictive Control algorithms use a defined and specific system model to predict the future response of that system over a pre-determined time horizon [13]. The main premise is that there is useful information contained in the future of that system which can be used to improve the system control and performance [14]. Though first developed to control power plants and petroleum refineries, their use is now widespread. At each time step, an MPC algorithm optimizes the sequence of control values, over the prediction horizon based on the predictions of the model [9]. The control predictions of the model are then applied to the model in real time. An MPC model has three distinct parts, the observer, the optimizer and the predictor. Dussault et al. [9], used an MPC control strategy with the objective of minimising the total energy consumption of the building. While the results of this strategy were promising, it was still outperformed by the RBC2 and GA strategies. A possible reason for this was that the simplicity of the building model did not allow the increased intelligence of the MPC controller to be fully utilised. A study by Favoino et al [4], found that MPC control strategies have a better energy performance than any of the reactive RBC strategies tested. This is because MPC strategies are able to minimise total building energy use, while the RBC strategies can only minimise total building loads. As the results of an MPC control strategy are only as good as the predictions of the system it is essential to identify the optimal predictors for any given system.

(iii) Genetic Algorithms

GA can be used either to find a single set of input variables that will optimise one or many performance requirements into a single solution or a set of optimal solutions that recognises the lack of any one perfect solution [15]. A GA would be recognised as easy to use and robust but can be slow compared to other optimisation methods. Due to being probabilistic, they can produce different results with the same inputs [9]. Dussault et al. [9], used a GA with the objective of minimising overall energy consumption, due to the computational expense and time associated with optimal GA solutions, a quasi–optimal solution was used [9]. It was found that with a traditional T8 fluorescent lighting system, the GA offered the lowest energy consumption of all control strategies, but with more efficient LED lighting, the simple RBC controllers performed as well as the GA.

Discussion

The difference in performance between their best and worst performing strategies has been found to be less than 10% [7] due to the small dynamic range of the Solar Heat Gain Coefficient (SHGC) (0.36 – 0.18, bleached and coloured respectively) for many EC windows. The multiple design constraints are bounded by limits set by the desire for large glazed areas to maximise daylighting and solar gains to reduce the need for artificial lighting/heating systems or smaller glazed areas to reduce cooling demand caused by solar gains which increases the need for artificial lighting [5]. Occupant comfort must be considered as part of any design or control strategy. Visual comfort plays such an important role in overall occupant comfort, that it requires very thorough consideration[16]. In cooling-dominated climates, the energy consumption of a building is very sensitive to the chosen control strategy and reactive control has been shown to be as effective as predictive control for dynamic glazing, whereas in heating-dominated climates, predictive control has yielded better results [4].

Conclusion

Simple control strategies work well on simple building models. Many authors have noted that the lack of modelling complexity has reduced the performance benefits of intelligent control strategies such as MPC and particularly GA. RBC strategies offer a simple means of control, that may yield building energy savings but it is generally accepted that they are unable to meet more than a single performance objective. There is enough research to suggest that current dynamic glazing alone may not provide sufficient flexibility to produce the desired combination of energy savings and visual comfort. A possible solution to this is presented in [17] through the use of a hybrid window using an infrared Chiral Liquid Crystal (CLC) mirror and SPD window to independently control solar radiant heat transmission, visible transmission and glare through the window. Studies combining the use of shading with dynamic glazing have suggested that when considering the application of smart facades, it may be necessary to consider the entire façade and not simply a single part.

Research conducted to date has used building simulations and virtual modelling environments. While these studies can clearly demonstrate the ways in which dynamic glazing may be controlled, it is necessary to conduct physical field trials and record the results of dynamic glazing being controlled in a variety of climates and with a variety of control methodologies.

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