PRELIMINARY FINDINGS OF A CASE STUDY INTO THE APPLICATION OF ELECTROCHROMIC GLAZING IN A UK OFFICE

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ABSTRACT

Electrochromic (EC) glazing has emerged onto the market as a viable alternative to fixed transmittance glazing with traditional shading devices. With a sufficiently large range between clear and fully tinted, EC glazing has the potential to control glare from direct sun or bright patches of sky thereby greatly reducing or perhaps even eliminating the need for additional internal or external shading. In contrast to traditional shading devices (*e.g.* venetian blinds) it is possible to see clearly through EC glazing when it is set to minimum transmission. Thus EC preserves the view to the outside even when set to offer maximum 'shading'.

Previous research into the application of EC glazing in buildings has been mainly computer simulation- or lab-based (*e.g.* using full scale test rooms). The response of building occupants has been explored in just a handful of studies, and none of these were in 'typical' workspaces.

This paper describes the preliminary findings of a case study evaluation of user acceptance of EC glazing in a typical office space. It is amongst the first of EC studies to examine the impact of the glazing material in a continuously occupied space over a long-term monitoring period, as well as being the first commissioned installation of EC glazing in the UK.

This paper will give an overview of the background and methodology of the case study and report on preliminary findings from the retrofit experience and early subjective monitoring data.

1. INTRODUCTION

Contemporary buildings with highly glazed facades often suffer from problems of visual discomfort and solar gain. This in turn can lead to poor daylighting since the blinds are regularly left closed for extended periods. External shading devices (fixed or moveable) can be costly to install and maintain, and can become dominant feature of the architecture. Electrochromic (EC) glazing is an advanced fenestration material that can vary its transmission properties in response to a small applied voltage. By providing dynamic shading that can be controlled automatically and unobtrusively, EC glazing has significant potential to improve daylighting and energy use in new and existing buildings.

When EC glazing is in its fully coloured (tinted) state it is still possible to see through it. The ability to provide shading whilst allowing a continuous, unobstructed view is a promising feature of this technology since research suggests that a window view can provide significant benefits to the health and wellbeing of building occupants [Collins 1976, Aries et al. 2010, Veitch 2011]. View is also believed to have a mitigating effect on daylight glare [Tuaycharoen & Tragenza 2005]. A view allows occupants to ‘connect’ with the external environment, be it natural or man-made, and it communicates to the building occupant important visual cues, *e.g.* the progression of time and local weather. Of particular importance for office workers, an unobstructed view allows the occupant to focus on distant objects, thereby enabling relaxation of the ocular muscles.

The principle of electrochromism as a means of varying glazing transmission to improve building performance first appeared in publications around the mid-1980s [Lampert 1984, Svensson et al. 1984]. Early research focussed on computer simulations and has continued to make up the bulk of research into EC glazing [Sullivan et al. 1994, Moeck et al. 1998, Fernandes et al. 2013, Gugliermetti et al. 2003 & 2005, and others]. The windows were controlled automatically by any sensed or simulated environmental parameter. Usually this was a luminous or thermal quantity, or some combination of the two.

In the late 1990s, physical studies of EC glazing prototypes began to emerge [Pennisi et al. 1999, Wittkopf et al. 1999]. More recently, a number of physical studies have been carried out, some using reduced scale models [Piccolo et al. 2009, Piccolo 2010], and some based in full-scale test cells [Lee et al. 2002, Lee et al. 2006, Clear et al. 2006, Zinzi 2006, Lee et al 2012].

Two of the studies mentioned above [Clear et al in 2006 and Zinzi in 2006] included human participants and thereby an assessment of the subjective effects. Whilst these studies provide valuable insights into the subjective experience of would-be occupants, they are limited by their nature as lab-based studies. Additionally these studies were carried out in climate regions that are cooling- rather than heating-dominated (California, US, in the case of Clear et al. and Rome, Italy, in the case of Zinzi).

Aside from a recent study by Lee et al. (2012), there do not appear to be any studies of real-world applications of EC glazing, *i.e.* in everyday workplace settings rather than laboratories or ‘test rooms’. The aforementioned study investigated the effects of EC glazing in a conference room in Washington DC, US. The work begins to address the dearth of real-world research into EC glazing, and also the lack of longitudinal studies into the application of the technology, as it reports on results obtained over six months of measurement. However, the transient occupancy patterns typical of conference rooms ruled out any systematic evaluation of the subjective impacts.

Studies to date have, in the main, indicated that EC glazing has considerable potential to improve the daylighting and lower the energy consumption of buildings through reductions in the use of electric lighting and air conditioning. However, the level of user acceptance of this technology will be a key factor to its long term success. It is also imperative to evaluate specific subjective effects of EC glazing, such as actual visual comfort, rather than relying on calculated indices to predict visual comfort. Hence, research that includes human participants carrying out their normal, everyday tasks in their usual workplace is much needed in this field.

It is evident from the literature that a study of EC glazing in a real-world application, that includes as assessment of subjective experience of occupants over a long term period, is needed to further our understanding of this technology. This paper describes the early stages of a study to evaluate user acceptance of EC glazing in a typical office space.

2. CASE STUDY

2.1 Case study rooms and EC glazing specification

As a means of studying the real-world application of EC glazing, a longitudinal case study is being conducted into the retrofit application of the technology in an ordinary UK office setting. In August 2012, the existing windows in two open plan offices in Leicester, UK were replaced with commercially available double-glazed EC units. The EC glazing used varies in transmission from 62% down to 2%. Figure 1 shows the interior of the case study offices before and after the replacement of the windows. Each office accommodates four workers who occupy the space for the majority of their work time. The building was converted to offices from its former use as a Victorian industrial building as some time in the past. As a result, the windows are large with window head heights of over 3m, although false ceilings have been installed which cut off the upper third of most of the windows. The façade has a southeast orientation, which receives a significant amount of sun throughout the year, including low-angle sun in winter. The exterior view can be seen in Figure 2. Note that the partition between the two offices divides the 'shared' window. Also, the second row of windows had to remain openable as per the original. Thus this particular installation of EC glazing demonstrated that the new technology was suitable for non-standard, 'bespoke' retrofit applications such as this historic building.

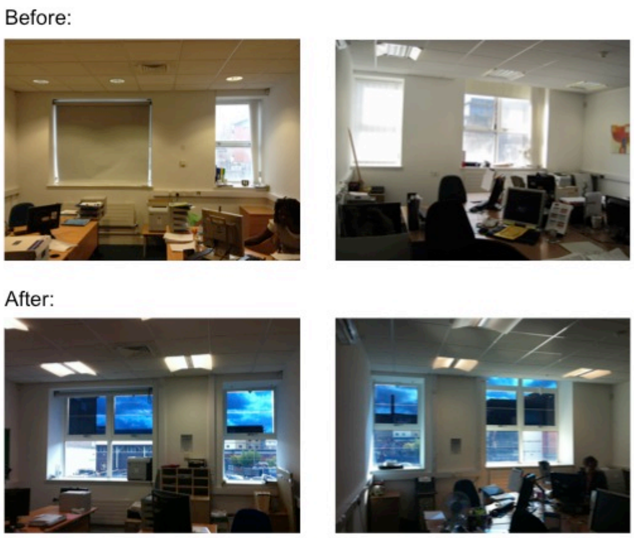

Figure 1 – Interior view of the case study rooms before and after the EC window installation

Figure 2 – Exterior view of the case study windows

Although continuously variable in transmission, the EC windows are usually set to operate with two intermediate states of 20% and 6% between the maximum of 62% (when fully bleached) and a minimum of 2% (when fully tinted). The spectral transmission curves for the EC glazing in these four states are given in Figure 3.

The windows are controlled automatically according to some sensed luminous parameter, with wall switches to allow manual override operation by the occupants if desired. The windows are zoned so that single panes or rows of panes can be controlled individually. The control algorithm uses an exterior illuminance sensor to regulate glass transmittance based on an upper and lower illuminance threshold inside the room. The lower zones have been configured so that they have a higher tolerance to tint, *i.e.* so that they stay less tinted for longer. This configuration is based on user feedback, which will be discussed in more detail in section 4. The transition time for the glass depends on the exterior temperature; in colder weather it takes longer. Typically, the windows take about 5 to 10 minutes to transition from one tint state to another depending on the ambient conditions. The time taken for the windows to change tint was noted by Zinzi (2006) as a potential user acceptance issue, and so highlights the importance of effective automatic controls to minimise the need for user interventions.

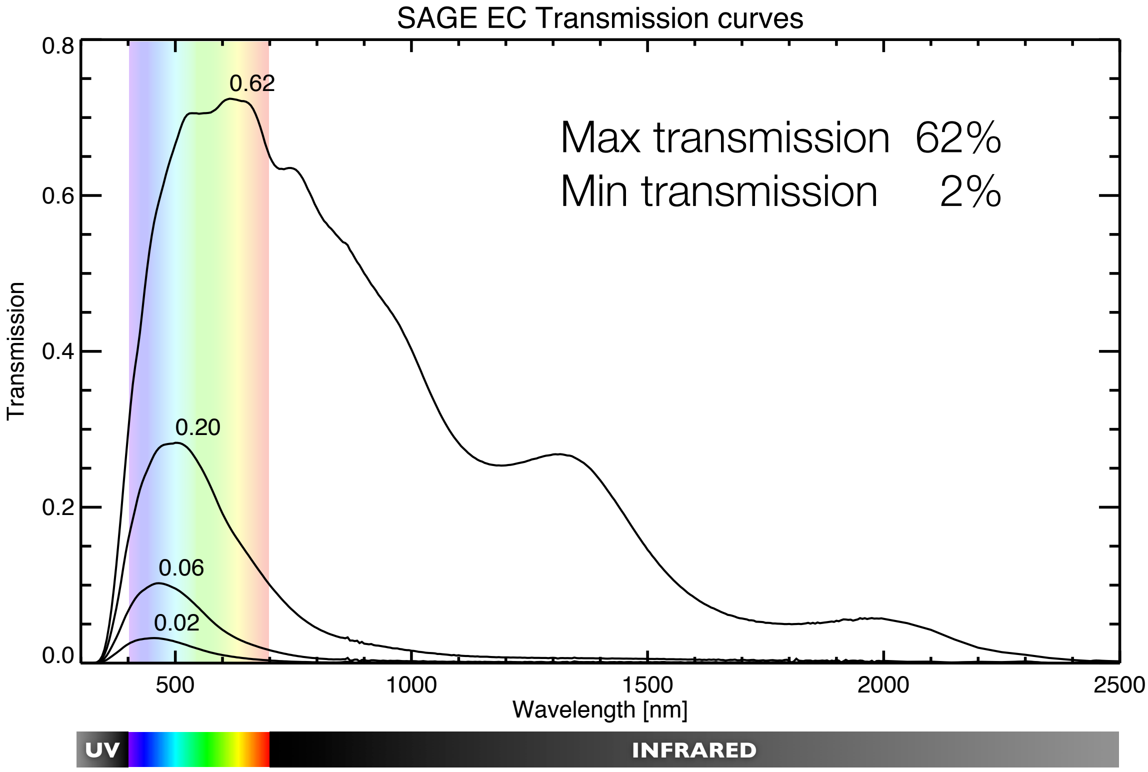

Figure 3 – Variable transmittance properties of the EC windows being studied
Data from the IGDB files supplied by SAGE

As described in Kelly et al 2012 and 2013a, the study aims to investigate the user acceptance of EC glazing in a typical office environment, and how that is dependent on external factors such as sky/sun conditions, and operational factors such as the control algorithm and office layout. As it is a longitudinal study, it allows an investigation of the variability in of glazing performance and occupant perception throughout the seasons. Importantly, the study also offers an insight into the practicalities of retrofit when an advanced façade technology is applied to an existing building. It can thus inform future retrofit projects, both in terms of technical issues as well as occupant perception of the change.

2.2 Monitoring programme

The study has been designed so that it assesses the impact of the EC glazing on physical parameters in the rooms as well as the subjective impact of the technology on the room occupants. The measurements, subjective and physical, are made at regular intervals (of varying length depending on the measure) throughout the monitoring period of 12 months. This mixed methods, repeated measures approach has been used by others to assess the visual comfort of building occupants [Painter et al. 2009, Konis et al. 2011].

A number of physical measurements are taken to assess the impact of the EC glazing on the room environment and on non-subjective visual comfort parameters. This includes physical room parameters (temperature, electrical lighting energy), room luminous parameters (horizontal workplane illuminance, visual field luminance using high dynamic range imaging), EC window parameters (tint state, control mode, energy consumption) and external luminous conditions (vertical façade illuminance, unobstructed horizontal illuminance nearby to the offices).

In order to understand the acceptance of EC glazing by the occupants in the two offices we are using a variety of qualitative and quantitative approaches. Across the approaches, the frequency of engagement with the participant is balanced with the level of detail of data obtained, *i.e.* less frequent, more detailed versus more frequent, less detailed. This data collection procedure has been developed to reduce and carefully manage participant burden. The self-report data collection approaches are summarised as follows:

- **Daily Experience Form:** This allows users to record their experience in very general terms, using a traffic light system; "good", "bad" or "neutral". It provides a coarse data set of occupant perception that can be linked with physical monitoring data.
- **Twice monthly online questionnaire:** This goes into more detail about different aspects of the experience, for example in terms of visual comfort and glare. The questionnaire has been designed to collect a good level of detail while still being short enough to be completed relatively quickly. This is a more traditional approach that will facilitate a deeper analysis of the links between physical conditions in the room and occupant perception of the glazing performance.
- **Quarterly one-to-one semi-structured interview:** This allows deeper exploration of the subjective narrative. While this is necessarily more time intensive, it will add important qualitative data that can help put the measurement data from the other sources into context.
- **Ad-hoc Participant Feedback/Researcher Observation:** On an ad-hoc basis, the occupants report their experiences verbally and via email. Participant feedback, along with pertinent observations by the researcher, are recorded in a diary by the researcher.
- **Blinds Diary:** This is a simple pro forma mounted on the window wall that allows occupants to record instances when they needed to use the blinds. When an occupant needs to lower a roller blind, they note the time and date, the initials of the occupant who benefits, and the reason (screen reflection, direct glare or other).

The subjective study design is described in more detail in Kelly et al. 2013b.

Noteworthy preliminary findings are starting to emerge from the subjective data that have been collected throughout the months following the EC glazing retrofit. These are explored in the following section.

3 PRELIMINARY FINDINGS

The post-installation settling-in period has provided valuable insight into the practical issues arising from the retrofit application of the technology in an office environment in the UK - a situation that has not been explored previously. The preliminary findings that emerge from the occupant feedback and researchers' observations include general installation issues, study specific challenges, and, in particular, the challenge of refining the control settings for the application of EC glazing in an office building. The following sections explore each of these issues in turn, using information gained through the daily experience sheet, interviews and ad-hoc study log.

3.1 Retrofit process

When considering a refurbishment programme the windows/facade are often identified as an area for improvement since an upgrade of these could significantly improve the buildings' energy performance. Even prior to the recent economic slowdown it was estimated that approximately 80% of the 2050 buildings are those already existing. That percentage estimate is likely to increase as the developed economies focus more on the refurbishment of existing domestic and non-domestic stock to improve energy efficiency and less on large-scale new build projects. It is therefore especially important to learn from the retrofit application of advanced glazing materials such as EC glazing so that the technology can be implemented effectively in the near future.

One of the main and obvious differences between EC windows and traditional windows is that they need electrical connections. There is also a need for the installation of control system hardware, and in this case, communications infrastructure to allow access to the control system over the internet. The electrical contractors who worked on this installation had not previously been involved with fitting advanced glazing such as this.

Despite this, the process of installing the windows was found to be relatively straightforward. The manufacturer provided the electrical contractor with wiring diagrams, which they were able to follow relatively easily, so that the electrical and communications wiring was completed within the same time frame as the window replacement. On-site commissioning and testing was carried out during the installation by a representative of the EC glazing manufacturer.

A few weeks after the EC window retrofit, some new furniture was installed in one of rooms, which consisted of a large cabinet around 1.5m high. This was placed in front of the window wall switches and had to be relocated to allow access to the switches. This is a simple but informative finding as it emphasises the need for building occupiers to be made aware of the main differences between a technology like EC windows, which many people have not seen before, compared with traditional windows with which everyone is familiar.

It should be noted however that recently announced developments in applied EC glazing technology could effectively eliminate these considerations. For example, the integration of small photovoltaic (PV) cells and battery store into the window will allow autonomous (i.e. 'off-grid') powering of the EC glazing. The addition of a wifi controller in the window (also powered by the PV cell) will eliminate the need for any wiring of the EC glazed panel for either power or control [Sanders, 2013]. These developments are expected in the next twelve months.

3.2 Window control data

The EC glazing system consists of the EC glazing panes and the control system hardware. As mentioned previously, the windows are split into several glazing zones that can be controlled individually. There is provision within the control system to record the status of each control zone as well as manual override events.

The collection of window control system data is a key part of the monitoring strategy. By being able to link external luminous conditions with window settings and data regarding the internal environment, it is possible to investigate how the EC glazing settings affect the visual office environment for specific conditions, *e.g.* high or low altitude sun. Linking this further with manual override data can give an indication as to when occupants find the automatically set glazing state uncomfortable, and what settings they (manually) select. The override data are therefore a very valuable component of the study. Moreover, during the settling-in period the override data can guide the commissioning process, *i.e.* to help establish optimum control settings.

The initially installed control system had various limitations that resulted in control data not being easily extractable, and technical problems with the logging mechanism resulted in periods where data were lost. It should be noted however that commercial EC control systems are generally not designed for research purposes, and so these and similar data collection issues should be expected. Whilst this did not impede the performance of the system generally, it meant that control system data could not consistently be used as a feedback mechanism to help with the refinement of the control algorithm.

A more reliable and comprehensive data logging facility is now in place, and data has now started to be acquired in a format that better facilitates data analysis and integration with the other data in the study. Resolving this issue has somewhat affected the monitoring time plan – this further highlights the challenges associated with carrying out research on advanced technologies in real-world settings. Notwithstanding those issues, valuable experience regarding the demands for reliable and easily useable control system data has been gained.

3.3 Control algorithm refinement

When the EC windows were installed, they had been pre-programmed so that they operated "out of the box" using default system settings. Whilst these settings provided a serviceable starting point, they needed to be adjusted several times before it was determined that occupants were as comfortable as possible. This process was complicated and prolonged by a number of factors, one of which was the situation with data acquisition mentioned in section 3.2. The complications of obtaining robust system data made it difficult to test if the new settings were resulting in fewer manual overrides. Instead of using manual override frequency as an indicator, we relied on the various forms of occupant feedback (in particular ad-hoc feedback and one-to-one interviews).

The process of refining the control algorithm to suit the needs of the occupants in this case study revealed several findings relating to the application of this technology in a real world setting, as follows:

Zone differentiation

Occupant feedback and researcher observations indicated that users preferred to have a mixture of tint levels across the zones, and typically with lower panes less tinted than upper ones. The users seemed to favour having a proportion of unfiltered daylight, which they perceived as more "natural". When the windows were heavily tinted, occupants reported that visitors to the rooms commented that the room appeared gloomy and that the occupants appeared to have a dull pallor to their skin tone, *i.e.* similar to the anecdotal responses noted for low-transmission fixed-tint glazing. When the window zones were in a mixture of clear and tinted states, the colour rendering of surfaces in the rooms appeared to be much less affected. Therefore one of the first adjustments was to change the settings for the lower window panes so that they stayed clearer for longer.

Control modes

The system has three control modes:

(i) Auto: Using the external illuminance sensor, each zone is controlled based on an upper and lower interior illuminance threshold. Exceeding the upper threshold triggers the system to tint the glass to the next lowest transmittance level, and falling below the lower threshold triggers the system to untint to the next highest transmittance level.

(ii) Glare: The system enters glare mode when the external illuminance sensor reads above an upper threshold, and when the sun's position is such that the rooms are receiving direct sunlight. (Note that 'glare' is the name given to an operational mode of the control system – it does not relate directly to the more common notion of glare as a visual phenomena.)

(iii) Manual: If a user presses a wall switch, the system responds to this command and overrides auto or glare mode. The system settings determined by the wall switch command remain for a period of two hours.

Glare mode is a feature which can mitigate the effect of transition time on user acceptance, since, under sunny conditions, it can pre-empt the need to tint the windows based on sun position in addition to absolute levels of sensed illuminance (at the external façade). Glare mode was not operational when the EC windows were first installed, but was implemented later (January 2013). Prior to the introduction of glare mode users reported some dissatisfaction with the response time of the system, particularly under changeable (cloudy/clear) weather conditions.

When glare mode was first implemented it did not allow override by the wall switches. In addition, it was applied to all window zones with no discrimination between upper and lower panes. This meant that, in glare mode, all panes went into a fully tinted state. The users in the main did not favour this mode of operation. At the same time, the initial configuration did not allow for effective manual override. The lack of control experienced by the occupants was keenly felt, and serves to emphasise the importance of occupant control with any automatically controlled technology.

Following the control system upgrade, the wall switches now have priority over all other control modes. Glare mode settings have also been modified so that the upper threshold on the external sensor is higher (to make the system less sensitive), and also so that it does not apply at all to the lower row of panes. Early indications suggest that these settings are working much better for the occupants than was previously the case.

Seasonal variability & furniture layout

Refining the control algorithm is an iterative process, and the effectiveness of settings can change with the seasons, *e.g.* the settings may work for an equinox period, but not during mid winter when the sun is mostly at low altitude.

Around the winter solstice period, an occupant who is seated facing the window reported visual discomfort on sunny days when the solar disc was directly in the field of view. This occurrence was expected since, even when viewed through glazing at 2% transmission, the solar disc can still be uncomfortably bright. In situations where the low sun causes discomfort for an occupant, they will lower a roller blind. Blind use is recorded using the Blinds Diary mentioned in section 2.

It would appear that the overall effectiveness of EC glazing would be maximised if the seating layout can be arranged to either: (a) avoid occurrences of low angle sun in the field of view; or (b) to allow occupants to adjust their view position in response to instantaneously occurring conditions.

Social dynamics and the affect on user acceptance

It has been instructive to see the impact of EC windows in a space with more than one occupant. As with blinds, occupants in an open-plan area need to reach a consensus when it comes to ensuring the comfort of themselves and their colleagues.

During one-to-one interviews, some occupants spoke on behalf of their colleagues and some indicated the need to accommodate the needs of a colleague who has a health issue which affects their vision. The empathy they felt towards their colleague influenced the consensus reached regarding the settings/operation for the window. Thus the data obtained from one-to-one interviews can be contextualised by an understanding of the group dynamics at play.

3.4 Performance 'Snapshot'

The images in Figure 4 were taken moments apart with the EC glazing constant in the state shown. This 'snapshot' in time helps to illustrate a number of performance aspects noted above which appear to be key to the long-term acceptance of EC glazing by building occupants. Of the eight EC panels that comprise the glazing in this office, at the time that the photos were taken seven were fully tinted (*i.e.* 2% transmission) and one was set to clear (*i.e.* 62% transmission). The expectation from the view to the window is that the daylight illumination in the space will have a predominantly blue hue. But, a general view of the office confounds that expectation and appears largely neutral. Colour perception is a complex phenomenon with several factors operating simultaneously and often in mutually dependant ways, *e.g.* colour constancy, relative/absolute levels of illumination, etc. However, a theoretical evaluation of the combined spectral effect of clear and tinted EC panels has shown that, provided at least one panel is left clear, the majority of the transmitted light will be from the clear panel and so the bulk of the daylight illumination will be perceived as largely neutral. For example, using the same 1:7 (clear:tinted) ratio as shown in the 'snapshot' photo, 81% of the transmitted daylight in the space came through the (one) panel in the clear state [Mardaljevic, 2013]. In the actual space, of course, the 'mixing' of light will depend on the incident spectrum, localised reflections etc., and so we would expect some variation across the space. In this example, the users applied an override to set the panel to clear, and the overall illumination benefitted from the (diffuse) reflection of sunlight on the wall. Thus, although the *view* of the tinted panels suggests otherwise, the light *received* at the eye is in fact largely neutral. This suggests that the findings on self-reported arousal etc. under fixed tinted glazing [Arsenault, 2012] are most likely not applicable to EC glazing provided that some of the panels are left clear.

Another key performance determinant for EC glazing will, we believe, be a joint consideration of both office layout and dynamic control. The occupant shown in the left photo reported that she could work comfortably with direct sunlight attenuated by 2% transmission glazing incident on both the computer display and the paperwork. However, as we expected, the same is often not the case for someone facing in the opposite direction where the orb of the sun would be directly visible in the field of view. Even through 2% transmission glazing, a direct view of the sun can be too intense for many people. The findings of Jakubiec and Reinhart (2012) show that the simulated annual occurrence of glare (under normal glazing) can be greatly reduced if the occupants are allowed some freedom to adjust their viewing position. This is commensurate with our intuitive experience of real spaces where a shift of view of, say, 45 degrees can effect a transition from intolerable to barely perceptible glare.

Figure 4 - Photos of EC Glazing in operation

4 CONCLUSION

A literature review of previous research on electrochromic glazing points to a lack of long-term studies in real world settings. Furthermore, there is a need to look in more depth at the user experience of this and similar technologies. The case study described in this paper will provide valuable data that addresses some of the gaps in current knowledge about the application of this technology. The study is necessarily restricted given the small number of participants, however this is compensated by the richly detailed feedback collected over a long time period.

The early part of this study has provided some useful insights into the practical implementation of EC windows in typical office spaces. Despite the novelty of the technology in the UK, the installation process was relatively straightforward. However, the process of tuning the control algorithm has proven to be more complex, and it is apparent that the quality of data acquisition from the control system has a significant impact on the process of control system refinement.

The separation of the windows into several control zones has enabled occupants to have different panes/zones in different tint states at any given time. Feedback from occupants has indicated that this feature is regularly utilised and that it is perceived as a benefit of the system. This suggests that this facility is desirable, particularly where there are large glazed areas. Through the experience of introducing the glare control mode, the importance of manual control has been highlighted.

These findings support the need for in-depth studies of green building technologies such as EC glazing under real-world conditions.

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