BRI **Building Research and Information**

Print ISSN: 0961-3218 Online ISSN: 1466-4321

Authors accepted revised submission of:

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(ID: 1245951 DOI:10.1080/09613218.2016.1245951)

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ABSTRACT

Naturally ventilated offices enable users to control their environment through the opening of windows. Whilst this level of control is welcomed by users it creates risk in terms of energy performance, especially during the heating season. In older office buildings, facilities managers usually obtain energy information at the building level. They are often unaware or unable to respond to non-ideal facade interaction by users often as a result of poor environmental control provision. In the summer months, this may mean poor use of free cooling opportunities, whereas in the winter, space heating may be wasteful. This paper describes a low cost, camera based system to automatically diagnose the status of each window (open or closed) in a facade. The system is shown to achieve a window status prediction accuracy level of 90%-97% across both winter and summer test periods in a case study building. A number of limitations are discussed including winter daylight hours, impact of rain and the use of fixed camera locations and how these may be addressed. Options to use this window opening information to engage with office users are explored.

Keywords: windows, adaptive behaviour, natural ventilation, personal control

1 INTRODUCTION

In 2015 in the UK, the services sector, incorporating public administration and commercial services, accounted for 14% of total final consumption of energy. Approximately 29% of the services sector (Commercial offices (8%), Education (13%) and Government (8%)), or ~4% of overall final energy consumption can be attributed to office type buildings (DBEIS, 2016).

By 2050, the total UK non-domestic floor area is expected to increase by 35%, with 60% of today's buildings still being in use. In addition, the Carbon Trust estimates that by 2050, non-domestic building stock improvements will lead to a positive net value from energy savings of around £13 billion with ~£3.1 billion being achieved through innovation in management and operation (TINA, 2012). Clearly, the built environment challenge in the UK is one of the buildings that exist today, rather than the new-build of tomorrow.

Engineers and building facility managers therefore, face a challenge to reduce energy consumption and carbon emissions, whilst achieving savings in the cost of services and delivering thermal comfort. One of the main barriers to achieving realistic design targets and good post-occupancy building energy performance is the unpredictable behaviour of the occupants (Fabi et al., 2012; Schweiker et al., 2012). Occupants will interact with the building control systems in order to adjust the indoor environment to maintain comfort (Rijal et al., 2007; Haldi & Robinson, 2008). Naturally ventilated office buildings (winter heating only, "free running" during the summer with no active cooling) are rising in popularity as they offer a more satisfactory indoor working environments and they can reduce energy use by avoiding air conditioning (Li et al., 2015; Wang & Greenberg, 2015). These buildings offer building occupants control mainly through the ability to open windows and adjust blinds. It should be noted however, that if occupant behaviour appears to be 'at odds' with the operating principles of the building this is often due to inherent limitations in the building design. Access to window openings or heating controls may be difficult or not intuitive to operate for example, not catering directly for the office users' needs.

Numerous studies in non-domestic buildings (PROBE, 1999; Clements-Croome, 2006) show that users prefer buildings with facades with which they can interact, as opposed to fully serviced spaces with sealed facades. Leaman and Bordass perhaps state this best in their PROBE Post Occupancy Evaluation (POE) analysis 'Simpler systems with usable controls and interfaces for occupants can give better results in terms of user satisfaction than more elaborate (and often more energy-consuming) systems with control interfaces which are poor in function, location, clarity and responsiveness, or even absent.' (Leaman & Bordass, 2001).

Armitage et al used Display Energy Certificates to quantify public sector office energy consumption. Their work indicates that naturally ventilated buildings on average have lower overall energy usage than air-conditioned offices. The median CO_2 emissions of air-conditioned offices was found to be around twice that of naturally ventilated offices, although it should be noted that the level of electrical equipment in air conditioned offices was typically higher (Armitage et al, 2015).

In a UK context, heating loads dominate over cooling (if present at all), especially for older non-domestic buildings. Whilst opening of windows in the summer months can deliver office environment benefits it can risk increasing winter space heating loads. The window-opening behaviour in office buildings is associated with both psychological and physical factors (Schweicker, 2010; Wei et al., 2011; Fabi et al., 2012). The main body of current research has focused on forecasting and modelling window opening behaviour patterns in relation to thermal discomfort and environmental parameters. These include indoor and the outdoor temperature; with indoor temperature showing a more prominent impact (Raja et al., 2001; Inkarojrit & Paliaga, 2004; Nicol & Humphreys, 2004; Haldi & Robinson, 2008; Herkel et al., 2008).

Some studies have indicated that the window opening behaviour in offices is strongly affected by the season (Herkel et al., 2008; Fabi et al., 2012) with the least number of windows being open during winter and the most during summer, indicating air quality as a strong motivation. It is suggested that most window control activities take place when the occupant arrives and leaves the office and the state of the window remains constant during the majority of the workday (Fritsch et al., 1990; Yun & Steemers, 2008). However, thermal comfort and the environmental factors are not the only drivers of changing the state of a window. There are “internal or individual factors” (Schweicker, 2010; Fabi et al., 2012) that play an important role such as gender, floor level, cultural background and personal preference (Wei et al., 2011). This primary driver of the work described in this paper is winter office window behaviour, where the risk is wasteful energy usage. The approach can equally be applied to summer periods where enhancing thermal comfort in naturally ventilated offices by making better use of thermal mass for example (and ultimately avoiding the need for air conditioning) is a key driver in what is a warming climate.

In a domestic setting, a householder is directly responsible for the energy bills and would therefore, not consciously leave a window open overnight during the heating season unless ventilation needs dictate this. In an office environment however, there is usually no direct monetary driver for the occupant to operate the façade in the same energy efficient manner that they would do so in their own home. Whilst there are several drivers to open a window in an office (such as air quality and seasonal summer night-time precooling (Yun & Steemers, 2008), the driver to close the window at the end of the working day (energy awareness) may be very weak unless there is an additional external driver such as external noise, wind, rain or a security risk which only exists on a ground floor office. Here we are highlighting the split incentive between occupants of offices and owner occupiers of domestic buildings. This is not to say however, that office buildings are often poorly designed, maintained and operated and fail to reflect the needs of their occupants. What we describe here as non-optimal window usage may be an artefact predominantly of the building's flaws rather than effect of the user. As highlighted by Hadi and Halfide in Going Green: The Psychology of Sustainability in the Workplace (Going Green, 2011), 'if users are uncomfortable they will adapt the building to meet their needs, even if this increases energy wastage'

Recent research in economics and psychology has shown that non-price interventions, including social approval, consumption feedback, energy reports comparing customers' energy usage with comparable households can have sizable effects on reducing energy usage, at least in the short-term (Allcott & Sendhil, 2010; Crowley et al., 2011). Similarly, much of human-computer interaction research in recent years has been devoted to 'design and evaluate' interventions that provide 'eco-feedback' about energy consumption (Froehlich et al., 2010), for end users to review (Agha-Hossein et al., 2015)). The fact that in a non-domestic building context, users do not pay the energy bill makes non-price interventions even more relevant.

Whilst there is a growing body of research that tries to understand the effects of non-price interventions on households' energy consumption, the literature is almost silent about the effectiveness of such policies in non-domestic buildings. Amongst the few exceptions, prior research (Siero et al., 2006) indicates that employees change behaviour when they are provided with tailored feedback about specific wasteful activities in the workplace (Coleman et al., 2013; Murtagh et al., 2013) and that this effect is stronger when a comparison with the behaviour of a similar group is also conveyed. Ackerly & Brager highlight that lower levels of participation with signalling systems occurred with occupants who tend to pay little attention to their windows (Ackerly & Brager, 2013). Jain et al (Jain et al., 2012) assessed various eco-feedback interfaces and demonstrated that historical comparison and incentives are design components that drive higher engagement and thus reductions in energy consumption. Brown et al (Brown et al, 2009) highlight the need for participants in building energy interventions to receive effective feedback on their adaptive behaviour stating'…occupants draw on a range of sources to form opinions about how well they know a building, how 'green' it is and whether or not it is comfortable. Results suggest that occupants can only truly be active participants if they receive effective feedback on their adaptive behaviour'.

Furthermore, domestic energy use studies suggest that the concept of a chain of "increased feedback to increased awareness to behaviour change to energy savings" (Wilhite & Ling, 1995) fails to represent all of the social and cultural parameters that affect energy use behaviour (Hargreaves et al., 2010). It is expected that despite the differences in the environment between houses and offices individuals will carry some characteristics of their background that will affect their interaction with the building controls in the workspace. More recent work around energy consumption feedback in the workplace (Foster et al., 2012; Jain et al., 2013) includes more general studies about employee's perceptions and attitudes around resources conservation and waste in the workplace.

Providing user control therefore, poses a real challenge to the facilities manager. 'Happy productive users' prefer control of the façade, which is what well designed non-domestic building environments should provide (Clements-Croome, 2006), but providing this control introduces significant heating season energy performance risk. Naturally ventilated office buildings in the UK in particular, often have very limited building management systems which provide very poor levels of information to the facilities manager. It is generally not economic to retrofit systems that could provide individual window status information or actuators for automated window control. There are a number of technical barriers notably the provision of power to sensors or actuators on a facade. An alternative low cost approach would be the use of cameras external to the facade of a building to automatically diagnose the status of the facade in terms of window opening, blind and internal lighting usage. This information could then be used to inform the Facilities Manager or engage directly with office users to raise awareness and engender behaviour change. It is an assessment of this low cost, camera based approach which is the focus of this paper.

Determining the level of glazing on the facade of a building using image processing techniques (Kulkarini V, 2011; Mayer & Reznik, 2005) or remote sensing approaches such has LIDAR (Aijazi A.K. et al, 2014) are fairly well established techniques. Estimation of window opening status is a far more difficult task and requires high frequency sampling of the facade to detect changes. Possible approaches include:

(1) Magnetic reed switches on individual windows, but this is generally not practical for retrofit. Wireless sensor networks may be used but sensor battery life and wireless range issues are limitations,

(2) Monitoring of temperature or CO_2 decay profiles overnight in offices or homes to estimate variability in air change rate which is strongly influenced by window opening level (Papafragkou A. et al, 2014). This approach cannot give real time analysis and only indicative average overnight window opening level.

(3) Visual estimation of facade status from camera images or surveys. Labour intensive, not economic at scale and not possible in real time.

(4) 3 axis accelerometers mounted on windows. Determines angle of a window and time of opening / closing event (Voigt J., 2015). Possible in real time for wireless sensors. Excellent for research studies, retrofit is easy, there are power and cost issues for deployment at scale.

2 UNDERSTANDING WHY PEOPLE OPEN AND CLOSE WINDOWS IN AN OFFICE

Prior to developing a technical solution to window opening estimation it is important to understand the drivers and motives of office users in relation to facade interaction, in essence 'why do people open and close windows in an office?'. An online questionnaire survey was distributed to develop some understanding of the context and motivation for office based window opening and closing. What are the drivers for facade interaction? To what extent is this learned 'time of day' behaviour or a perceived response on the part of the occupant to environmental conditions? Previous work (James et al, 2006; James et al, 2008) has identified security as a strong driver on ground floor offices and bad weather in particular. Window type also has an important role to play, offices with centre pivot windows for example, have a particular issue with driven rain which means occupants 'learn' to close them through personal experience.

In September 2015, an online questionnaire was sent by through a University mailing list and then also snowballed (people were asked to forward to others and other mailing lists. There were 91 valid questionnaire responses (response rate unknown). The sample comprised 32 female and 59 male participants aged between 22 and 71 years old (median: 37). The online survey consisted of questions related to (1) to the occupants' understanding of energy waste in the workplace and (2) to the drivers for interaction with a building's facade and in particular with the windows. 78 of the respondents stated they could open a window in their workspace.

The questions related to the window opening behaviour distinguish between the seasons and were based on open ended responses. That was dictated by the seasonal change between heating and cooling requirements in the UK and the differences expected to the occupants' behaviour due to thermal comfort. A question asking about personal standpoint in relation to energy saving in general was included in order to explore the motivation of the participants and the level of their environmental awareness.

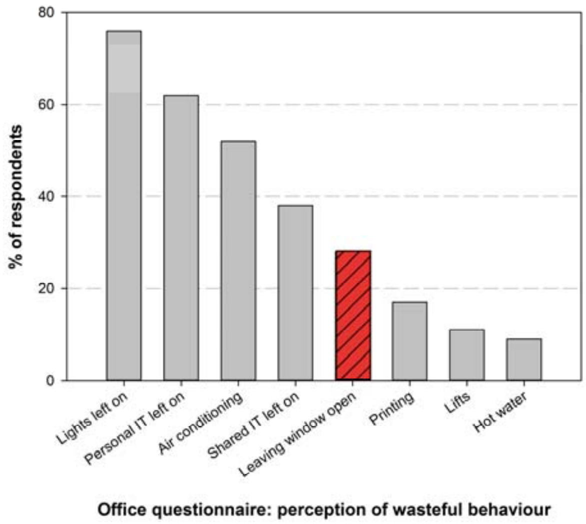

Figure 1 Office questionnaire responses - user perception of wasteful types of energy related behaviour in a naturally ventilated office. 'Leaving window open' responses are highlighted in red.

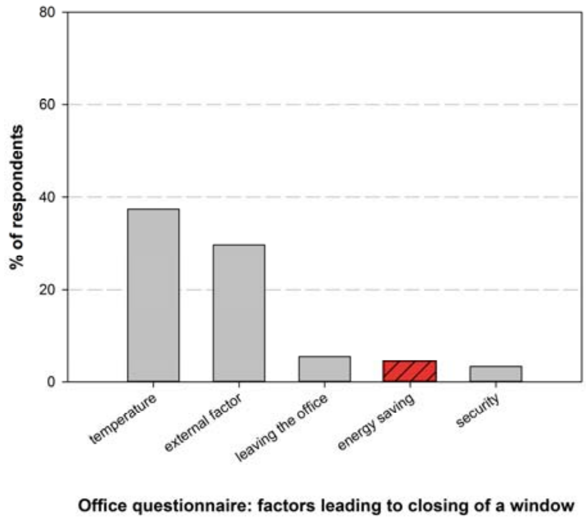

Figure 2 Office questionnaire responses – reasons for closing a window in a naturally ventilated office. 'Energy saving' responses are highlighted in red.

It would intuitively be expected that individuals highly motivated towards environmental protection would adopt resource saving habits across all aspects of their life. Surprisingly, the vast majority of the respondents did not associate wasting heat with energy waste (i.e. appeared unaware of this issue) despite their stated high level of environmental awareness (Figure 1). Most responses indicate that occupants of office buildings are inclined to save electricity but not heat. This decoupling of heat from energy 'saving' is one of the research questions that interventions following this reported study will try to address. The reasons for closing of a window are more associated with environmental influences (temperature, noise, rain, wind), energy appears as a weak driver in this respect (Figure 2).

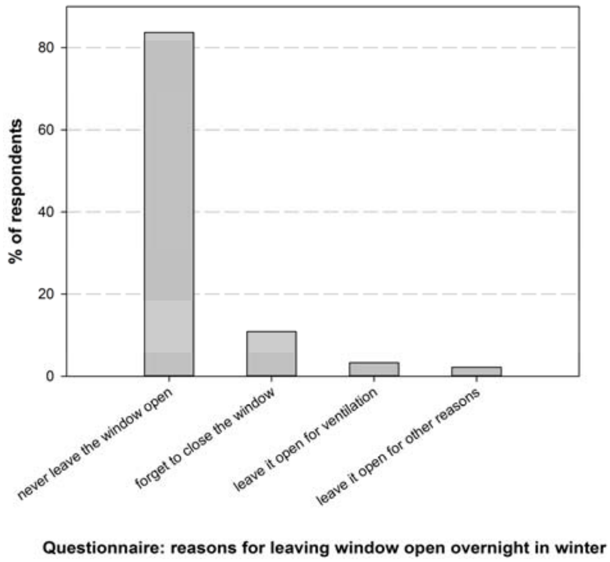

***Figure 3** Office questionnaire responses – reasons for 'leaving a window open overnight during the winter'.*

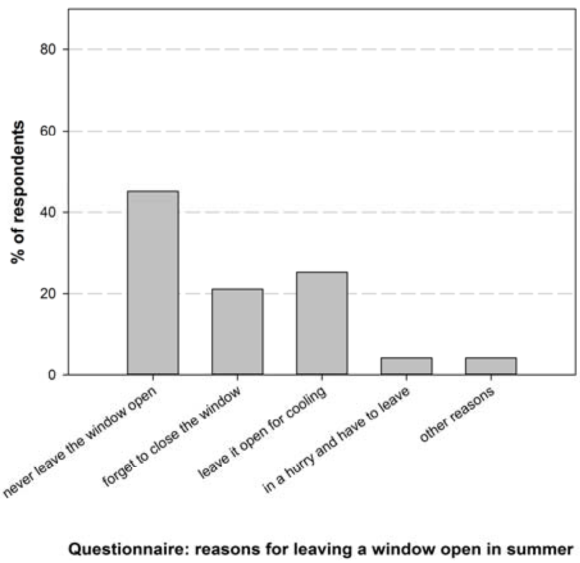

***Figure 4** Office questionnaire responses – reasons for 'leaving a window open overnight during the summer'.*

The respondents were also asked whether they leave the office windows open during the night in winter. 55 out of the 71 participants (77%) that have access to an external window replied that they never leave the window open overnight during winter (Figure 3). The main reason for leaving the window open was 'forgetfulness' while some responses pointed out the important role of ventilation rates. Regarding the summer period, 45% of the respondents with access to a window replied that they would never leave the window open overnight (Figure 4). This behaviour has significant potential to impact on the night cooling potential of naturally ventilated buildings which is clearly desirable in naturally ventilated buildings. Only 25% of the participants in the survey have indicated that they leave the windows open for cooling or ventilation purposes. The results underline that a large number of office occupants may, (1) not be informed about the function of the building or the use of its control(s) and (2) they may have difficulties or obstacles in operating any building controls successfully (e.g. windows near IT equipment, security and building design issues).

3 METHODOLOGY

This paper details the technical assessment of an optical camera based approach to determine window opening status of a facade of a naturally ventilated office building at the University of Southampton.

3.1 Technical specification of optical camera based approach

A 16 MP Samsung Galaxy digital camera (model EK-GC100, 3G and Wi-fi enabled) running Android is used to take images of a facade. Facade status detection is based on the geometrical features of the windows and it is limited to hours of the day in which there is sufficient daylight to distinguish the windows in the captured images. The images acquired from the digital camera are automatically and periodically uploaded via FTP to a server for processing. Each image was segmented into individual windows. Each window sub-image was then processed to identify the most dominant parallel lines, which generally correspond to the lines of the window frame. The angle that the lines make when crossing each other is used to determine whether the window is open or shut. As shown in Figure 5, intuitively, when the window is shut, the lines will cross at 90 degrees, while when the window is open, they will cross at different angles, and the values of the angles can be used to estimate how widely the window is open.

The majority of buildings have planar facades which enables a perspective transformation is applied to each image (Hartley, 2004). This is a matrix-based transformation which makes the entire façade appear perpendicular to (i.e "front facing") the camera. Because the camera position is fixed with respect to the building, the transformation matrix is calculated only once, on the first image acquired, based on the manually selected four corners of the façade, and then applied to each subsequently captured image. The first (back) projected image is then manually segmented into rectangular regions of interest (ROIs), such that each ROI contains a single window, and a small surrounding frame (the frame being approximately 10% of the window size, in order to include at least a portion of the window pane, if the window is open, see Figure 5 bottom row). Again, given that the camera position is fixed with respect to the building, this manual operation is calculated only on the first frame, and then applied to all subsequent ones.

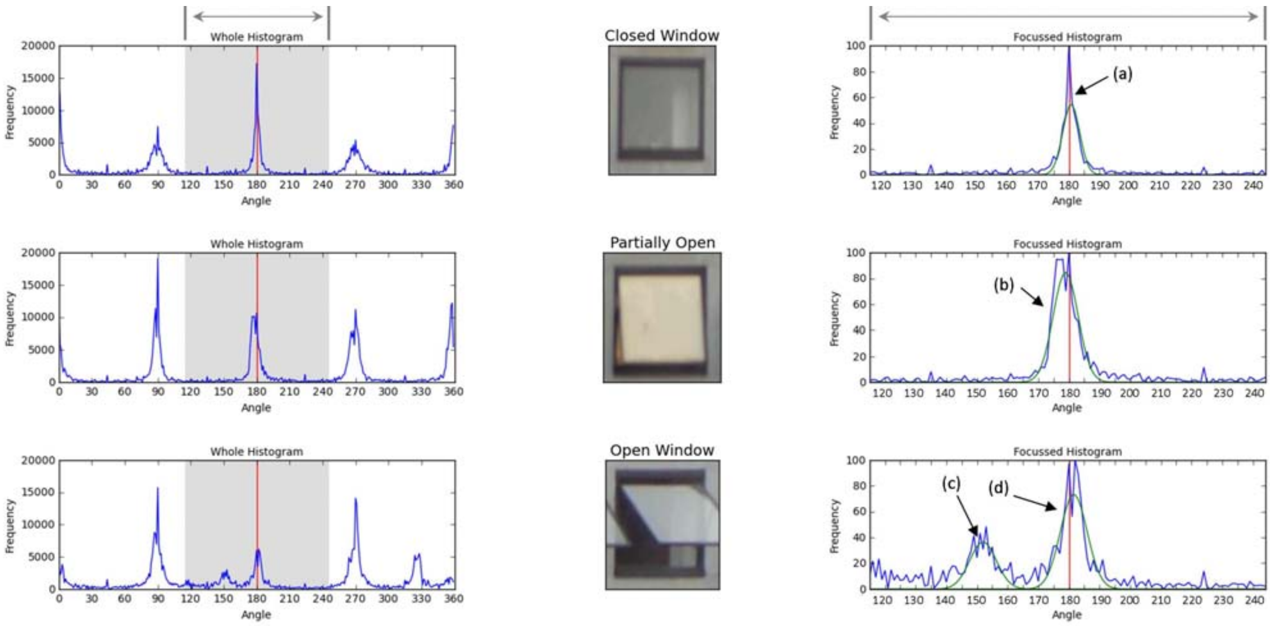

Figure 5 *Histogram analysis of a closed (top), partially open (middle) and open (bottom) window. An asymmetric histogram is generated in the case of an open window.*

As outlined above, the analysis of whether each window is ‘open’ or ‘shut’ is based on the dominant straight parallel lines found in each window. A standard edge detection operator, the Sobel filter (Gonzalez & Wood, 2008), with mask size 3 pixels, is applied to each ROI. This filter performs a two dimensional spatial gradient measurement on the image resulting in an image with emphasized edges. In image processing 'edges' are defined as set of points where there are discontinuities in the image brightness. The Sobel filter was chosen because it yields information about both the intensity (magnitude) and the direction (phase) of edges in the image. A histogram is then produced to summarize the edge orientation over the entire ROI. For this purpose the phase of the edge at each pixel is weighted by the corresponding edge magnitude. Peaks within this histogram correspond to dominant edges within the ROI.

The histogram is then smoothed through a one-dimensional Gaussian filter (size 10 samples, variance 2 samples); this filter was chosen in order to remove high frequency noise, whilst preserving the sort of peaks that correspond to windows (the values were tuned empirically). A threshold is applied to the smoothed histogram data to remove values below 1, which correspond to image noise, rather than actual edges. In the case of top hinged windows (as observed in this study), the most informative edges are the ones that are vertical or close to vertical, these correspond to the interval (binned distribution) of the histogram surrounding the vertical axis (180 ^{o}): from 112.5 ^{o} to 247.5^o. This interval of the histogram is then automatically segmented into individual peaks. A Gaussian curve is then automatically fitted to each peak through a nonlinear least square error minimisation in order to identify the centre of each peak with sub-pixel accuracy. A threshold is applied to the smoothed histogram data to remove values which correspond to image noise. Each window is then classified as 'closed', 'marginally open' or 'open', as follows:

- the window is considered closed if there is a single peak centred within 1^o of the vertical (phase angle 180^o), shown as (a) in Figure 5. This corresponds to the situation where the window pane is aligned to the window frame, and all the non-horizontal edges are perfectly vertical.

- the window is considered partially open if there is a single peak with its centre further than 1^o from vertical (phase angle 180^o), shown as (b) in Figure 5. In this case, the window pane is slightly misaligned with respect to the frame, so the non-horizontal edges corresponding to the frame are vertical, but the ones corresponding to the window pane are "slightly slanted". Because the offset between the two peaks is small, they show as a combined wider peak.

- the window is considered open if two (or more) peaks are detected -- the peaks represent the vertical edge of the window frame and the slanted edge of the window pane, (phase angle 180^o), shown as (c) and (d) in Figure 5. We take the furthest peak from the focus angle as determining the angle of the window (30^o in the case of (c) in Figure 5). The output of the analysis process is the window opening classification state and window angle for each assessed image. The greater the estimated window open angle, the greater the confidence in the prediction of a specific window opening state. Here, we have taken 10^o as our threshold for 'window open' status to enable comparative visual ground truth validation.

The accuracy of the proposed approach is clearly dependant on a number of site specific variables including: (i) the camera angle to the facade (ideally ~ 45 degrees), (ii) how close a particular window in a facade is to the camera (images have finer detail for closer windows) in addition to environmental conditions (daylight level, rain, glare etc). Daylight level is a particular issue for the approach during the winter months. To reduce noise in the camera based estimation, two consecutive 5 minute readings with the same state and a minimum open angle estimate of 10 degrees was specified to classify a window as open. This does however, have implications for the winter case in particular where windows are generally open at a far shallower angle for trickle ventilation compared to the summer case of far wider open windows.

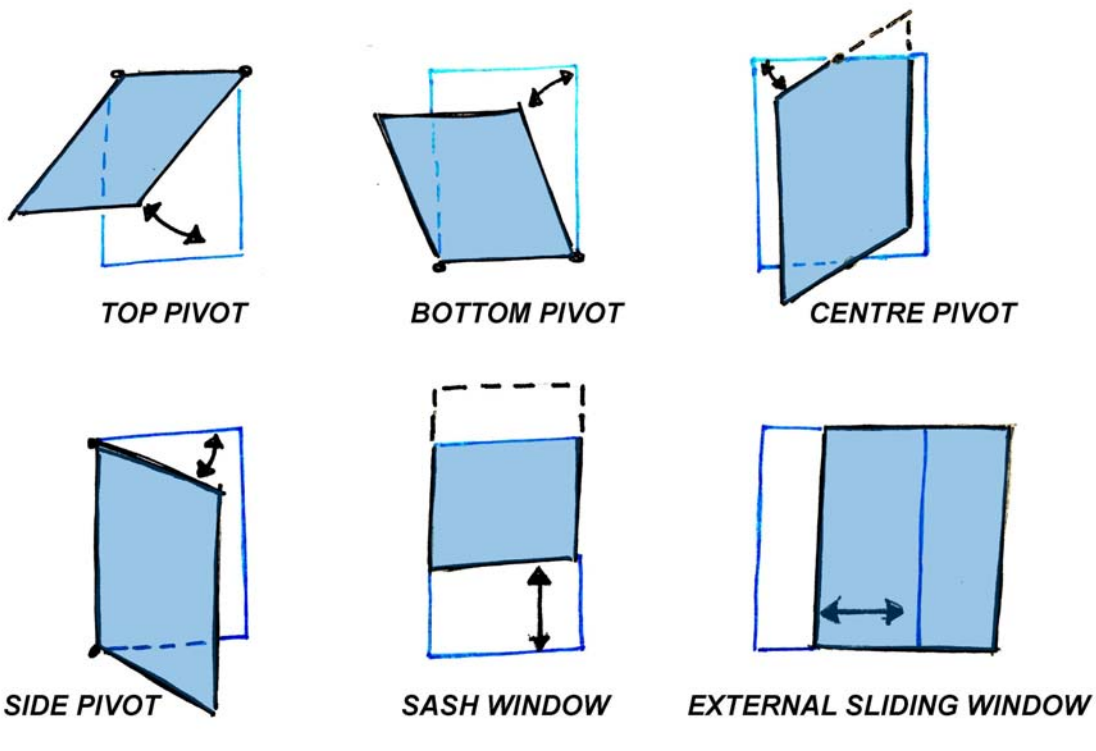

Figure 6 *Six possible window types which are appropriate for edge based (frame) detection.*

Daylight hours on the shortest day of the year (21st December) for Southampton are (08:06-16:02) which clearly creates a potential constraint for this approach. For around 3 months of the year, sunset will occur before the end of the working day which means the last recorded window state may not be representative of the overnight status. An office user could choose to open or close their window during 'dark working hours' which the system will not detect. However, if the first following morning state is consistent the last previous afternoon daylight state, this is indicative of no change during the night working hours of the previous day. The analysis described here corresponds to one of several 'top pivot' window type facades we are studying but could also be applied to sash, sliding and bottom, centre or side pivot window types with adaptation of the algorithm (see Figure 6).

3.2 Window opening assessment using a 3 axis accelerometer

Window state (open/close) and opening angle were also estimated using a 3-axis linear accelerometer attached to a window's internal glass pane (see Figure 7).

Figure 7 *3 axis accelerometer logger fixed to inside of window. Secondary cable fixing provided for safety.*

These sensors were developed by the research team and Redfern Electronics Ltd. The datalogger comprises a MEMS (Micro-Electro-Mechanical Systems) FXLS8471Q sensor, with raw acceleration signal as output expressed in units of gravitational acceleration (g). The specifications of the sensor are as follows: dimensions of 50x35x15mm, range of ±2g or 19.6 m/s2, sampling frequency of 12.5Hz, logging resolution of 8-bit value for each axis equivalent to 15.625mg or 0.15m/s2 with full-scale set to ±2g, and operating temperature of -40°C to +85°C. To maximise battery and storage capacity, the device was programmed to log when a change in linear acceleration was above 0.051 g or 0.5 m/s2 was detected. The linear acceleration is defined as the normalised magnitude of the acceleration vector minus the Earth's gravity. Recording stopped when four successive magnitudes fell below 13-bit unsigned equivalent to 0.244mg or 0.0024 m/s2 with full-scale set to ±2g.

To process the data, R, the statistical computing package [R, 2016] was used as the main computational tool. The first step of the data processing estimated the linear acceleration for each log entry (i.e. was there an acceleration change observed on any of the 3 axis at each timestep). This determined changes in window position by reviewing the frequency of the movement intensity. Then the window's opening angle (A) was estimated using the vertical acceleration (Az); the results were validated using the horizontal acceleration (Ax) perpendicular to the glass pane. The following equations were used:

A = arccos(Az/g) and A = arcsin(Ax/g)

3.3 Office CO_2 decay rates to estimate air-change rates in offices as a function of window opening level.

The air-changes per hour rate of offices in the case study building as a function of window opening level was determined by measuring CO_2 decay rates. The CO_2 in an office was raised to ~ 1200 ppm through high occupancy (8-10 people in the room), the office was then vacated and the rate of CO_2 decay recorded using a CO_2/humidity/temperature datalogger (Extech SD800). The external CO_2 concentration at window height was measured from outside another office window further along the facade. Typical recorded CO_2 decay curves are shown in Figure 8 and are determined by the air change per hour rate (level of mixing) with the external CO_2 air. The overall relationship between facade status and air change rate is shown in Figure 9. For example, if all the windows were open at an angle of 20^o this would represent a 22% open facade [(20^o/90^o) x 100 = 22%] with an air-change rate of 18.5 ac/h. Ideally, there should be very large dataset of CO_2 decay rates for each building being studied representing different conditions of temperature, wind (direction, speed), relative humidity and air pressure. This could be achieved by either, (i) incorporating CO_2 sensors in a selected number of offices into the existing building management system (if possible), or, (ii) adding standalone monitoring, coupled to the window opening analysis platform.

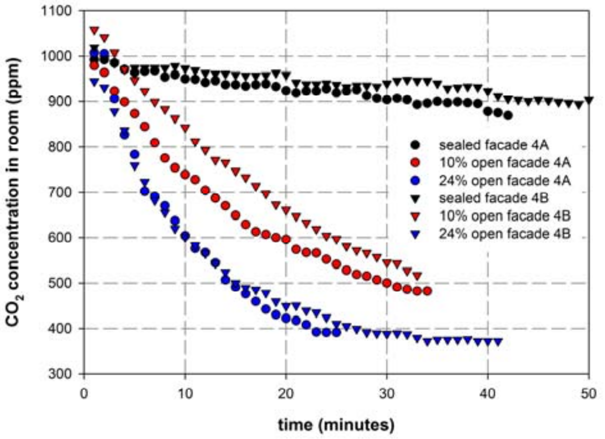

Figure 8 *Sample CO_2 decay curves for different levels of window opening for seminar rooms on the East facade of the Law building, University of Southampton. Tests are shown for two rooms '4A' and '4B' on the level 4 of the building.*

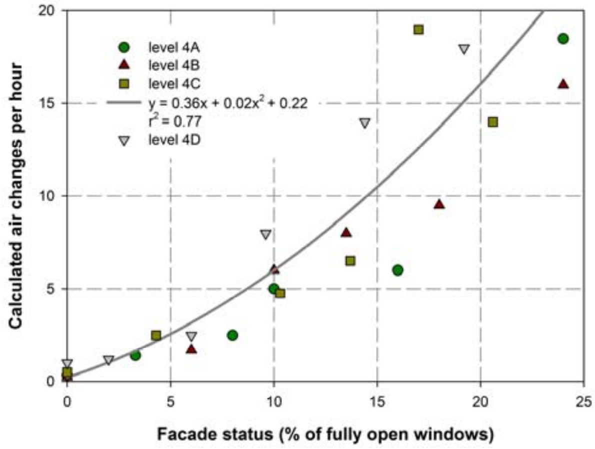

Figure 9 *Calculated correlation between facade opening status and air changes per hour. 0% = fully closed, tilt angle = 0^o, 100% = all windows fully open at 90^o tilt angle. Law building, University of Southampton. 22% open = 18.5 ac/h highlighted. Tests are shown for four rooms '4A, 4B, 4C & 4D' on the level 4 of the building.*

4 VALIDATION OF CAMERA BASED APPROACH

4.1 Case study facade

The east facade of the Law building at the University of Southampton was used to test the camera window system. This is a 1960s naturally ventilated semi-cellular office and seminar room building with identical major east and west facades either side of a central corridor that runs along the spine of the building. The windows are the original steel framed, single glazed, with the entire building clad in Portland stone (Figure 10.).

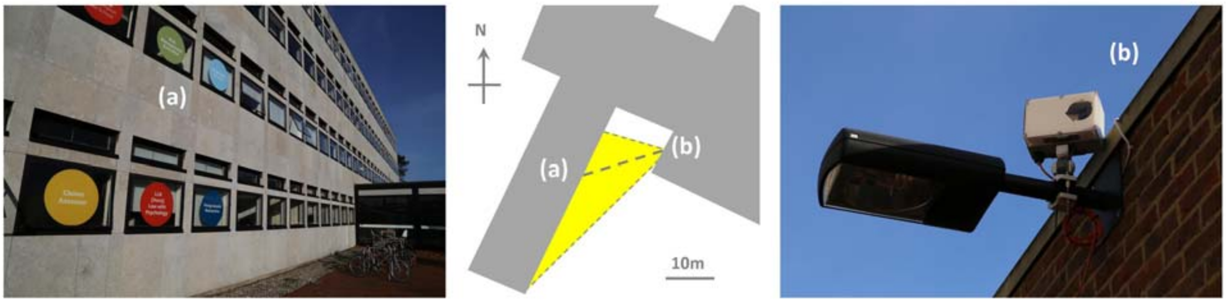

Figure 10 *Case study facade, east facing elevation of Law building, University of Southampton. Camera position (b) orientated 45 degrees to east facade (a) on a street light.*

The digital camera was positioned at approximately 45 degrees to the facade to enable capture of a side view of the windows (Figure 10). The field of view of the camera is around 60^{o}, at a distance of approximately 10 metres from the closest window and 35 metres from the window that is farthest away. The heating controls in the building are generally inaccessible (which from our experience of older UK naturally ventilated office buildings is not unusual) and this exacerbates poor window behaviour – many users feel their only option in response to overheating is to open a window. This is not to say that this ‘energy wasteful behaviour’ is the ‘fault’ of the building user but more the provision of poor user controls within offices. The building is connected to the University’s combined heat and power (CHP) heat network – the heating strategy of the campus is essentially seasonal in terms of operation (ON / OFF). Since the hot water supply of the heating system runs in series from office to office, if a number of neighbouring offices close their windows this raises the return water temperature, risking further overheating of offices further down the heating loop. The unprotected, in terms of solar gain, east elevation can also experience high levels of solar gain in the morning, especially during the winter due to the low solar zenith angle. This unpredictable solar gain exacerbates the issue of poor heating control and leads to greater direct user engagement with the facade. Operation of the camera system has been assessed across both summer and winter periods corresponding to overheating and wasteful heating risk.

4.2 Summer camera operation

The summer period reported here is 17/05/2015-23/05/2015 and 7/06/2015-20/06/2015 inclusive (21 days). The gap in the sampling corresponds to a period when there were issues with the camera's automated timed image acquisition and FTP transfer software which have now been resolved. Over the studied period 3024 images were recorded, each of which was then split into 40 'window images' for window status determination using the automated image processing described above (see section 3 and Figure 5) and human 'by-eye' ground truth validation of the raw images (manual classification of each window image into one of four states). The total number of window images to analyse was therefore, 120,960 (3024 images x 40 windows). Classification of images was into one of four conditions as follows, either 'open', 'closed', 'unknown' or 'too dark' (Figure 11). Here, 'open' from human 'by-eye' is considered equivalent to the 'open' two histogram peak classification of the camera based system. The human 'by-eye' processing task took approximately 5s per image, corresponding to ~168h of manual processing time. There was an ~97% agreement between the human by-eye ground truth and automated processing between 07:00 and 19:00 which shows the success of the technique under summer conditions. During this period there were only four days when it rained and in each case it was for a short period.

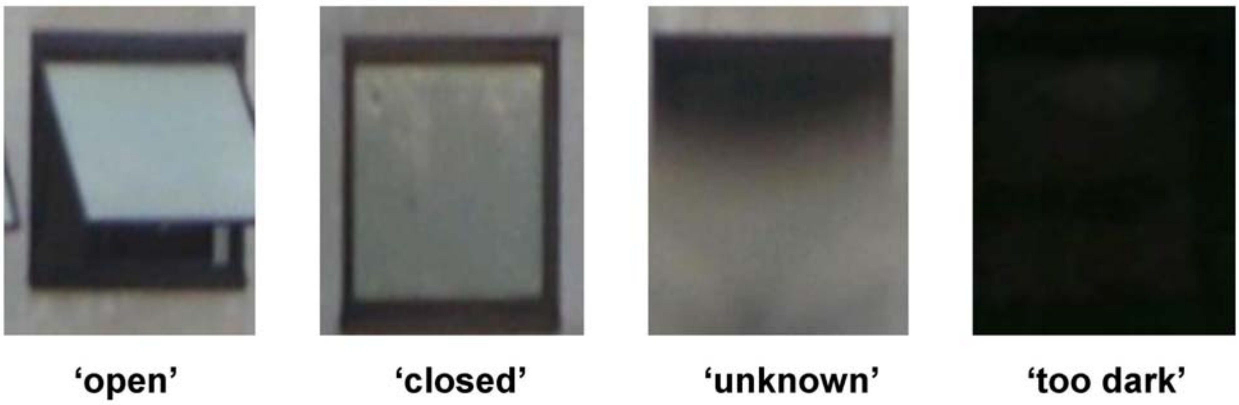

***Figure 11** Four classification window states for human 'by-eye' ground truth validation of automated camera based image processing algorithm.*

4.3 Winter camera operation

The winter period test period shown here is November 2015 (30 days) which unlike the dry summer period was characterised by several periods of rain. November was chosen as a study month as it is in the middle of the 10 week term where office and teaching room use would be expected to be consistently high. Here we report on the camera system's prediction of window status for 4 rooms on this facade (level 1 (ground), 2, 3 and 4) which include selected accelerometer window measurement. In total, across these 4 rooms there are 19 windows. The estimated window opening level across an illustrative five day period is shown in Figure 12. In comparison to the summer period, we observed that windows were generally opened to a far smaller tilt angle and less frequently left open overnight. Driven rain was observed to be the primary driver for subsequent closing of a window. To further validate the camera system in the winter matchbox sized accelerometer loggers were mounted on nine windows of the facade within these 4 rooms. This 3-axis MEMS linear accelerometer 50Hz datalogger enabled (i) the monitoring of window opening behaviour (open/close), and (ii) the estimation of the top pivot opening pane's tilt angle (see Figure 7). The camera system had a post-processing tilt threshold set of 10 degree opening for a window and two consecutive frames with the same status before returning an opening event to reduce noise in predictions during this period.

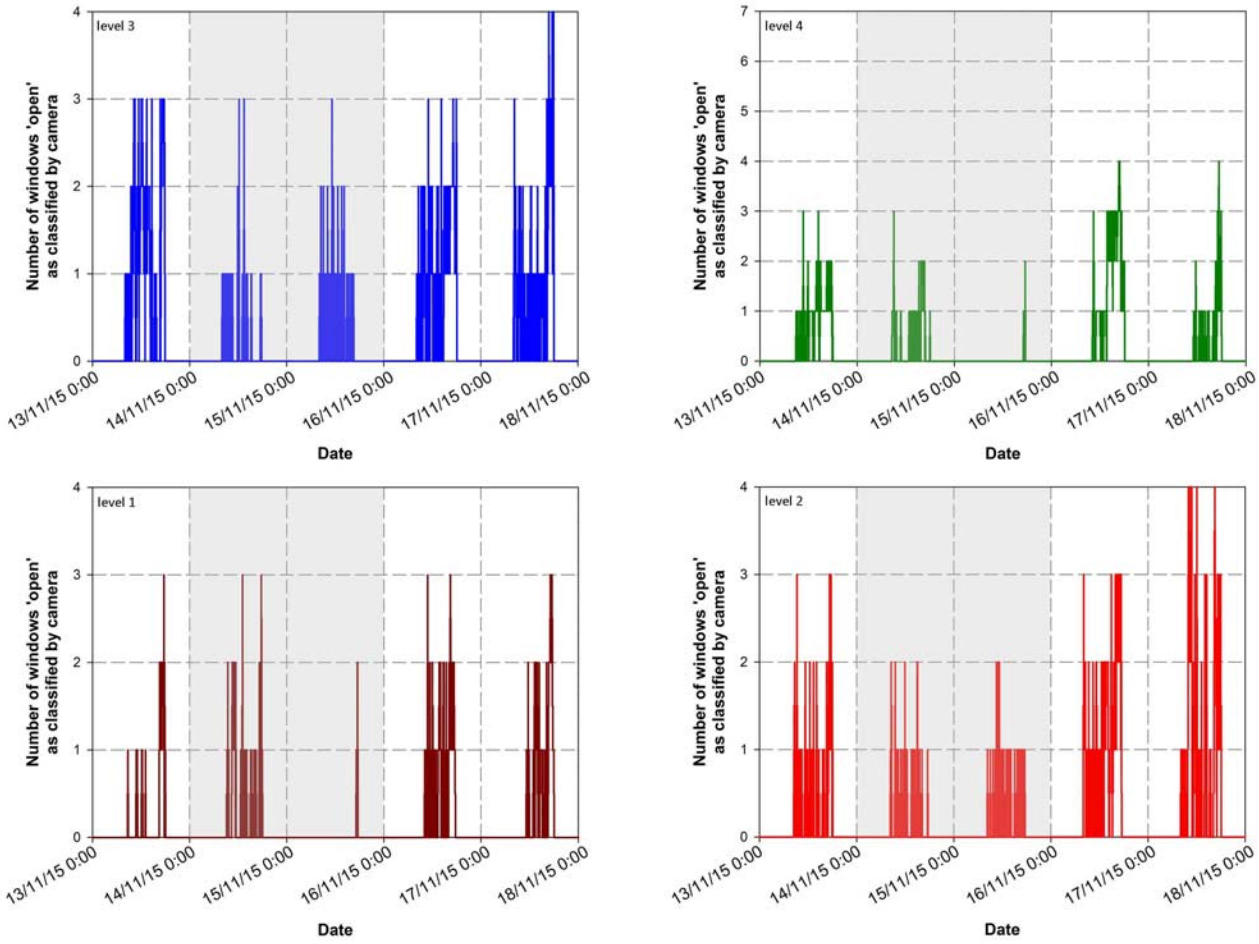

Figure 12 *Camera based estimate of window opening over a 5 day period 13/11/2015 (Friday)-18/11/2015 (Wednesday). Grey periods represent the weekend – where 9 windows with accelerometers recorded no periods of opening. NOTE: camera based estimate of a status during working hours only is shown (07:00-19:00)*

The daytime accuracy (07:00-18:00) of the camera system against the MEMS accelerometers during November 2015 was found to be around 91%. This is worse than the 97% summer agreement and is a reflection of the more challenging conditions for winter camera operation (rain, daylight hours) rather than the use of a different validation method. The human by eye ground-truth approach was not undertaken in the winter case due to its labour intensive nature compared to the accelerometer approach. In addition, the accelerometer approach does not require daylight, which is a winter issue for the camera based approach and so provides complete 24h coverage of the state of each window.

The camera based system was observed to produce a number of false window open estimates (~ 3%) during the winter period. This is highlighted in Figure 13 which compares the camera and 3-axis logger assessment of two windows. In the level 2 room (left in Figure 13), there are false positive events on 16/11/2015 and 19/11/2015. There are also 3 window opening events which the camera did not detect (narrow blue line on 17/11/2015, 18/11/2015 and 19/11/2015) all of which were of a very short duration (2 camera frames over 10 minutes).

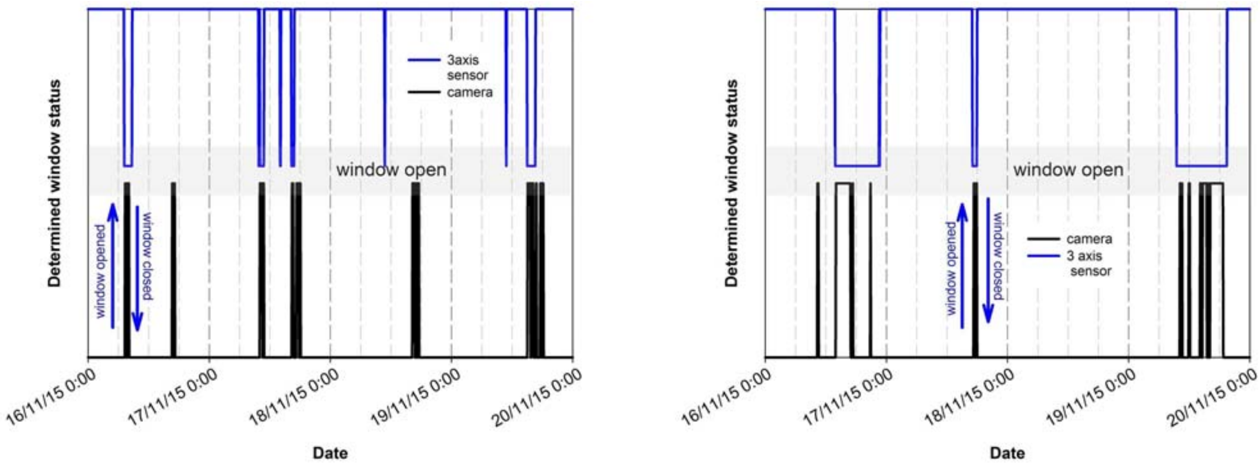

Figure 13 *Comparison of camera based estimate (lower black) of window open status with 3-axis accelerometer logger (upper blue) for two windows of level 2 room (left) and level 4 room (right). When the blue and black line co-incide the window is open and the camera detects the status correctly.*

There are a number of possible reasons for the slightly reduced winter performance of the camera based system in comparison to its summer operation. These include:

- Raindrops on the camera housing distorting the images
- Greater number of clouds creating rapid changes in contrast between images
- Lower zenith angle sun which exacerbates glare issues on the facade
- General lower levels of contrast in images due to overcast days with low light levels
- Low light levels at critical window operation periods (07:00-09:00 and 16:00-18:00) due to the shorter winter daylight hours

- Windows are opened to a lower angle in the winter than the summer – this is a combination of thermal discomfort (draft, higher wind-speeds) and greater probability of rain. This creates a more challenging facade for the camera based system to analyse.

5 ENERGY IMPACT OF OPENING A WINDOW?

The observed CO_2 profiles in 4 seminar rooms and the corresponding aggregated window opening level are shown in Figure 14 and 15 respectively. A number of windows in the seminar rooms on levels 2, 3 and 4 are open during the day which results in a rapid fall in CO_2 concentration after occupants have left the room. In contrast, the level 1 room shows a very slow CO_2 decay which indicates that the windows were either closed at the point that occupants left or were closed all day. The latter is the more commonly observed pattern on level 1 due to security and noise disruption if windows are open.

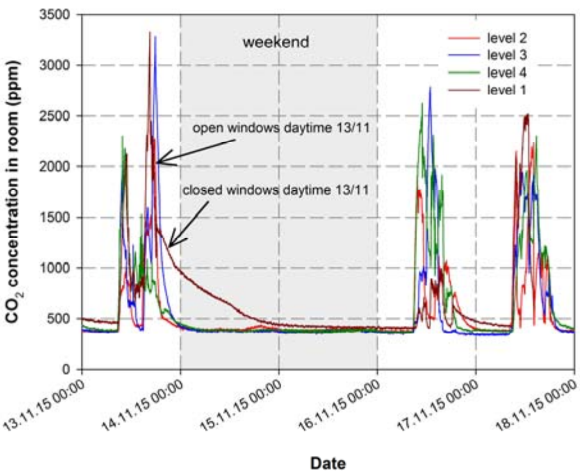

Figure 14 *Observed CO_2 decay patterns in 4 seminar rooms, 13/11/2015-18/11/2015. The weekend is highlighted in grey.*

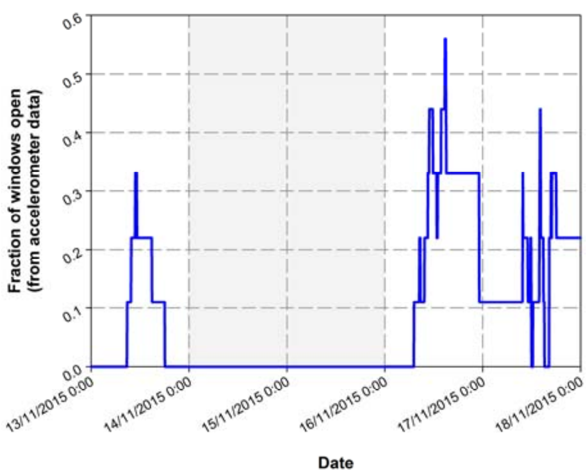

Figure 15 *Fraction of windows on the facade defined as open by accelerometer loggers. Note all windows with accelerometers were closed over the weekend. The weekend is highlighted in grey.*

This facade forms the boundary of a main thoroughfare of the campus and so experiences high levels of foot traffic as students move between lectures. In addition, due to security risks this window would be closed each evening as a matter of course. It should be noted that all windows with accelerometers were closed over the weekend (shown in grey).

The average angle of an open window recorded by the accelerometers was 20 degrees. Outside of the working hours (07:00-19:00) the average level of window opening was recorded as ~10% (see Figure 16). 10% of windows open at an angle of 20 degrees corresponds to an effective air change rate across the entire facade of ~1.85 ac/h (see Figure 12, [(20^o/90^o) x 100 = 22%). In contrast the air change rate of the facade with the windows closed (the infiltration rate) was measured at ~0.6 ac/h. The net air change rate associated with out of hours open windows is therefore the difference, approximately 1.25 ac/h. NOTE - These tests were undertaken under calm weather conditions and so will represent an underassessment of air change rates during periods of high winds when there will be a larger pressure differential on the facade.

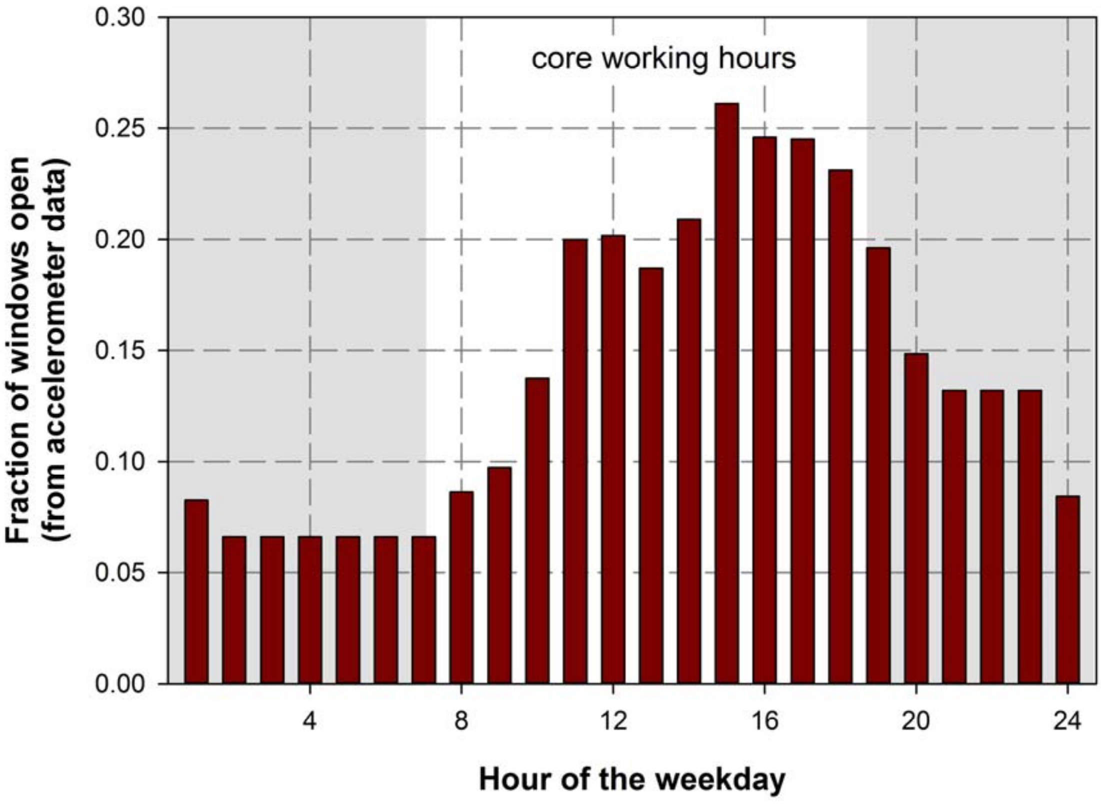

Figure 16 Window open profile for a working day (Monday – Friday) during the 'winter months' as defined by 3 axis accelerometer loggers. Outside of the core working hours (07:00-19:00), the fraction of windows which are open is ~10%, with an average angle of 20 degrees.

5.1 Simple indicative calculation of waste heat impact

The typical energy associated with ventilation, Q_v, can be estimated using the well-known formula (CIBSE, 2005) $Q_v = (nV/3)\ .\ \Delta\theta$ *[W days]*

Where n, is the number of air changes per hour, V, the volume of the room and $\Delta\theta$ is the number of degree days in the heating season for the location.

If we consider the CIBSE TRY weather file for Southampton (analysis year range 1978-2000), this can be used to estimate the typical temperature gradient between the office (maintained at 21 deg C) and ambient. Here we assume that 'out of hours' corresponds to Monday: Friday (18:00-08:00 inclusive) and Saturday:Sunday (00:00-24:00 inclusive). We have also assumed a 'heating season' of five months, 1st November:31st March inclusive, which corresponds to 2106 heating degree days between ambient and 21 deg C.

The energy implications of the observed open window behaviour for this period – if this effect was replicated across the above heating season would therefore be: ((1.25 x 83)/3) x 2106 W days for a typical 83 m^3, 36 m^2 seminar room. This corresponds to a floor space heating load of 49 kWh/m^2 annum.

This approach delivers a quick, first order estimate of heating associated with 'out of hours' window opening use. Clearly dynamic simulation modelling will deliver a more robust estimate but this is both time consuming and expensive and so does not fit with the premise of a camera system which is a widely deployable, low cost solution. If however, a Facilities Manager wishes to assess the energy implications of window opening in further detail, clearly the measured window patterns will feed directly into a dynamic model.

The Display Energy Certificate (DCLG, 2015) of the case study building (rated F on a scale of A (best) to G (worst)) lists the heating load as 259 kWh/m^2 annum and the electrical load as 102 kWh/m^2 annum. This simple analysis estimates <u>out of hours window behaviour to account for around 19% of the annual heating load of the building</u>. Display Energy Certificates are updated annually in public sector buildings and provide a clear, validated approach to assessing the energy saving impact of a window use intervention for the Facilities Manager or building owner.

6 CONCLUSIONS AND FUTURE WORK

This study has demonstrated the proof of concept of a camera based diagnostic approach for windows on an office building facade. Across the summer (97%) and winter (90%) study periods reported here there is a good agreement between the automated camera system and a ground truth of either a window mounted accelerometer or human diagnostic (by eye) classification during working hours. In the case study building a correlation between level of facade opening and air change rate enables the status of a facade to be converted to an annual 'window energy waste' estimation. Potential unnecessary window opening has been estimated at around 19% of annual heating load in the case study building. This figure should be considered as the upper limit of potential energy saving as clearly user behaviour will not transition to the 'building physics ideal' following any office user engagement approach.

In relation to future work, the study is now deploying the described approach across six naturally ventilated buildings at the University of Southampton. These buildings will form the basis of a control: intervention(s) longitudinal six month study where we will apply the window diagnostic software to automatically engage with building users. This longitudinal study will test escalating levels of intervention in terms of 'personalisation' from 'your building' to 'your office' and 'how you perform in relation to your peers'. This reflects the current literature in this field where providing contextual information has been shown to deliver far greater levels of user engagement. Here we will determine the level of personalisation required and if sustained behaviour change / engagement can be achieved using such a system.

From a building management perspective, seamless automated engagement with building users is attractive, but this must be realised with low operative cost. In this respect, email is the probably the easiest method for a company to deploy within an office environment. We will be trailing additional automated personalised contact, through for example, messages to smartphones. In terms of technology infrastructure, these are also easy to implement, but almost all non-company email approaches require additional levels of co-operation / permission from the office users which reduces ease of use and reach. In terms of common learning / meeting space it is envisaged that a company's room booking system would be integrated with the window diagnostics to contact the users known to be in a space at a specific time of the day.

There are a number of clear limitations to using fixed camera positions as described in this paper. Whilst they provide the desired geometrically consistent images for image processing this inevitably restricts the number of potential facade sites due to field of view and mains power requirements for camera siting. These restrictions have led the research team to develop a camera smartphone application which enables images of a facade taken from a 'similar position' to be automatically geometrically corrected to become consistent. These images may then follow the image processing steps described in this paper and this approach removes the requirement for fixed camera locations. This also opens up more unusual options for sourcing images such as wider crowdsourcing, security staff or from the building users themselves. However, in addition to technical issues, there are a number of ethical issues associated with imaging of a workplace facade and contextual engagement with office users which have to addressed at the facilities manager and office user level. Quantifying the summer benefits of better use of thermal mass (night time pre-cooling) through optimised window opening is a more complex and building specific problem than the winter example described in this paper. This will form the basis of future work to address overheating risk in naturally ventilated offices in a warming climate.

7 Acknowledgements

This work has been funded under RCUK EPSRC grant "APERIO: LOW COST FAÇADE MANAGEMENT IN NATURALLY VENTILATED BUILDINGS", reference EP/L024608/1.

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SUPPORTING DATA

Selected datasets which underly the analysis reported in this paper are available to download from the eprints.soton.ac.uk repository.

BRI_APERIO_DATA.zip 17/01/2017 09:29 12,752 KB

This archive has the following:

(1) Data archive explanation document, data_explanation_BRI_bourikas_APERIO.pdf

(2) Raw accelerometer data, folder ..\accelerometer\

(3) Unprocessed camera images for summer and winter case, under bright and dull conditions, folder ..\camera_images

(4) Room carbon dioxide measurements (ppm), folder ..\CO2