Control Strategies for Building Services: the role of the user

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Summary

Modern control and energy management systems offer great potential both to improve individual comfort and to reduce energy consumption. However, recent surveys of office buildings suggest that aspects of manual and automatic control are not always well suited to the requirements and behaviour of occupants and management. Relationships between control systems and user responses, comfort, satisfaction, and energy efficiency are discussed, with a strategic approach to considering the integration of manual and automatic controls.

Introduction

Modern control and energy management systems have the potential to improve individual comfort and reduce energy consumption at the same time. However, fully automatic control may not be the complete answer.

i There is a growing demand for individual control. Studies of building-related illness [1] also reveal fewer sickness symptoms and greater productivity as perceived levels of individual control increase.

ii For energy efficiency, advanced control systems do not always stop building services running wastefully and unnecessarily, and sometimes can even become barriers, not aids to effective operational management.

Textbooks and guidance material tend to imply that building services controls only need to be designed, installed and commissioned in the engineering sense ("to keep the measured variables within the specified tolerances") [2] to do the job properly. General texts on systems behaviour [eg:3] present a broader view, reviewing the contexts in which controls are used, the interactions between different types of control operating simultaneously, and the operational requirements of the user interfaces. They also recognise that users will want to alter the targets the systems are asked to achieve. In spite of this, the ways in which controls in buildings are actually perceived and used by people (both management and individuals), although vital to performance and to human comfort, has been little researched and is usually treated only incidentally. It is therefore perhaps not surprising that in buildings one finds problems with the user interface, both for the individual and for building and organisational management.

Systems should therefore aim to both:

i keep the measured variables within suitable tolerances, and

ii be capable of responding effectively when, for one reason or other, the measured variables or set parameters are regarded as inappropriate or unsatisfactory.

This approach conforms with thermal comfort theory, where comfort is best defined by the absence of discomfort [for example: 4]. It is therefore curious that building design tends to put more explicit emphasis on the elements of control intended to deliver comfort than those which can alleviate discomfort. Haigh's work on comfort, control and energy in schools [5] found that teachers took control action only when a "crisis of discomfort" was reached, and then became very unhappy with systems which proved unable to respond, as in sealed, mechanically-ventilated buildings.

User and occupant controls

Recent studies for BRE have investigated relationship between building design, building management, control systems and energy performance in offices. This was part of the Department of the Environment's Energy-Related Environmental Issues (EnREI) programme, which aims to reduce carbon dioxide emissions associated with energy use in buildings. Systematic field studies have been carried out in eleven office buildings, with

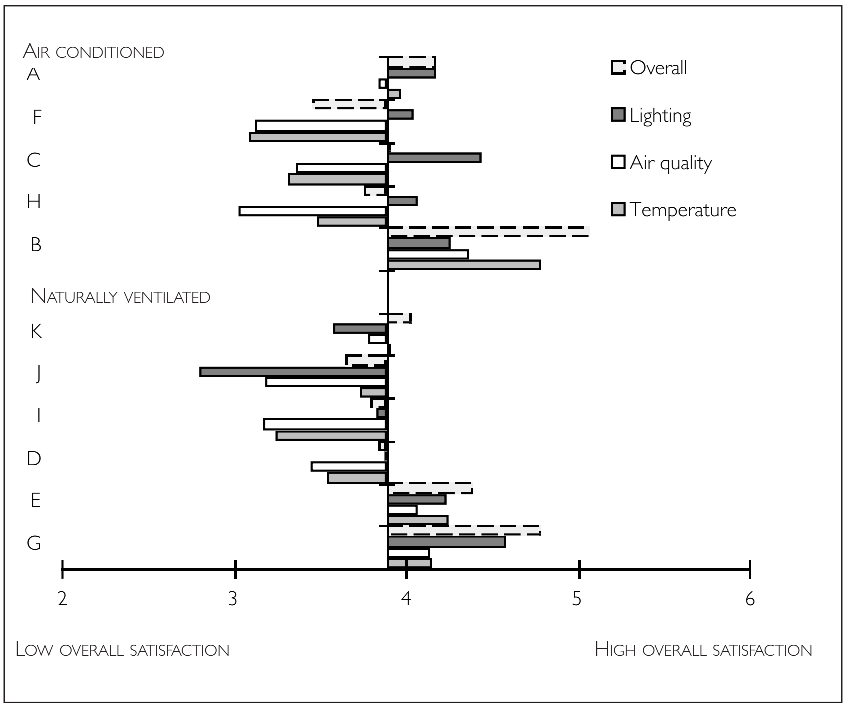

Figure 1
Average perceived comfort scores in the 11 buildings.
The least energy-efficient buildings in each group are at the top.

Buildings A,F,C,H and B are air-conditioned; K,J,I,D and E naturally-ventilated. The scale is a 7-point satisfaction scale (1=low, 7=high). The scores are hinged at 3.8 (a 50-building average for overall comfort from reference 1).

further background from other studies covering nearly 100 buildings.

In the first series of surveys, six 1980s open-plan offices,of which four were air-conditioned, were chosen to illustrate a diverse range of occupancies, qualities, servicing and management. These were investigated by a team of social scientists and engineers, using questionnaire surveys of individual occupants, structured interviews of building management staff, professional assessments of the control installations, and energy survey techniques.

At the same time, other studies [summarised in 6,7,8] were finding that some measures advocated to improve comfort and to save energy were very sensitive to how the controls were actually implemented and operated. Controls, both manual and automatic, were often not behaving in the manner anticipated. For example, some buildings with good daylight and automatic lighting controls, often had the blinds closed and/or the lights on. Control problems had been found previously [9] in offices designed to use thermal mass and/or night ventilation for summer cooling: here summertime temperatures and energy consumption were generally higher than anticipated, though not always uncomfortably so. In the second series of surveys, ten of these buildings were visited, the management interviewed, and impressions recorded. In five of these buildings, staff questionnaires were carried-out as in the first set of surveys, and some combined results are shown in figures 1 and 2. The emphasis in the second series was on naturally-ventilated buildings (only one, Building 4 was air-conditioned) and on the relationship between the individual and local control systems, in particular openable windows, electronic lighting controls, and automatically-operated solar blinds.

Indicative Findings

Figures 1 and 2 show average comfort and control scores for the eleven buildings in which there were staff questionnaires. They indicate that:

- Average perceived comfort and control tended to be higher in the lower-energy buildings.
- Perceived comfort related better to energy efficiency with natural ventilation than air-conditioning.
- Across the sample, there was little difference in overall comfort between the naturally-ventilated and air-conditioned buildings. However, the least and most comfortable buildings (2 and 5 respectively) were air-conditioned.
- The naturally-ventilated buildings had higher perceived degrees of control, but only for lighting and ventilation. Those with poorer ventilation control scores (6, 7 and 9) had poorer window design. Even in buildings with good scores, the windows could usually have been far better, especially for summer night-time ventilation, draught-free cross ventilation and ease of operation generally. Almost trivial conflicts, eg: desks in front of windows, could substantially undermine some natural ventilation strategies.

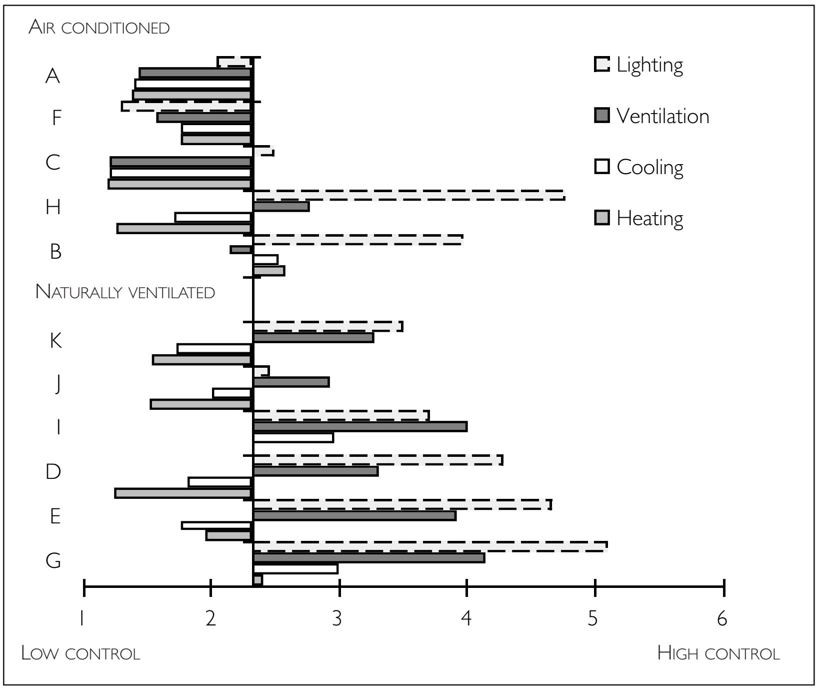

Figure 2 Average perceived control scores (compare with figure 1)
VAV=Variable Air Volume air-conditioning (A/C) system

- In Buildings 10, 11 and particularly 5, overall comfort was higher than any of the individual comfort scores for temperature, air quality and lighting. We call this “forgiveness” because when occupants rate comfort favourably they appear to forgive individual shortcomings: it is significantly associated with good perceived control over heating and cooling, much less so for lighting or ventilation. It tended to be high in buildings which were particularly well managed.

The buildings with higher lighting control scores normally had good manual or electronic controls. Those with low scores normally had block central switching or group switches by the doors. However, individually-controlled lighting did not guarantee comfort, nor did combinations of manual and automatic lighting controls guarantee better user satisfaction and energy efficiency. For example, in Building 7, metal halide uplighters were not only slow to strike, but their local switches were on the ballast units which were inaccessibly stowed under desks. Since many workstations also required adjacent lights to be on (with switches not readily accessible either), both comfort and control were rated as poor. The inaccessibility of the manual switches and the prolonged run-up and restrike times had caused the automatic “off” controls to be abandoned except late at night, while automatic timed “on” had been added to some lights for safety.

A strategic diagram

Figure 3 shows the four essential areas in which control systems which aim to maximise comfort with minimum energy use should perform. Controls can be manual or automatic (vertical axis) and reactive or forward-looking (horizontal axis), dividing the diagram into four quadrants, discussed further in the four subsections below. A satisfactory control strategy should consider relevant issues in each quadrant, plus interactions between them. For example, a feedback device (Quadrant A) will usually need programming or setting (Quadrant B), requiring manual intervention either at the time (Quadrant C) or beforehand (Quadrant D).Figure 3 A strategic diagram.

Quadrant A - FEEDBACK: Automatic, Reactive

Building services controls are predominantly, often almost exclusively, seen to be largely within this quadrant. Systems operate on closed loops, with the differences between measured and desired levels of suitable variables used to drive controllers to correct the errors. We call this the "process control" analogy. It is a vital component of control, both for comfort by providing stable conditions within an appropriate range, and for energy efficiency by helping to avoid wasteful over-provision. However, but for some continuously-running systems, attributes from the other three quadrants are essential for energy efficiency, as these stop systems being on too much. They can also improve perceived comfort, as discussed later.

Feedback can be unstable, both during operation, under conditions of rapid change and on start-up. In buildings, stability is seldom safety-critical as systems usually react slowly. However, unstable and uncontrollable systems are quite common, leading to energy waste, comfort problems and excessive wear, for example through "hunting", say of sequence controls for modular plant. In practice, troublesome features causing instability

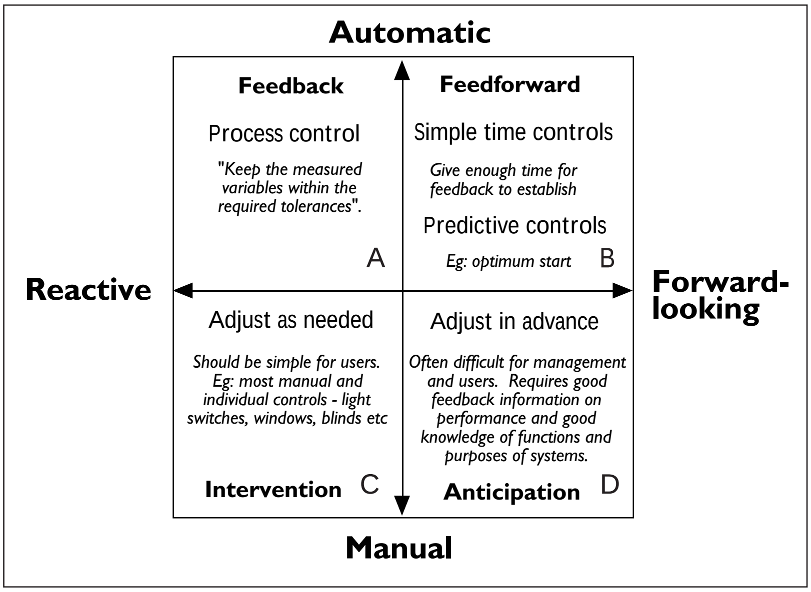

Figure 3
Control Strategies for Building Services

(and perhaps, say, a chiller lockout) are often overridden by commissioning engineers or building management. Subsequently plant will usually run for longer or at a higher intensity than it needs to, wasting energy.

Where systems are overlaid, faults in one component can persist undetected if the feedback loops for other components automatically compensate and maintain satisfactory service, usually by consuming more energy. Heat recovery systems often fail like this, wasting energy in at least three ways:

i not operating the system when required, causing unnecessary demands on the boiler

ii operating when not required, causing unnecessary cooling loads

iii requiring extra electricity whether or not they are operating.

This happened in Building 1 - the least energy efficient of the air-conditioned buildings but perversely (though not unusually) the one nominally having the most energy-saving technologies. Nobody was aware of the failure because comfort was not affected and the controls gave no feedback to management on performance or energy consumption. In this building, even if they had, action might not have been taken because all energy costs - however high - were recoverable in full from the tenants via their service charges.

Quadrant B - FEEDFORWARD: Automatic, forward looking

In most controls texts this is the poor relation of Quadrant A. However, many control features intended to reduce energy consumption are found here, for instance:

- Time switches, programmed for example to provide enough warm-up time to get the building's temperature up (or down) and its feedback systems operating before occupancy starts.
- Their advanced variants, optimisers, which try (often with some difficulty) to determine the warm-up time necessary each day and sometimes also decide is systems can be switched-off early.
- Open-loop HVAC controls such as compensators and schedulers, which aim to avoid over-supply by providing central supplies of heating and cooling at progressively lower temperatures as the outside temperature increases.
- Photoelectric controls, which judge the need for daylight inside from the illumination outside.
- Solar blind controls, which judge the need for shading by radiant intensity outside.

These have more recently been joined by controls for passive cooling, running fans if necessary overnight to remove excess heat built-up during the preceding day. Similar systems are now being discussed to control natural ventilation.

Cruder examples are frost and condensation protection systems (which circulate water and start plant if inside and/or outside temperatures fall below predetermined levels) and hold-off thermostats, which stop boilers operating if the outside temperatures are too high and chillers if too low. Energy surveys show that these are often poorly set, causing energy waste. One mis-set thermostat can easily bring plant on unnecessarily and often un-noticed: in daytime any extra will be difficult to detect, at night nobody often knows.

One also finds frost thermostats which switch-on all the plant including air handling units and chillers, as in Building 3!

Controls in Quadrant B rely upon predictions and so are potentially more difficult to programme and commission than feedback control. However, their detailed design, operation and testing often receives less attention too, so their performance in practice tends to be worse than assumed. In most buildings the main emphasis is on service, not energy efficiency: if the service is adequate, no questions asked; if inadequate, a quick and easy solution is to leave systems running, and this asymmetry predisposes systems to run liberally or wastefully. A critical missing link in most predictive systems is appropriate management information on their performance: sometimes they provide none, often it is difficult to interpret (particularly if the controls are complex and difficult to follow) or sometimes it is buried in too many trivial error messages. Only in the hands of skilled and motivated management do they normally work well. Case studies [8,9] of buildings with thermal mass and night cooling provide good examples. Few of the mechanical night ventilation systems studied were able to maximise cooling effect with minimum energy use, because design, installation, maintenance and control faults persisted undetected. While a simple difference of supply air temperature and outside temperature could easily have been calculated and the management alerted if it exceeded, say, 2°C, it never was, even when there were BEMSs which could have easily done so.

Where predictive automatic systems are used to control visible devices: in particular electric lighting and solar shading, results are too often patchy and disappointing, perhaps because:

- People often assume that one standard will suit everybody. In practice things are more context-dependent. For example, if daylight is deemed adequate and the lights go off, what of the individual with poor eyesight, an exacting task, or with a blind down to control glare? If the control zones are too big, the odd person with an exceptional requirement may cause the entire system to be over-ridden. Sometimes groups of zones are interlinked too, causing vast areas to be lit to meet a single unexpected requirement. These days to be functional lighting control zones may frequently need to be no larger than the individual workstation.
- The algorithms used may be inappropriate. For example, dimming systems tend to aim for a fixed desktop illuminance, while the eye responds to contrasts. So if daylight increases, preferred illuminance is likely to as well.
- Perceptions of what is appropriate may differ. For example, in summer the designer may regard sunshine as a source of unwanted solar gain, while some occupants may welcome it, at least for a while. In winter, the designer may have seen it as a useful source of heat, some occupants as an impossible source of glare.
- Lighting and solar control systems are seldom fully integrated with each other.

Predictive control therefore requires more thought in research, design and management. Work is required on both appropriate control features and devices and on suitable diagnostic functions.

Quadrant C - INTERVENTION: Adjust as needed

Here occupants interact with the controls, be they manual or automatic, responding to perceived needs. Too dark: raise the blinds or turn on the lights? Too hot: lower the blinds, turn down the thermostat, or open the window? The case studies suggest that:

i When discomfort arises, what gets operated first is what comes easiest, not what is desirable technically. If people find it easier to operate the light switch than the blinds (which may anyway have been left down from the previous day), "blinds down, lights on" may well become the most probable state. Control design should therefore follow a principle attributed to Einstein: "aim to make the bad difficult and the good easy".

ii People may become quite uncomfortable before they take action. This is partly due to inertia ("Maybe the sun will go in soon.") and partly to poor control ergonomics. For instance, in many of naturally-ventilated offices studied, window controls were poorly functional and/or difficult to reach. Since the reaction is delayed, when a response is perceived to be necessary, people want it fast [5].

iii In open-plan offices, many control actions affect a lot of people, and often different individuals in different ways. For example, opening the window on the lee of a cross-ventilated building may cause unacceptable draughts on the windward side, particularly if the air enters at high velocity at low level, and this may cause these windows to be shut, inhibiting cross-ventilation. With such irreconcilable requirements, available controls can cease to be used.

For example, in Building 8, which had sash windows, the lower sashes tended to stay shut in hot weather owing to the draughts. The upper sashes, which could well have worked effectively, were also seldom opened because they were difficult to reach, difficult to operate, and dirty. Instead desk fans had been introduced and there was talk of air-conditioning.

iv Systems are often asymmetrical in their behaviour, as is well-known for lighting [10]: people turn the light on when they perceive illumination as inadequate (how many lights depends on how the switching is arranged) nothing tends to be switched-off until (or after) the last person leaves. Switching for these two purposes may also need to be different: for example it may be convenient and economical for individuals to switch on lights when they reach their workstations, but facilities for switching-off may be required at the exit door too: otherwise lights left on inadvertently will stay on.

v Exceptions can easily "flip" unstable systems into undesired, high-energy states. For example, only one person needs be affected by glare for all the blinds affecting a large area of open-plan office to come down and the lights go on, and only one person may need to come in at the weekend (particularly if a senior one), for all the air-conditioning to be left on for them.

To improve energy efficiency, it will be important to study what triggers demands for a system to change and how these demands can be met in the most effective and economical manner.

For the individual occupant, this study suggests that good local of control of heating and cooling is more important than control of ventilation and lighting (except where glare occurs or automatic systems interfere noticeably with daylight and view). People would also like to control noise but usually have little choice in the matter, except by shutting the door of a cellular office. The intrusiveness of noise cannot always be measured in decibels: for example occupants of Building 11 were more tolerant of traffic noise than might have been expected, probably because windows could be closed locally as necessary without severely affecting summertime ventilation generally. For internally-generated noise, that from one's own working group (which conveys information) is much more acceptable than that from other groups or from passers-by (which creates distraction).

Individual, readily-understandable control affects perceptions of comfort and this in turn may be used to reduce energy consumption. While people are not particularly bothered about comfort itself, they can easily tell if they are uncomfortable. As Humphreys [11] has said: " thermal discomfort is not caused by the room temperature itself, but by a mismatch between actual temperature and desired temperature: the desired temperature is variable, depending on a complex web of factors…”.

Similar arguments may apply to other environmental variables too. Efforts solely to provide "ideal" comfort conditions remotely and automatically are therefore probably doomed to be less successful than anticipated if they are not combined with facilities to allow perceived discomfort, when it arises, to be alleviated. This, and adaptation, may help to explain why reported comfort levels in naturally-ventilated buildings are often similar to those in air-conditioned ones. Systems which respond rapidly (even if not perfectly) when discomfort is perceived, may allow permissible comfort envelopes to be broadened-out and energy to be saved.

Conversely, where automatic systems by their very operation create conditions or changes which are regarded as intrusive or comfort-reducing (for example blinds coming down when one was perfectly happy with the sunshine) they may be disliked. Occupants reacted like this to the motorised external blinds in Building 6, and to a lesser extent in Building 7 (where the windows were smaller and the blinds one metre in front of them). Many people were also unhappy with retro-fitted fixed solar shading in another building studied [8]. While the shading had reduced the summertime temperatures they had been complaining about, the occupants felt that occasional high temperatures were preferable to the reduced daylight and view which the shading brought. This again confirms the importance of the perception of environment as a whole, the facilities for occupant override, and clear strategies for integrating manual and automatic control within any system,

Annoyance also occurs when automatic systems do not work when occupants think they should. For example, in Buildings 6 and 7, external blinds could not be operated in "high winds": conditions which actually occurred quite frequently at the corners of the building and had damaged the blinds initially. Wind-triggered retraction (which affected all the blinds in the building and not just those suffering the greatest exposure) was reported to make the blinds unavailable for 5-10 per cent of the time, causing widespread complaints.

While individual control is clearly a good idea, feedback from the case study buildings suggests that it can be difficult to provide, particularly in open-plan offices where the one-to-one relationship between the individual and the environmental control systems breaks down quite severely. However, the surveys suggested that the perception of individual control was significantly increased by good management - as in Building 5: telephoning when there was a problem and knowing that there would be a suitable response appeared to have as good an outcome as operating a control device directly, particularly here where the management had also learned how to operate the system to avoid many complaints (see Quadrant D below).

However, individuals at their workstations are not the only level at which people want to - or need to - influence system operation for greater comfort and energy efficiency. There should also be a close relationship between the management and communications systems of a building's occupiers and the facilities for intervention with the controls. Unfortunately, however, these are often not provided in the right ways or in the right places. Problems range from having to stand on a desk to open a window, to centralised facilities in BEMSs in the hands of people with little understanding of how to use them, little knowledge of what the occupants want, and no incentive to run systems efficiently: this too often occurs in tenanted offices. Although some excellent services engineers and facilities managers have made good use of centralised systems, they then become the hub of an information network in which many functions might have been better delegated to those more directly involved. For instance, why collect and programme operating schedules for conference room plant when they could be entered directly by the person who keeps the diary, or even by an on-demand push-button in the room?

The problems outlined above may also afflict some of the proposed new generation of low-energy "green" office buildings, being developed today. Some techniques they advocate, although sound computationally, also require subtle changes in function and in the user interface which may:

i not be operable as intended;

ii not be operated or managed as intended;

iii in their operation, cause annoyance;

iv in aiming for optimum modelled comfort, mistakenly remove from the buildings some of the simple, easy-to-understand features which currently help to alleviate perceived discomfort and increase occupant tolerance of naturally-ventilated buildings

v fall into disuse quickly because of misunderstandings or too complicated management procedures.

Care is therefore required in developing novel ideas in practice, and adding to the principles of building physics and control design, insights from ergonomics, human factors and management theory.

Quadrant D. ANTICIPATION: Adjust in advance

This quadrant is perhaps the most difficult: manual adjustment in advance of need. It also includes routine setting of automatic control systems to ensure that services run at the right levels at the right times: in principle an easy enough task, but in practice more difficult, because the question of who is responsible for what is not clearly-enough defined.

Some of the adjustments may be skilled technical functions, others occupants may be able to do easily - like setting normal programmes and adjusting them for exceptional requirements, like holiday and weekend working. Frequently, however, operational and maintenance functions get confused. For instance, adjustments of all types may have to be made at control panels or via BEMS consoles which are not accessible to the occupying organisations (as in the multi-tenanted Building 1 and the contract-managed 4), or guarded by people with limited understanding, (as in Buildings 3 and 9). If access is daunting, through location (who wants to have to go to a remote, unfamiliar, unsettling, and sometimes uncomfortable and dirty plant room?), interfaces with poor ergonomics (people fear they will get electrocuted or damage the system), or complex electronic systems (few things are less flexible than software whose function is not thoroughly defined or understood), building services will often run too liberally and get left on just in case they are needed.

In addition, interventions that are made (for example: changing time schedules) often get done unsuitably (eg: by over-riding a time clock entirely) and then not reversed (perhaps owing to inconvenient access or absence of warnings).

Thought should be given to identifying separately "engineering" controls (requiring attention maintenance) and "operational" controls (requiring direct intervention by occupants and management at various levels), plus better diagnostic systems to draw clear attention to ineffective or wasteful operation.

Low-energy designs often place considerable reliance upon anticipatory manual systems: for example, passive cooling by natural ventilation overnight. While this is easily modelled on computers, it seldom seems to work like this in practice. In particular:

- i Windows are not used as intended. For example, if the element of the window designated for night ventilation is more difficult to operate than another element, the other element will be used instead.
- ii The window design is not suitable for being left open overnight, owing to problems with security, rain or occasionally insects or, at Building 8, squirrels!
- iii Whether or not the windows are functional, they are often routinely closed by occupants on departure or by cleaning or security staff, often to signal "job done" or for security.
- iv People get caught out if it turns cold unexpectedly, particularly over a weekend. Here the manual anticipatory system may need linking to a reactive system which closes the windows if the building threatens to get too cold. This could be manual (for example: the security guard are required to close the windows if it is getting cold), automatic (for example: a window catch is automatically released) or hybrid (for example: a temperature monitoring system alerts the guard).

Conclusions

Figure 3 allows one to review the manual and automatic control strategies for a building as a whole or of individual systems or sub-systems, and to think about user intervention. The best buildings surveyed tended to rate well in all four quadrants, though sometimes additional attention in one area - in particular management - made up for shortcomings in another. If this is not understood, attempts at repeating successes by copying the technology into environments with different occupancy and management priorities may be disappointing. When this occurs, the designer may then point to the need for better management: however, in practice good management is often a scarcer resource than energy, so where possible designers should seek good outcomes for comfort and energy while also reducing the management burden to a reasonable minimum.

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