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Case study

Summary A quasi-automatic system has been developed to monitor the energy and environmental performance of a new university learning resource centre. The centre is a THERMIE demonstration project. Monitoring has concentrated on global performance indicators, to describe envelope and environmental provision effectiveness; Micro-performance indicators, to describe performance at the zonal level and ancillary performance indicators, to describe the performance of parameters which cannot be sensed automatically. The effectiveness of the building in reducing energy consumption and providing a pleasant internal environment has been quantified in both physical and psychological terms. Results suggest that, when designing similar buildings in future, greater attention should be paid to humidifcation, distributing daylight, and the provision and thorough commissioning of appropriate automatic and manual occupant controls.

Passively cooled and ventilated learning resource centre: Performance appraisal

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1 Introduction

Non-industrial buildings within the UK consume 43 % of all supplied energy(1). In recent years, therefore, passive features have been increasingly emphasised in building design. The aim is to reduce the consumption of fossil fuels and so degrade the environment less. This approach to design has also begun an evolution of traditional architect led design so as to integrate design team members more closely(2). The building fabric must now serve additional environmental functions to displace the mechanical systems which would otherwise be needed.

The resulting buildings are usually naturally ventilated and are increasingly passively cooled. This approach implies that the buildings are highly sensitive to the transience of their local external climate. This climate is modified by the building fabric, but the scope for control is greatly reduced by avoiding active systems. It is therefore important that the energy and environmental performances of the first generation of these buildings be appraised to ascertain the effectiveness of the solutions adopted, and their potential for replication. A detailed monitoring system is essential if their performance is to be determined and quantified firmly. A bespoke monitoring system is needed, capable of handling a large number of sensors and of analysing data with minimal human intervention.

2 Project background

The Learning Resource Centre (LRC) at Anglia Polytechnic University (APU) was completed in September 1994 and was runner-up for the 1996 Green Building of the Year Award(3). It is one of eight non-domestic buildings in the European Commission's THERMIE demonstration project EC2000. The purpose of EC2000 is to demonstrate 'the substantial energy savings and reduced environmental impact which can be achieved through the use of an integrated design approach in new public and commercial buildings'. The specific targets are: to avoid air conditioning; to provide a comfortable internal environment; to reduce energy consumption to 50% of that of traditional counterpart buildings. It is required that the second and third objectives above be assessed by a 12-month monitoring project for each building. This paper describes the first such monitoring project.

3 Building description

The completed building (Figure 1) encloses a total floor area of 6012 m^2. It is supported by a reinforced concrete frame and exposed waffle floors, but a steel frame supports the roof and two full-height atria. The architectural massing of the building is dominated by the front south-easterly facade. The building reduces from four storeys to just two at the north-westerly rear, where the bar, kitchen and conference facilities are located, facing the River Chelmer. The two atria lie at the centre of the four-storey (south) and three- storey (north) 'global zones' of the building. The south global zone services the library. Administrative staff are located on the third floor. The north global zone services the university secretariat and media production staff. There are thus three key types of use (from south to north): library, office and services (catering and conferences). Monitoring has focused on the library and office uses. These are similar in nature, and the fundamental functions of the buildings.

The building fabric is highly insulated (area-weighted average *U*-value 0.49) to minimise winter heat losses. Thermal mass is provided internally by exposed concrete waffle floors, the internal faces of the façade walls, internal full- and part-height blockwork privacy partitions and exposed precast concrete roof elements The thermal mass absorbs thermal energy during the day and releases it at night, thus dampening the effective daytime temperature rise. The façade glazing system (Figure 2) is a novel feature of the design. It consists of three major elements. The first element is a vision window, consisting of an hermetically sealed argon-filled double glazed unit, with a low-*e* coating on the internal layer, followed by a 25 mm ventilated air gap housing adjustable perforated blinds, and a further single-glazed layer. The blinds offer the option

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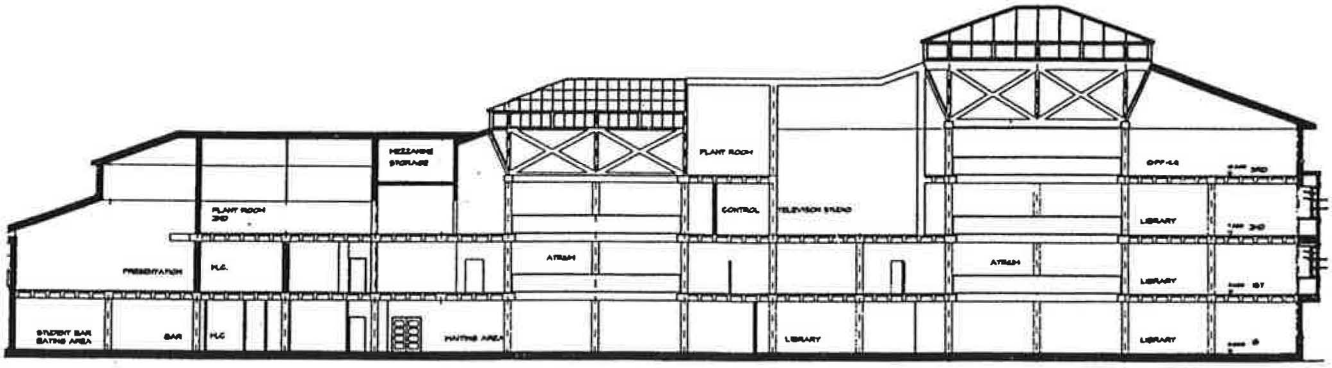

Figure 1 Cross-section of Learning Resource Centre

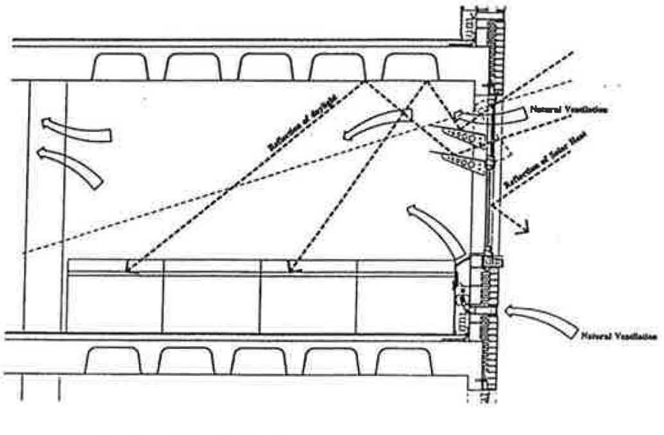

Figure 2 Section of façade glazing system

of glare control and the ventilated cavity helps to reduce local resultant temperature rise. The second element is a triple-glazed clerestory window. This can be opened automatically by the building energy management system (BEMS) to provide natural ventilation. The third element consists of double mirror-reflective internal light shelves 0.7m deep, to prevent low-altitude solar glare and to redistribute daylight internally so as to increase uniformity. Glare is also prevented from the high-level atria light sources by white perforated fabric sails suspended from the underside of the atrium roof to the 3.2 m high concrete perimeter beams.

3.1 Plant systems and environmental controls

The heating input to the building is provided by gas-fired condensing boilers generating hot water at 70–80°C. Post-condensing efficiency is ~86% and nitrogen oxide (NO_x) emissions are low. Domestic hot water (DHW) is provided by two 500 litre calorifiers. These use a water–water heat exchanger sourced by the central boilers with heat-recovery preheating from the bar cooler. The boilers are sequence controlled by the BEMS when activated either by an optimum start switch at the beginning of occupancy or by fixed time starts. Low-temperature hot water (LTHW) flows to convective finned tube heat exchangers at the perimeter. These preheat trickle ventilation air entering from airbricks. The BEMS enables flow when a signal is received that the temperature at a given outstation (one for each thermal zone) has fallen below its temperature setpoint. There is one outstation for each thermal zone.

Within the office and library global zones, ventilation and cooling are provided entirely naturally. The BEMS-actuated perimeter clerestory and atrium windows provide the source for natural ventilation under zonal temperature control (unless the global zone contaminant sensor measures excessive hydrocarbons, in which case all windows are opened). Under this control rule the perimeter windows are opened at 25% increments over a proportional band between 22°C and 26°C.

Atrium windows are controlled so that the total opened area is proportional to the sum of the areas of all perimeter window openings servicing a particular atrium. An additional controlling input to the atrium actuators is provided to prevent pressures caused by cross-flow through these openings from undermining stack-driven airflow egress. At such times, should the wind speed exceed 1 m s^{-1} for longer than 600 s, the windows on the exposed façade are closed and those on the leeward side proportionally opened by the same amount, so as to preserve the total opened area. Finally, if rain is detected, all atrium windows are closed, and perimeter windows proportionally closed to a maximum openable position of 25%. However, the possible consequence of this safety measure is that if it rains during hot weather there is no stack-driven airflow to provide occupant/fabric cooling.

A particularly novel feature of this learning resource centre is the night cooling system. During occupation, the BEMS logs the amount in degree hours (DH) by which the average internal space temperature exceeds the room temperature setpoint. Should the threshold of 5 DH be exceeded at the end of occupancy, all windows are modulated to their fully open position. They are later closed proportionally when the achieved DH of cooling (determined by reference of the space temperature to the thermal mass set point — a theoretical equivalent of the average thermal mass temperature) is equal to that of the accrued DH of excess heat gains(4). During the next day, should the average space temperature drift beyond the limits of 21°C and 25°C, the thermal mass set point is adjusted (24±2°C) from its initial set point of 22°C to counter this trend during later days. The extent of adjustment is dictated by a self-learning algorithm which consults the building's thermal performance history over the previous three days.

A further set of control laws relate to the provision of internal high-frequency ballast compact-fluorescent background lighting. All open-plan lighting is initially time-controlled at the start of occupancy, except for luminaires located within emergency egress routes. These operate continuously. However, luminaires within daylit zones are also subject to photosensory override. The photosensory input is based on the illuminance received by vertically mounted external photocells facing each of the four orientations. If the illuminance received exceeds 7500 lux at one of the two-hourly polling intervals from 10.00 until 16.00, then all the associated luminaires located within the daylit zone for that orientation are switched off. This external illuminance control input was designed to prevent 'blinds down, lights on' under peak solar loading. There is no input commanding the lights on when external illuminance falls below 7500 lux. In this situation the onus is on the occupant. Lights are intended to remain off for extended periods.

Within individual offices which are decentralised from the global zones (because of full height partitions), all luminaire fittings are under local manual control. The only remaining lighting control mechanism is that for the WC areas. This is activated by infra-red presence detectors, again except for fittings in emergency egress routes.

A number of local control options are provided at each of the 750 IT-wired workstations. For example, the background lighting level can be supplemented on overcast days by local task lighting. The mid-pane blinds can also be raised or tilted open or closed. Warm-air admission can be controlled from the perimeter convector heaters. If these measures are inadequate, the BEMS set points can in principle be adjusted at the operator's terminal to modify the environment of the relevant global zone.

4 Development of monitoring system

A survey of monitoring hardware and software indicated that current systems are inflexible. They cannot easily be adapted to a given project and usually only provide indicative building energy and environmental performance feedback. A dedicated holistic monitoring system was therefore developed. It requires minimal human intervention and utilises the existing BEMS to acquire and store data$^{(5)}$. This system is inherently flexible enough to be adaptable to other building projects. It comprises a customised BEMS, which downloads sensory data files at prescribed intervals; a batch file conglomeration program (which reduces the 1192 files for a 31-day month to 18); and software for data analysis with a graphical user interface.

The analysis software environment developed is called AutoMDAS (*automatic monitoring data analysis software*). The user may select visually one of a number of analysis options from within three distinct hierarchical structures (Figure 3). The user may analyse global performance indicators, micro-performance indicators, or ancillary performance indicators.

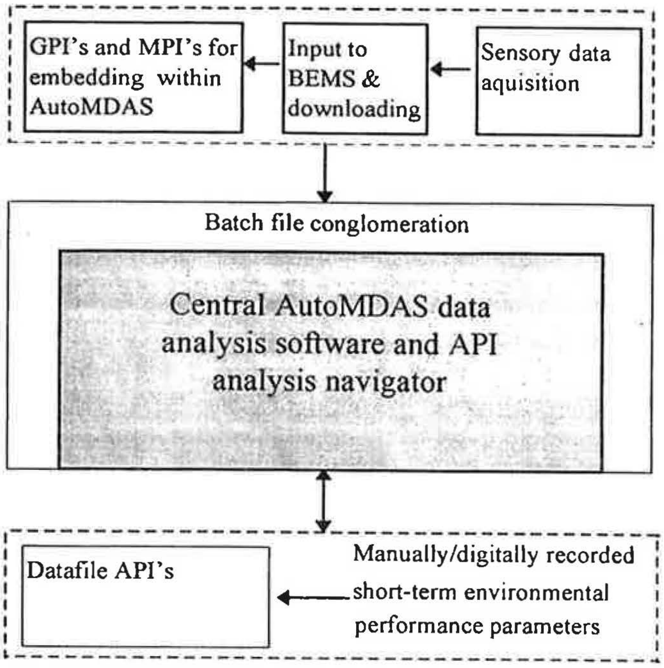

Figure 3 Schematic diagram of monitoring system

4.1 *Global performance indicators (GPIs)*

The following GPIs are available within AutoMDAS: Zonal temperature frequency bins; mains and component energy consumption; Daily minimum, mean and maximum internal dry-bulb and (derived) radiant, and external dry-bulb temperature; Maximum internal contaminant concentrations and heating medium flow temperature; Minimum and average relative humidity (RH); Minimum, mean and maximum climatic variables (temperature, wind speed, wind direction and insolation on the southern vertical plane).

These GPIs provide a useful 'generic fingerprint' of seasonal, monthly and daily building performance. They can be used to determine which uses have increased/decreased their energy consumption, which zones have experienced over-/underheating and whether internal relative humidity and contaminant levels have been too high/low. Relationships between building performance and external climatic variables can also be investigated rapidly.

4.2 *Micro-performance indicators (MPIs)*

MPIs can be analysed for any zone of the building (defined as a thermal zone in part passively conditioned by a separately

Table 1 Monitored sensory inputs to BEMS

Control parameter	No. of sensors	Control parameter	No. of sensors
Zone temperature†‡	23	Global zone humidity†	1§
Window open position†‡	23	External temperature†‡	1
Window open area†‡	23	Wind speed†	1
Excess DH	23	Wind direction†	1
Purged DH	23	Solar radiation†	1§
Lighting energy consumption†	6§	Rain status	1
Heating medium flow temperature†‡	4	Globe temperature†	1§
Small power energy consumption†	8§	Main gas consumption†	1
External daylight level	4	Main electrical consumption†	1
Perimeter total open area	2	Sub-metre gas†	1§
Sub-metre electricity†	2	**Total no. of sensors**	152

†GPI
‡MPI
§Monitoring installation

controlled bay of windows), by selection from image-mapped digital floor plans (by associating the two-dimensional spatial positions of an image with non-spatial actions(6)). Immediately after zone selection, performance summary data are produced for each day of a defined month, detailing minimum, mean and maximum internal and external temperature, a window opening indicator and maximum flow temperature of the heating medium.

These daily performance indicators are then used to identify a day in which it is of particular interest to produce a chart of hourly performance for that zone. These charts display the dampening effect of the thermal mass on the internal temperature swing, and the influences of window openings and the heating system on internal temperature.

4.3 Ancillary performance indicators (APIs)

All APIs have been measured manually. The resultant data are archived in separate files accessible from AutoMDAS. APIs included the following: Daylight factor measurements; Questionnaire results of occupant response to the building's environmental performance; Detailed internal air quality assessment: for a 6m two-dimensional grid of the library first floor, air temperature and velocity, relative humidity, carbon dioxide (CO_2) concentration, mean radiant temperature and operative temperature measured for three-dimensional chart visualisation; Results of sulphur hexafluoride (SF_6) decay rate tracer gas tests.

The three performance indicator types (GPIs, MPIs and APIs) provide an holistic assessment of energy and environmental performance within the building and a relatively comprehensive assessment of the external climate. They were developed both to fulfil the monitoring obligations and to ensure that the monitored data could be used proactively to support building performance fine-tuning.

5 Performance assessment: General

Although the LRC has satisfied the EC2000 criterion of avoiding air conditioning throughout (except for two niche high-gain areas), it is necessary to determine the implications of its absence on occupant comfort and energy consumption.

6 Assessment of occupant comfort

Thermal, visual and aural environmental performance are the three key parameters which affect occupant comfort, as well as the usability of controls. The results from physical measurements have been derived from the GPI facility, and subjective results from a detailed questionnaire.

6.1 Thermal comfort, indoor air quality and occupant health

The night cooling system has not operated optimally since completion. During the first summer (1995) night cooling only happened due to early morning cleaning, with consequent BEMS actuation of window opening under perceived occupancy. After drafting a building performance review this problem was rectified, though only temporarily due to upward drift of the theoretical thermal mass set point. This resulted from injudicious control logic. The building has overheated significantly without optimally functioning night cooling. Temperatures greater than 28°C occurred for 1.88% of the occupied year, as compared with the BRECSU target of 1%(7). Temperatures were greater than 27°C for 166 hours, as compared with the design target of 43 hours (Table 2).

It is useful to place such simple comparisons with benchmarks in the context of temperature variations in space and time, and opportunities for occupants to regulate their environment. This is because transient physiological stimuli and the awareness of time passing can be psychologically beneficial. Occupants tolerate thermal stress better when they know that they can control the causes of physiological stimuli (such as opening a window to increase air movement in summer). Here, the mode of ventilation in the Queen's Building has produced a strong relationship between internal and external air temperature in summer (Figure 4), though this is imperfect due to the thermal mass damping temperature fluctuations. This relationship attenuates significantly in winter when windows are closed and auxiliary heating is activated. The extent of this seasonal temporal thermal variation (6.3°C) is more evident when examining the thermal conditions within the building, averaged over each zone and for days in the month (Figure 5). In winter, daytime temperature rises more slowly, though the distinct night-time temperature reduction without auxiliary heating evidently remains. There is also significant spatial variation, particularly in the vertical domain. There were respectively 30, 127, 209 and 297 hours in which 27°C was exceeded from the ground floor to the third floor. Adaptive opportunities for staff within the Queen's Building include opening windows, modifying posture and clothing, adjusting activity and adjusting drinking patterns. Staff may also alter certain controls indirectly, and with less ease change their seating location. Students are also unhindered in these opportunities except for window control, which is automated for security purposes. Although the availability of adaptive opportunities depends on occupant status, there is a relatively broad range for all.

Table 2 Summary of long term measurements of thermal environmental parameters

Performance parameter	Quantitative results		Target
	Value	Standard deviation	
Infiltration	0.55 ac h^{-1}	0.17	0.25 ac h^{-1}
Ventilation: Typical summertime mode	2.15 ac h^{-1}	0.42	4.5 ac h^{-1}†
Ventilation: Night cooling mode (15 July 1995 at 22.30)	11.08 ac h^{-1}	2.09	—
Average CO_2 concentration	645 ppm		1000 ppm(8)
Average overheating, 1995–96 (un-normalised, 27°C base)	166 h (no night cooling)		43 h‡
Winter time relative humidity, 1995-96: minimum	22.7%		40%(9)
Winter time relative humidity, 1995-96: average	30.3%		40–70%§

†Determined under design-day external climatic conditions

‡Represents the excess of dry resultant temperature over the 27°C base

§Represents the recommended range for mechanically conditioned buildings

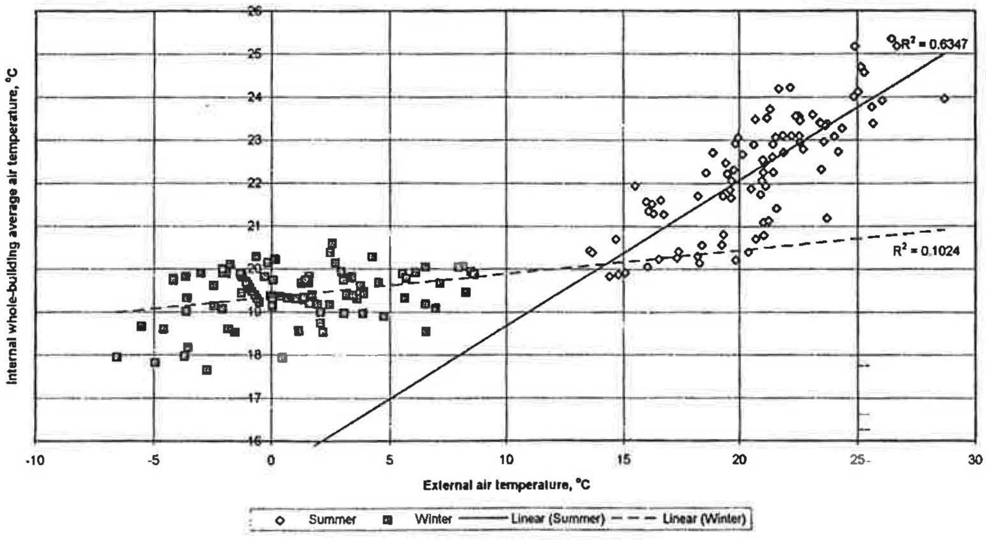

Figure 4 Mean internal versus external daily mean air temperature

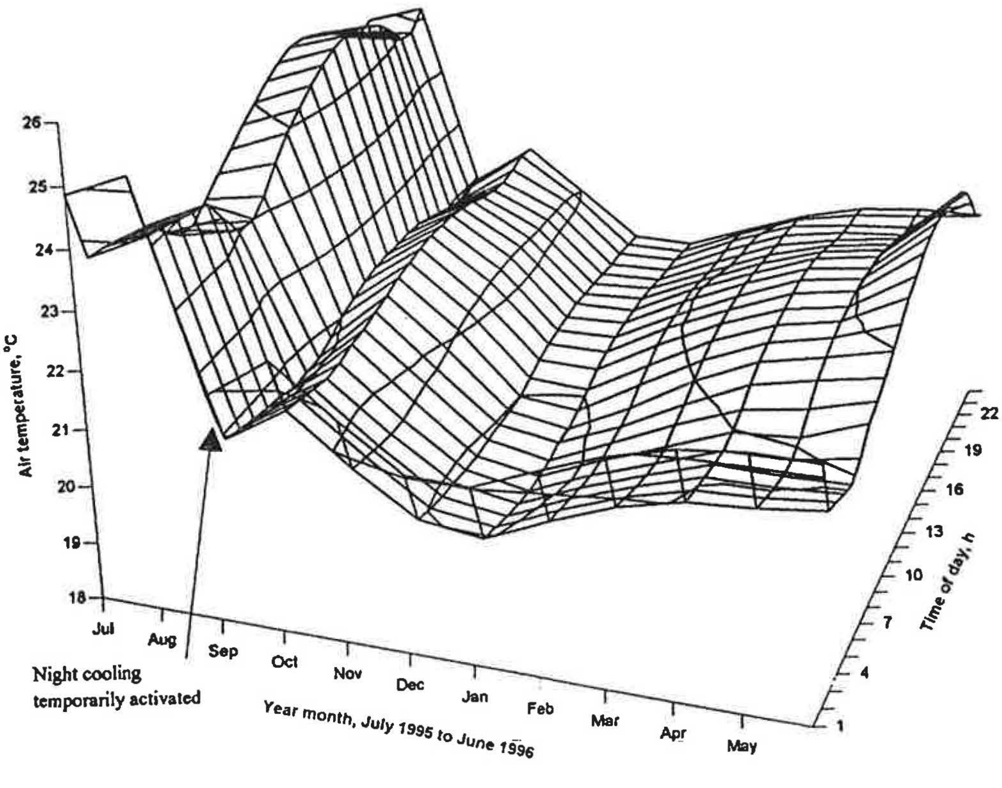

Figure 5 Mean internal air temperature variation with time

In addition to overheating, another adverse consequence of the ventilation method is large hourly internal air temperature fluctuations (Figure 6). In winter months the low external air temperature occasionally results in large and sudden falls in internal air temperature, with a consequently similar rise to the historical mean. Conversely, in summer months the high external temperature leads to sudden rises in internal temperature, which is then matched by a similar reduction ($R^2 = 0.73$ between monthly maximum hourly temperature rise and fall).

Subjective occupant assessment is perhaps the *de facto* test of the appropriateness of the thermal environment. It aggregates variations in time and space as well as adaptivity. Unless an extremely elaborate and sensitive questionnaire is used, however, subjective assessment must be combined with objective physical measurements if the causes of discomfort are to be identified. The two approaches are complementary.

A detailed transversely sampled questionnaire, in which an entire population was targeted to avoid sampling bias, was administered in both winter and summer seasons. This assessed thermal, visual and aural comfort, occupant health, internal air quality and aspects of controllability. Table 3 details the principal results from the thermal comfort component of the questionnaire. Digital files (obtained by optical mark reading) were combined with a temperature retrieval subroutine within AutoMDAS to read in air temperatures for the appropriate time and location. Objective measurements were compared with subjective assessments (Figure 7).

The subjective assessment of thermal comfort shows that the building errs on the warm side of neutral. However the steepness of the weighted regression gradient suggests that mean subjective responses are relatively insensitive to air temperature, particularly in winter (to the extent that neutral temperatures cannot be reliably derived). Both the marginal departure from neutrality and the poor correlation of thermal sen-

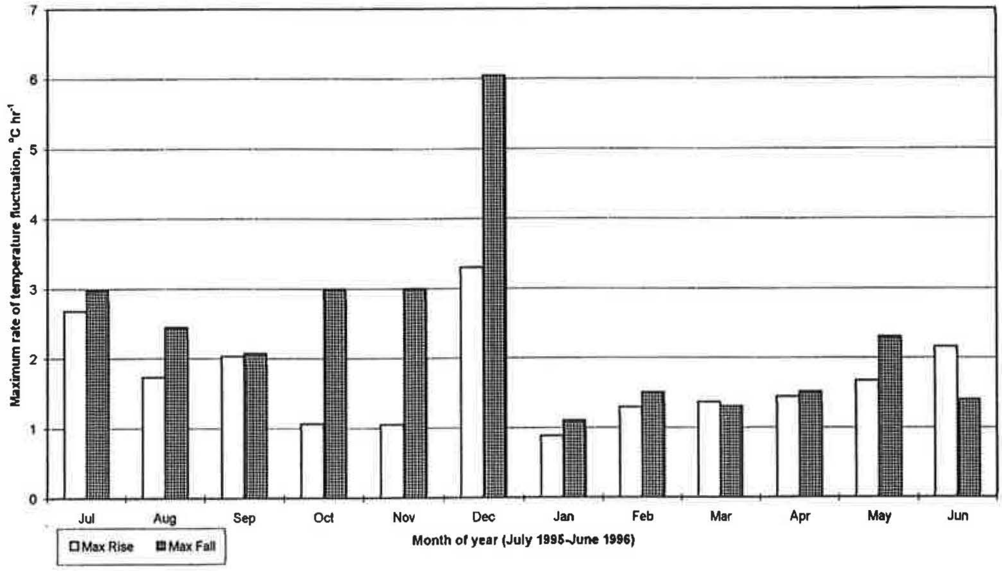

Figure 6 Temperature fluctuation as a consequence of untreated airflow

Table 3 Thermal comfort responses and analyses

Statistical indicator	Summer	Winter
Percentage dissatisfied on ASHRAE thermal sensation scale (beyond 4 ± 1)	25	15.7
Percentage dissatisfied on three-point thermal preference scale (beyond 0)	53	36.2
Mean vote (where 4.00 is neutral)	4.80 (1.039†)	4.68 (1.011†)
Mean air temperature (°C) for each questionnaire	23.62 (0.922†)	21.99 (0.753†)
Percentage voting neutral who would prefer to be warmer or cooler	4	11.8
Correlation of thermal sensation with temperature T_i	0.040 (0.687‡)	0.088 (0.386‡)
Correlation of thermal preference with sensation	0.652 (0.000‡)	0.580 (0.086‡)
Leaman(10) (1 = unsatisfactory, 7 = satisfactory) (Students: 5.17‡)	3.83 (3.81§)	3.88 (3.96§)

†Standard deviation of the mean result
‡Degree of significance
§National BUS benchmark

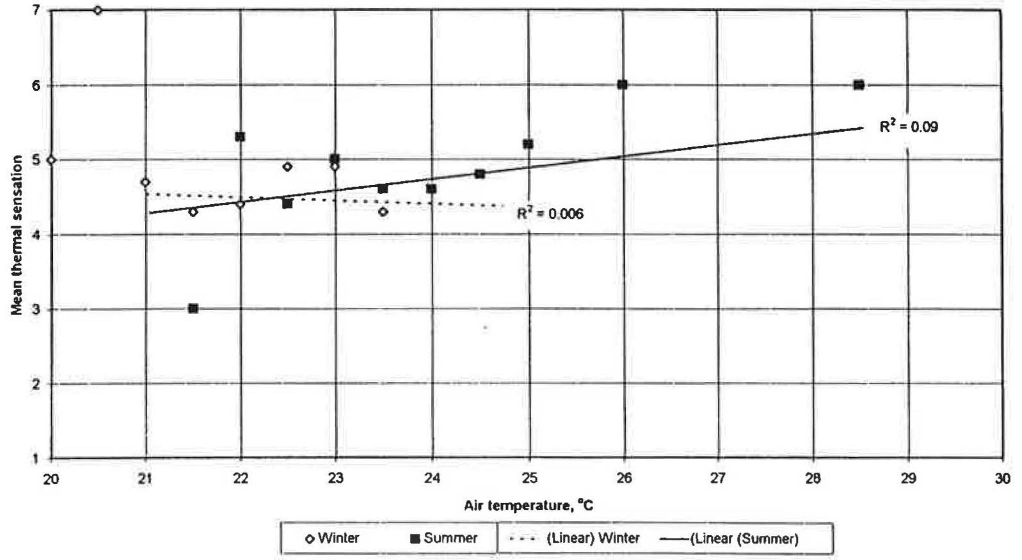

Figure 7 Mean subjective response versus 'binned' air temperature

sation with temperature suggest that occupants may be benefiting (albeit insufficiently) both from their adaptive opportunities and temperature variations. Flexible thermal performance targets may be needed which take these psychological benefits into account. Perhaps of greater concern are the complaints of draughts received from 37% of questionnaire recipients in winter (18% in summer). These are probably caused by automatic window opening causing the large temporary temperature drops described above.

Excessively low relative humidities (RHs) have been recorded frequently. Humidities below 25% occurred for a total of 254 hours during the period 08.00 to 18.00 between January and June 1996. An absolute minimum of 16% was recorded during winter 1995. Using external air temperature as a surrogate for external RH (this is qualified by an observed correlation between external dry-bulb and wet-bulb air temperature of 0.981 for a two-year climate data series for Aberdeen), it would appear that internal books and furnishings respectively sequester and absorb moisture in winter and summer to maintain an annual mean of 29%, with only relatively minor variations (Figure 8). Complaints of dryness from 61% of winter questionnaire returns (27% in summer) and symptoms of dry noses from 58% of returns (9% in summer) support the conclusion that some form of humidification is required, particularly in winter. It has therefore been proposed that the annual mean internal RH be raised by automatic humidification of plants(11).

The high infiltration rate, however, provides a good exchange of internal air, to the extent that the average occupancy-generated CO_2 concentration is only 645 ppm, with a maximum of 731 ppm. Curiously however, questionnaire responses contradict the physical measurement of internal air quality. A significant proportion of occupants complain of stuffiness throughout the year (33.5 ± 3.5%), although a greater proportion complain of this problem in winter when more windows are closed. (The mean air velocity was 0.052 m s^{-1}. It is therefore unlikely that stagnant air would be the cause of stuffiness). Complaints of stuffiness are matched by the second most prevalent symptom, that of sleepiness. The seasonal mean occurrence was 34% of questionnaire respondents. This may suggest that the seasonal average temperature from the questionnaires of 22.8°C is excessively high (further confirming the thermal comfort assessments), and may indicate poor productivity. A subjective measure of 5.6% productivity loss among staff(10) serves to confirm this hypothesis.

6.2 *Visual comfort*

Questionnaire feedback indicates that adequate (perceived) daylight is provided within the space, but that this can result in glare, particularly from winter sun at low altitude (Table 4). Direct admission of solar radiation also results in visual and some thermal discomfort. These results tend to contradict physical measurements. For example, the average daylight factor for the first floor was 1.60% and the uniformity ratio only 0.06. However, because the luminaires are designed for minimum glare, the transition from daylight to artificial light as one moves away from the atria and perimeter daylight sources is not noticeable, thus giving the impression of a well daylit space.

Thermal discomfort from direct solar radiation is not significant. It correlates with measurements of resultant temperature at typical perimeter study desks for summer. These are on average only 0.55°C greater than the air temperature (measured for June 1996).

6.3 *Aural comfort*

Both physical and qualitative assessments indicate that noise levels are excessive within the LRC. The equivalent continuous sound level L_{eq} was measured at 48.9 dBA, which is only marginally over the recommended threshold for large open offices of 45 dBA(12). On the other hand complaints of excessive noise levels from 49% of occupants for both winter and summer indicate that this target should be significantly lower for this building. This dissatisfaction with noise would appear to result largely from the conflict between the need to provide a large area of exposed thermal mass and the need for acoustic absorptance to reduce the reflection of noise. This conclusion is supported by the measured average octave-band-centred reverberation time (RT) of 1.49 s (where the ideal RT was calculated at 0.9s using Sabine's simplified expression(13)). The noise source perceived as dominant is occupant speech (Table 5). This results from the evolving use of modern University libraries from the traditional silent reading rooms to spaces accommodating group study, IT for individual project work

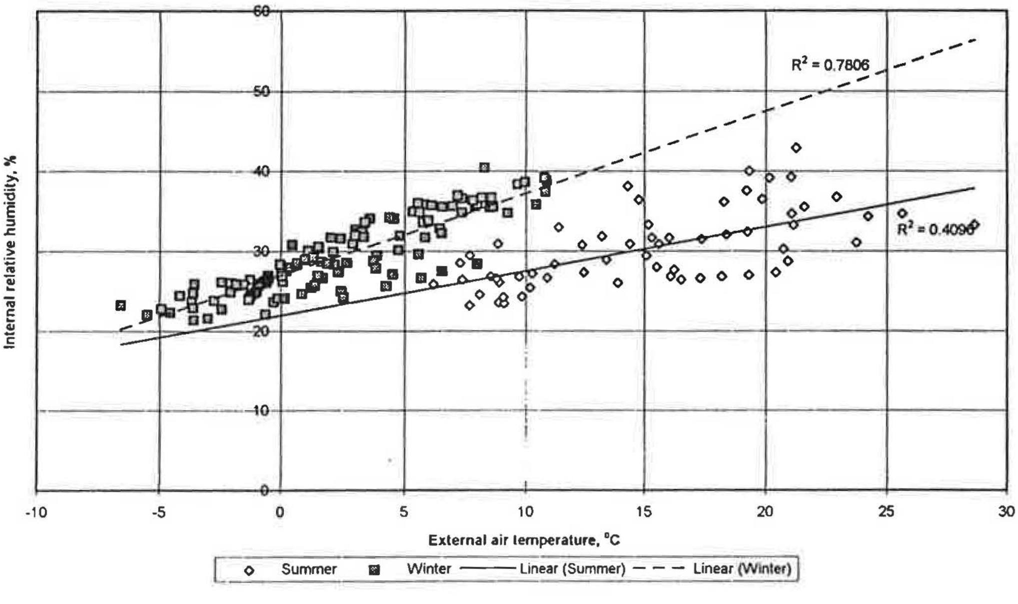

Figure 8 Seasonal relative humidity variations as a function of external air temperature

Table 4 Visual environment qualitative feedback

Statement on comfort parameter	Winter response (% agreement)	Summer response (% agreement)
Glare is a problem.	40	28
There is adequate daylight.	80	90
Direct solar radiation results in visual discomfort.	27	19
Direct solar radiation results in thermal discomfort.	3	11
Direct solar radiation results in visual and thermal discomfort.	28	22
Direct solar radiation results in no discomfort.	42	48

and the assimilation of retrieved materials. This evolving multi-functionality is therefore also a source of conflict, strengthening the need for noise control. This could be either by providing compartmentalised silent areas to segregate source from annoyance, and/or appropriate surface treatment with acoustically absorptive material to alleviate the sound reflection.

Table 5 Number of complaints and importance ranking of individual noise sources

Noise source	Importance of noise source (No. of complaints) (1 = most important; 5 = least important)				
	1	2	3	4	5
Business machines	10†	17	21	26	25
Occupant noise	**58**	**21**	13	3	4
External noise	9	11	18	25	36
Telephones	11	10	14	21	43
Shoes on stairs	3	4	17	24	50
Other	3	2	7	2	5
Total	94	65	90	101	153

†Integers for categorised noise sources may be read as a percentage of total.

6.4 *Acceptability of controls*

It is possible that the mismatch between feedback from the thermal sensation and preference scales (Table 3) results from the dissatisfaction of occupants with the degree of control that they have over their thermal environment (Table 6). The PPD assessed on the thermal preference scale is 53% in summer and 36% in winter. The PPD using the thermal control index is 70% in summer and 84% in winter. The dissatisfaction on both scales is high, possibly indicating a link between the two parameters. The trends in responses are, however, very different as between seasons. They indicate that control is less of an issue in summer than in winter. This perhaps reflects greater opportunities for occupants to adapt to higher temperatures in summer. (That is, windows are opened infrequently in winter due to low external temperatures.). In winter a high proportion of people voting for no change would prefer greater thermal control (bold entries in table). This, too, is less of an issue in summer. It may also reflect the lack of personal control that occupants perceive during the more thermally stable winter months.

Regarding control over their visual environment, half of the recipients complained that they did not have control over admitted daylight (49 ± 3%). A lower proportion would prefer more control (30%) in winter and than in summer (66%), perhaps to reduce daylight levels. (Note that this conflicts with perceived glare problems, which are more pronounced in winter.). 57 ± 4% of recipients complain that they do not have control over artificial lighting, and 41% would prefer more control. Unfortunately the questionnaire did not discriminate between sources of dissatisfaction, although it is likely that this stems from a combined dissatisfaction with photoresponsive lighting controls and the decentralisation of timed/photocell override controls.

7 Assessment of energy consumption

The annual energy consumption of the LRC compares favourably with that of the selected notional building (ignoring catering energy consumption), in this case a typical air-conditioned office building[14]. This reflects the general use of the building, the extent of its IT provision, and the fact that conventional University libraries are air-conditioned. The annual measured energy consumption for the LRC is 132 kWh m^{-2} treated floor area (TFA), as compared with 417 kWh m^{-2} TFA for the notional building. This represents a reduction in energy consumption of 68%. The reduction in CO_2 emissions from heating thermal energy consumption was calculated as 60%. This is particularly significant when account is taken of the occupancy profiles of the LRC as compared with that of a typical office building. This anomaly may effectively be removed by multiplying the LRC energy consumption by the ratio of the weekly occupied hours (assumed to be 50) of the notional building to those of the LRC (area weighted by use), giving 0.82. On a comparable basis the reduction of annual energy consumption is now 74%. At the whole-building level, the LRC has improved on the EC2000 target.

7.1 *Assessment of energy performance of individual components: General*

By judicious selection of electrical circuits for monitoring, which are representative of typical usage, it has been possible by extrapolation to determine confidently the split of end-use energy consumption[5]. The whole-building thermal energy balance is summarised in terms of its component parts in Figure 9. (It is assumed for electrical appliances that 1W of electricity input is equal to 1W of thermal energy output). The unaccounted gains reflect the small percentage of the whole which could not be accounted for explicitly by the methodology adopted.

7.2 *Effectiveness of fenestration*

The fenestration has proved to be an extremely effective net energy provider, with a gain-to-loss ratio (GLR) of 6.898 for vertical windows facing south. However the daylighting performance of the fenestration throughout the building is not quite as effective, with an average daylight factor for the first floor of the library (including the contribution from the atrium) of 1.60. The uniformity ratio is on average only 0.06, where a minimum of 0.3 is recommended to avoid the appearance of 'gloom' and potential discomfort glare. (This is however improved to 1.28% with a uniformity of 0.31 on the plane of perimeter study desks.) The low average daylight fac-

Table 6 Cross tabulation of thermal preference with control acceptability and preference

Thermal preference	Winter responses				Summer responses			
	Do you have control over your thermal environment?		Would you like more/to be able to control (over) your thermal environment?		Do you have control over your thermal environment?		Would you like more/to be able to control (over) your thermal environment?	
	Yes	No	Yes	No	Yes	No	Yes	No
Warmer	3	21	16	7		1	1	
No change	3	62	**57**	7	11	36	24	22
Cooler	4	9	11	1	6	46	44	7
Totals	10	92	84	15	17	83	69	29

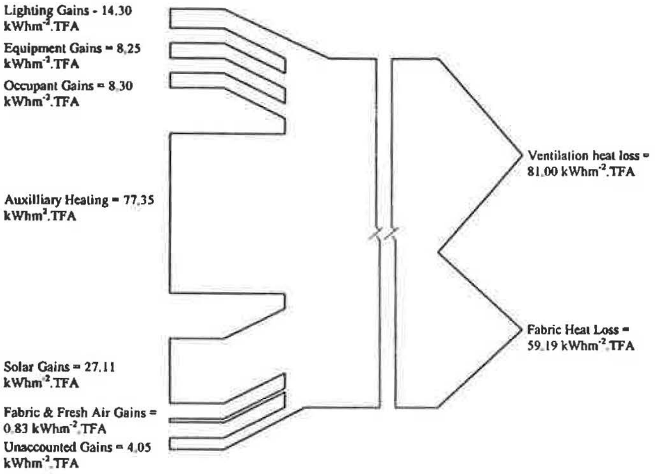

Figure 9 Sankey diagram of annual thermal energy gains and losses (Ventilation heat loss derived using air change rate of 0.545 ac h^{-1} as determined from SF_6 decay rate tracer gas tests.)

tors may be at least partially attributed to the low utilisation factor for the glazing of 0.69. This is caused by the proportion of the total opening area which is obstructed by the window frames. The low uniformity ratio is attributable to the double light shelves which cause inter-reflection between each light shelf projection and inter-reflection of upwardly reflected light between vertical rebates of the coffer recesses, and the fact that the daylighting contribution of the atrium is minimal, because it enters lower floors at increasingly obtuse angles and is largely absorbed by the carpet. The combined result is that daylight levels fall very quickly with distance from its source. On the third floor however, the daylighting method is very effective (DF = 4.7%), although this is principally due to the *direct* contribution of diffuse daylight, transmitted through the calico light sails from the atrium.

7.3 *Effectiveness of lighting controls*

The photoresponsive lighting controls have proved to be highly effective for displacing energy consumption when adequate daylight is present. There is a a net energy saving of 47% over their timed counterparts, although occupants appear to be perturbed by the way that the lights are controlled. (See section 6.) Control of the emergency and circulation lighting system is excessively poor because the lamps are on throughout the year (Figure 10). If this were not the case the control rules of the timed and photoresponsive circuits within which they are installed would prevail, with centralised activation of emergency lighting in the event of a contingency, so resulting in significant energy savings.

7.4 *Effectiveness of natural ventilation and night cooling*

It is at present difficult to make any firm informed judgement as to how successful the design is in the *long term* in providing pleasant thermal environmental conditions. This is because the night cooling system did not function during the first summer of operation, and during the recent summer it has not functioned as was intended. Despite this, it was possible to force the system into correct activation temporarily by lowering the thermal mass set point and increasing the number of DH overheating using the BEMS, to ensure that the windows remained open throughout the night. The effect of this artificially induced night cooling is illustrated in Table 7 (as well as in Figure 5, for the period of June 1996).

The benefit that night cooling has to offer is clearly illustrated, as is the ensuing need for proper commissioning of controls. With respect to the natural ventilation, measurements of CO_2 concentration (section 6.1) indicate that the method is adequate for removing internal pollutants, although there is conflict in the responses from the occupants as to fresh air provision (which may partly be due to continuous relatively high internal temperatures). Reported draughts, as a consequence of admitted airflow at a temperature significantly different from that within the building, are also problematic.

7.5 *Effectiveness of heating system and fabric insulation*

The effectiveness of the heating system and fabric insulation can only be judged in terms of the seasonal boiler combustion efficiency and weather compensation controls, the overall building heat loss coefficient, and the heating energy consumption when compared with that of the notional office building. The boiler combustion efficiency is high. The operating average is 86.3% and weather compensation is excellent. (For a plot of heating gas consumption versus heating degree days $R^2 = 0.949$.) The building overall heat loss coefficient is only 1.172 $WK^{-1}m^{-2}$ TFA. The thermal heating energy consumption is only 89.6 kWh m^{-2} TFA, as compared with 222 kWh m^{-2} TFA for the notional building. The building has performed well in terms of each of these parameters.

8 Fine tuning of performance

Concerns from MPI analyses prompted a report which reviewed the building's operation, leading to a meeting with the project engineers. The control problems (including excessive heating flow temperatures, high internal temperature setpoints, inappropriate time scheduling and uninvoked night cooling) were reviewed and remedied. Unfortunately, although the night cooling has now been enabled the system operates only rarely because the thermal mass set-point continually 'self-learns' to its upper limit of 24°C.

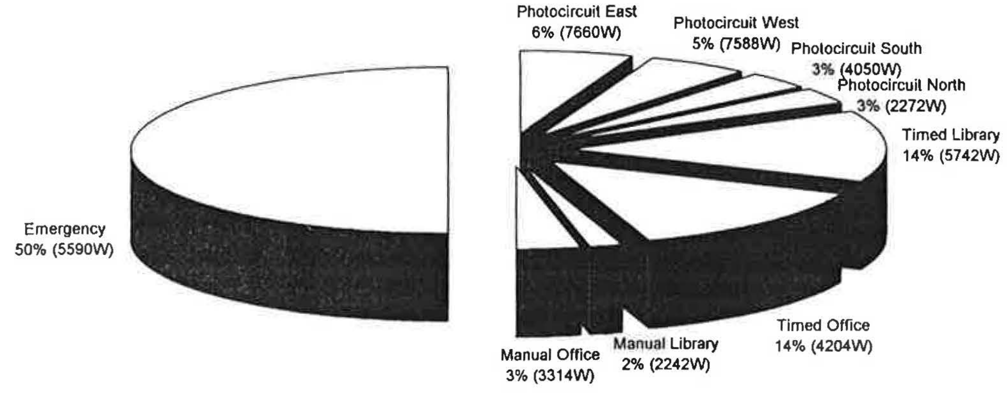

Figure 10 Annual lighting energy consumption split by use (135 069 kWh total electrical energy use; component installed load shown in brackets)

Table 7 Comparison of performance with and without night cooling: Library first floor south zone

Comparative dry-bulb temperature parameter (°C)	With night cooling 10–11 June 1996	Without night cooling 6–7 June 1996
Internal start at 21.00	24.60	25.68
Internal finish at 05.00	19.60	25.30
ΔT_{max} (internal– external): 21.00–05.00	4.66	9.22
Extent of cooling achieved	**5.00**	**0.38**

With regard to future fine tuning, the university property services manager has contracted the author to implement a number of suggestions to improve the energy and environmental performance of the building. The effectiveness of the night purging will be further investigated by implementing a set-point consultation algorithm correctly. Changes will be made one at a time. The energy and environmental performance of the building before and after each change will be compared to assess their impacts independently.

9 Conclusions

The energy and environmental performance of a passively ventilated and night cooled learning resource centre has been monitored rigorously and quasi-automatically for the twelve-month period July 1995–June 1996 inclusive. Costs were saved through the lack of human intervention in acquiring and analysing data. This allowed for additional equipment to split electrical energy consumption by use, and to assess in greater depth the acceptability of the internal environment. The monitoring system can be adapted to other buildings. It could facilitate monitoring multiple buildings through connecting BEMS supervisors via the Internet.

The learning resource centre may be regarded as a highly successful example of *energy*-efficient design. It also ejects contaminants effectively and has demonstrated its *potential* to stabilise internal summertime temperatures using passive night cooling. However, closer inspection shows much scope for improvement not only in energy consumption but also in providing a pleasanter working environment. The following improvements could be made, and should be considered by designers of future similar buildings.

— The lighting control system operates the emergency and circulation route lighting luminaries continuously. They consume a great deal more energy than if they were enabled for emergency purposes only, under fused fire-switch override (though it is acknowledged that basal loads may be required for the visually impaired). The photosensory control system has also not been commissioned properly. Lights often remain on when external illuminance is high.

— In this application exposed internal thermal mass conflicts with the need for acoustically quiet internal conditions. Ways to install acoustic absorptance without reducing the effectiveness of exposed thermal mass should therefore be investigated.

— The effectiveness of the night cooling control system should be thoroughly investigated by simulation/emulation before installation. This would ensure that the anticipated control rules are appropriate. Once installed the systems should be commissioned as carefully as normal air-conditioning systems.

— Passive humidification of naturally ventilated buildings should be investigated.

— Greater attention should be paid to the distribution of daylight from façade fenestration and from atria, with lighting control systems designed to respond accordingly(15). Care should be taken to provide local control for occupants.

Many of the performance shortfalls observed throughout the performance monitoring of this building have resulted from failing to relate performance to commissioning in contracts. It was attempted in procurement to ensure that commissioning was adequate by requiring the main contractor to monitor the building's performance for one week in winter and summer. However, the measurement dates, the scope of the monitoring and its output were not specified. A series of unscaled, unintelligible graphs were produced directly from the BEMS supervisor interface. They offered no indication of the degree of success of the commissioning process because appraisal was not planned and the results were not thoroughly analysed. It is therefore recommended that procurers of future building projects, particularly those with novel control of transient natural airflow, provide a commissioning performance specification alongside the construction performance specification. A monitoring system similar to that described in this paper would be a useful resource to assist with this commissioning.

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