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Delivery and performance of a low-energy ventilation and cooling strategy

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There is an appreciable literature exploring environmental design strategies for low-energy, naturally ventilated and cooled buildings, but less is recorded about their implementation in practice. The commissioning and monitoring of the passive downdraught-cooled UCL School of Slavonic and East European Studies (SSEES), London, is reported. The building contractor, his suppliers and subcontractors experienced considerable difficulty in achieving defect-free environmental systems, adversely affecting the practical delivery of the strategy for an extended period. The design team was closely involved throughout this period to assist in establishing a stable controls regime reflecting the design intent. However, this intent was itself modified by feedback provided by monitoring. The widely used professional appointment and construction contracts employed for this project do not envisage the need for such extensive commissioning. However, it is argued here that the new generation of advanced naturally ventilated buildings, much encouraged by policy-makers worldwide, will require just such a comprehensive commissioning exercise to deliver anything like their full designed performance.

Keywords: building performance, commissioning, feedback, monitoring, natural ventilation, passive downdraught cooling, procurement, project delivery, sustainable construction

Il existe une importante littérature consacrée aux stratégies de conception environnementale pour les bâtiments à faible énergie, ventilation et réfrigération naturelles; en revanche, elle est moins fournie en ce qui concerne la mise en œuvre de ces techniques. Cet article décrit la mise en service et la surveillance, à Londres, du bâtiment de l'UCL School of Slavonic and East European Studies (SSEES) qui est réfrigéré par aspiration descendante. L'entrepreneur de construction de ce bâtiment, ses fournisseurs et ses sous-traitants ont été confrontés à de grandes difficultés lors de la réalisation de systèmes environnementaux sans défaut, ce qui a retardé pendant longtemps la mise en pratique de cette stratégie. L'équipe de conception, étroitement associée pendant toute cette période, a apporté sa contribution à la réalisation d'un régime de contrôle stable reflétant le concept. Toutefois, ce concept était lui-même modifié par des retours d'informations provenant du système de surveillance. Les contrats de désignation de professionnels et de construction, largement utilisés pour ce projet n'envisagent pas la nécessité d'une telle mise en service. Toutefois, on fait valoir ici que la nouvelle génération de bâtiments de pointe à ventilation naturelle, très encouragée par les décideurs politiques dans le monde entier, nécessiteront une mise en service complète pour que ces bâtiments offrent toutes les performances spécifiées.

Mots clés: performances de bâtiments, mise en service, retour d'information, surveillance, ventilation naturelle, réfrigération passive par aspiration descendante, approvisionnement, livraison du projet, construction durable

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Background

Detailed consideration of commissioning 'non-standard' buildings is surprisingly rare. Bordass *et al.* (2001b) make mention of professional appointment conditions, insurers' strictures, and final account settlements as constraints on candid exposure of 'real life' experience. They observe:

> the sad fact is that few architectural or engineering design practices consistently collect information on whether or not their buildings work and none make the information available in the public domain.
>
> (p. 154)

Industry-wide knowledge of these processes is 'tacit' as identified by Cole and Lorch (2003). The Construction Process Protocol (Cooper *et al.*, 1997) adds additional work phases to the standard Royal Institute of British Architects (RIBA) *Plan of Work* (1972), but jumps from 'Construction' to 'Operating and Maintenance'. The assumption is that completing the project is not an issue, enabling a timely 'first project review'. Similarly, Blyth and Worthington (2001) in their 'Process Primer' model process, deal only briefly with the post-project stage 'Commissioning the building' (Chapter 10), which is concerned with 'adjusting the building to its needs' and 'testing the building against stated performance criteria'. Trebilock (2004) elaborates a five-phase 'supply chain selection protocol' which includes a fifth 'Proving Period' phase. Risk management and logistics thinking proceed throughout this concluding phase, although the full application of 'Management Processes' ceases and is shown to be discontinuous through phase 5, clearly thought to be only minimally required (Chapter 20, Managing Design and Construction, p. 165). The Building Services Research and Information Association (BSRIA) is encouraging on this topic (Martin, 1996). Its guidance on the control of natural ventilation reads, in Chapter 6, 'Commissioning and fine tuning procedures':

> The commissioning (setting to work) of the BMS-controlled, naturally ventilated building is comparatively straightforward.
>
> (Martin, 1996)

However, the guidance continues, perceptively, to warn: 'It is the fine tuning that is more likely to cause problems.'

It refers to the difficulties of achieving balances in the airflow regimes of 'ever-changing conditions'. It recommends three visits of three to four days' duration in the year following Practical Completion.

Bordass and Leaman (2005) remind us that work stage M – Feedback – was withdrawn by the RIBA in the 1972 edition of the *Plan of Work for Design Team Operation* as the economy slowed and architects were unwilling to offer a service for which they believed they were unlikely to be remunerated. The 'Soft Landings' initiative (Way and Bordass, 2005) (of which the first author has direct experience from the Cambridge University Estates Committee) attempts to extend the positive involvement of the design and construction team well beyond Practical Completion, at a cost.

The environmental design strategy for the UCL School of Slavonic and East European Studies (SSEES) is described by Short *et al.* (2004) and Woods *et al.* (2003a, 2003b). Its situation at the epicentre of the London urban heat island, as measured by Watkins *et al.* (2002), required additional mechanical cooling in peak summer conditions to deliver comfort to current UK guidance (Chartered Institution of Building Services Engineers (CIBSE), 2006). Short *et al.* (2004) explored how the wholly passive strategy applied to the Lanchester Library in Coventry could be modified to perform within the heat island by the addition of passive downdraught cooling (PDC). PDC is passive in the sense that no fans are employed to drive a pre-cooled airflow through the building. However, the control regime required additional modes of operation and is, as a consequence, more complex.

The Lanchester Library broadly performs to its design intent. Results from a two-year monitoring exercise have been published by Krausse *et al.* (2006). The building was intensively commissioned over a six-month period. Krausse *et al.* record:

> Even during prolonged hot spells, which, in the period June 2004–June 2006, included outside air temperatures as high as 35.4°C, the internal temperature did not exceed 26.4°C, thus internal temperatures were up to 9 K below peak ambient temperatures. All floors of the building therefore comfortably met the prevailing CIBSE *Guide A* [2006] thermal comfort criterion: that there should be no more than 1% of occupied hours with a dry-resultant temperature above 28°C. In fact, the building also met the tougher criterion, mentioned in CIBSE *Guide J* [2002], that there should be no more than 5% of occupied hours over 25°C.
>
> (p. 10)

Figure 1 depicts the configuration of controls on airflow across the seven-storey section of the SSEES building as designed and built.

Outside summer peak conditions, air is introduced via a low-level plenum into a central lightwell, from which it is encouraged to flow across the floors to the perimeter by the natural buoyancy forces generated between the inlets and the exhausts. In the heating season, heat may be introduced within the supply plenum and again at the point of entry to each floor.

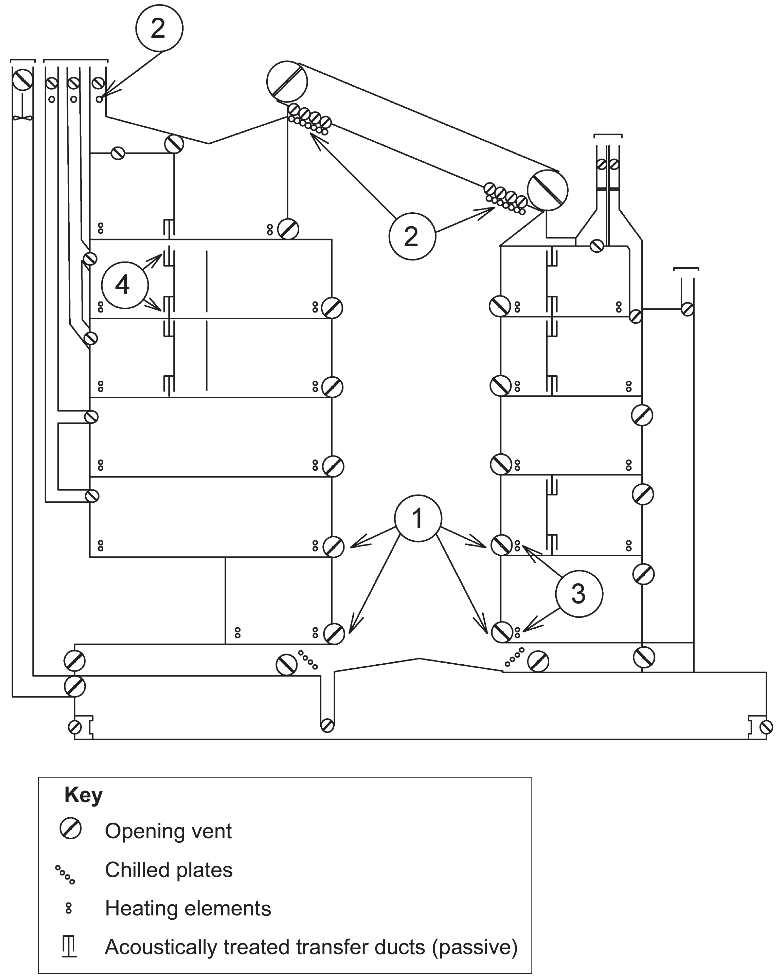


Figure 1 Mechanical controls driven by the Building Management System. ① Actuated opening windows; ② dampers; ③ cooling coils at the atrium head and waste heat batteries in the exhaust stacks; and ④ acoustic transfer ducts at partitions

In mid-season and moderate summer conditions, night purging across the exposed concrete structure was to be employed to reduce daytime peak temperatures. In peak summer periods, PDC was to be operated in daytime to supplement the preceding night purge. The design envisaged downward flow through cooling coils at high level in the central lightwell such that cooled air would drop into the lightwell and fill it, before being released across the occupied floors. Waste heat from the chiller was to be diverted to heater batteries in the stack terminations to encourage upward flow when external temperatures are potentially as high or higher than the exhaust air. Simulations detected a possibility of stalling in these conditions (Woods, 2003b).

Control modes as designed

The original design for the design control regime is shown in Figures 2–4, informed by guidance from BSRIA (Martin and Banyard, 1998).

For 'heating and fresh air ventilation mode', the building was to be configured as in Figure 2, in which mode:

- Perimeter hot water radiators located around the lightwell and the perimeter were intended to heat occupied spaces to 21°C, whilst the lightwell temperature was to be permitted to rise to 16°C by the beginning of occupancy.
- Throughout the occupied day, the temperature was to be maintained at 21°C. However, if the average of the slab and air temperatures exceeded 24°C, the 'ventilation cooling mode' was to be engaged. Dampers controlling airflow rates to prevent CO_2 levels in the occupied spaces rising above 1000 ppm were to have a variable opening capability, perhaps five settings. They are shown in Figure 2 as semi-open. Dampers at stack top and double-facade exhausts are shown fully open, and were to have only two modes, full open or closed,

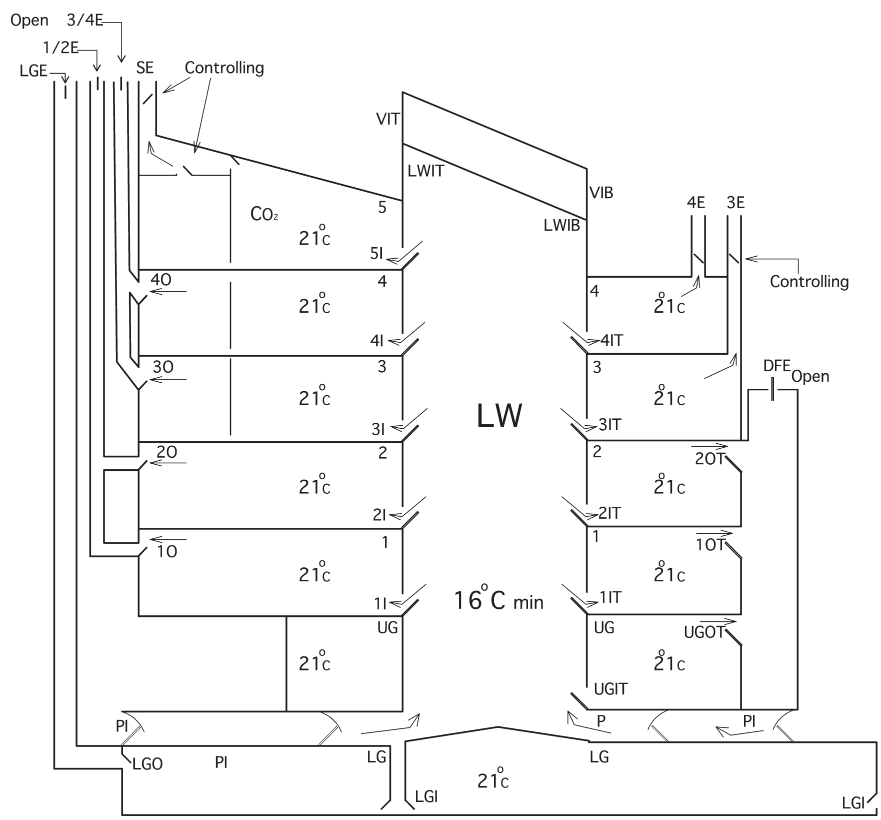


Figure 2 Heating and fresh air ventilation mode, $T_{air} = 21°C$ and $CO_2 < 1000$ ppm. **Key to Figures 2, 3 and 4: VIT** – ventilation inlet top of lightwell cavity; **VIB** – ventilation inlet bottom of lightwell cavity; **LWIT** – lightwell inlet top (inlet dampers around the upper edge of the lightwell collar); **LWIB** – lightwell inlet bottom (inlet dampers around lower edge of lightwell collar); **1I, 2I DFE** – low level inlets from the lightwell to the various floors of the building on the north east side; **1IT, 1IT** – low level inlets between the lightwell on the Taviton side of the building; **1O, 2O DFE** – outlets from each floor at high level into the stacks on the Chemistry side of the building; **1OT, 2OT, UGOT** – high level outlets from each of the floors to the double façade on the Taviton side of the building; **LGE, 1/2E, 3/4E DFE** – exhaust outlets from the Lower Ground, First, Second, Third & Fourth, and Double Façade; **PI** – plenum inlets; **LGI** – inlets to lower ground from outside, from the ventilating corridors and from lightwell

and to remain closed until the first call for fresh air ventilation was received.

- As the day progressed, CO_2 levels were expected to rise. At 1000 ppm the inlet vents connecting the lightwell to the affected space were to open. The air in the lightwell was anticipated to be cooler than the occupied spaces, but both were expected to be warmer than the exterior, so that the static head of cooler air in the lightwell would theoretically drive a flow of fresh air into the space with increasing CO_2 levels. It was envisaged that this connection to the lightwell alone might be adequate.

- The lightwell top was to remain closed and airtight throughout this mode.

- Should CO_2 levels continue to rise, the air outlets from the affected sector were to open on their first setting, inducing a cross flow of air from the lightwell, across the space, and up the exhaust stack. The heating elements at the lightwell inlets were to be required to temper air arriving in the occupied floor from the cooler atrium. Inlets to the low-level plenum were then to open to make up air in the lightwell. Inlet dampers to be distributed in series to provide a finer grade of control. In the built version, each is independently controlled.

It was thought to be important that the lightwell temperature be maintained below the target space temperature. The denser air would flow down into the lower ground floor as required. More densely occupied spaces at the lower levels, the computing and video laboratories, would benefit from the ‘ventilation cooling mode’ without less densely occupied spaces being inadvertently over-cooled. Furthermore, it was believed that maintaining lower lightwell temperatures would reduce heat losses through the translucent lantern at its head.

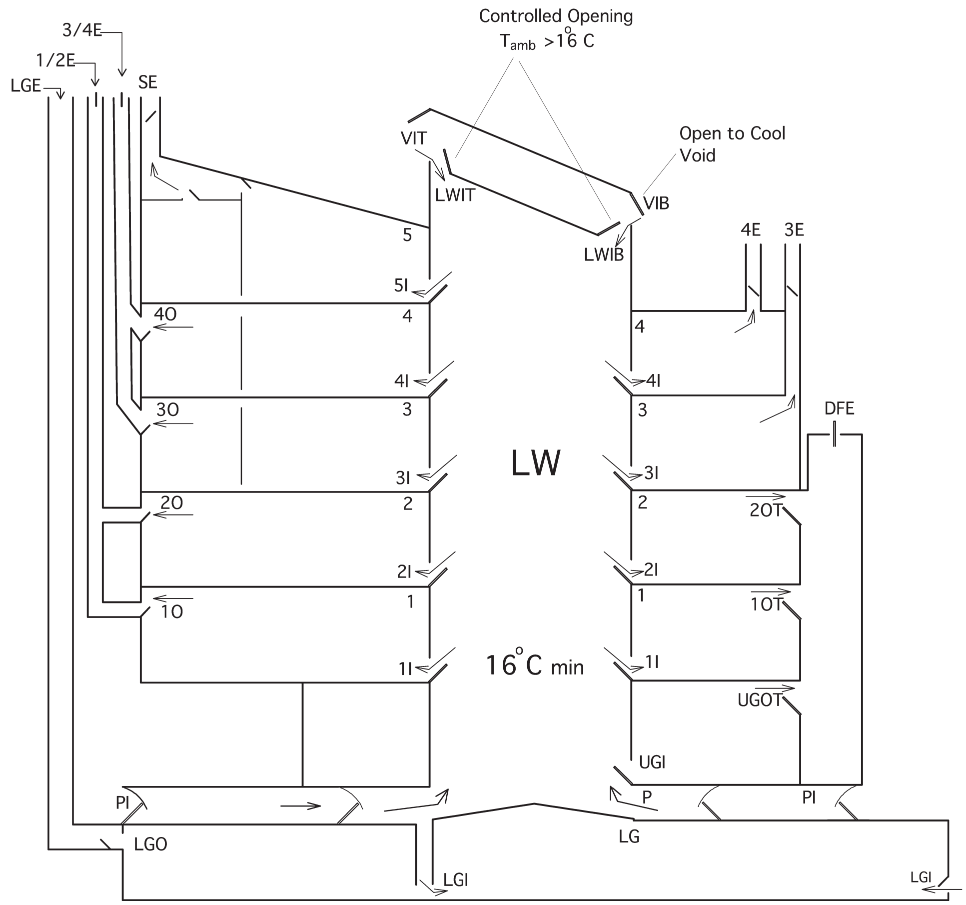


Figure 3 Ventilation cooling, Av T_{slab} and T_{air} $> 22°C$ and $T_{ambient} < 22°C$. (For the key see Figure 2)

Ventilation cooling mode

Figure 3 depicts the configuration of dampers in 'ventilation cooling mode'. It was designed to be an incrementally introduced strategy. Air was to be supplied at low level, via the plenum, into the lightwell until the ambient temperature reached 16°C or until the total free area of the inlets, the sum of all inlet opening area in all floors, exceeded the maximum free area of inlet available to the plenum (approximately 13 m^2).

At either of these moments, the lightwell head was to be opened to supplement inlet area. The ventilation cooling mode set point was fixed (T_{vent}) at the design stage to be 22°C, the average of the slab and air temperatures in a given zone. The air inlet was to lead the control sequence. It was thought connection to the lightwell alone could correct temperatures through exchange flow, without the need to stack ventilate the building to the exterior.

- When the ambient temperature exceeded the space temperature but the space temperature was still below the cooling set point, the controls would revert to 'CO_2 control mode'. However, if the inlets were fully open and space temperatures were still in excess of ambient temperature, this full 'open top and bottom mode' would be maintained until the assisted cooling (PDC) set point was reached, set at design stage as 25°C.

Night ventilation

- The settings for inlets and outlets for night ventilation were designed to be as for day ventilation. It was envisioned that night ventilation would commence at 23.00 hours and cease at 06.00 hours, or whenever ambient temperatures started to rise at dawn. The original design strategy foresaw that the building might become cooled below the heating set point for occupied periods once the vents were closed at the cessation of the night vent mode, but was unsophisticated in its provision to mitigate or prevent this, mindful, however, of the guidance provided by BSRIA (Martin and Fletcher, 1996).

- It was thought that the controls would monitor floor-slab temperatures to control the duration of

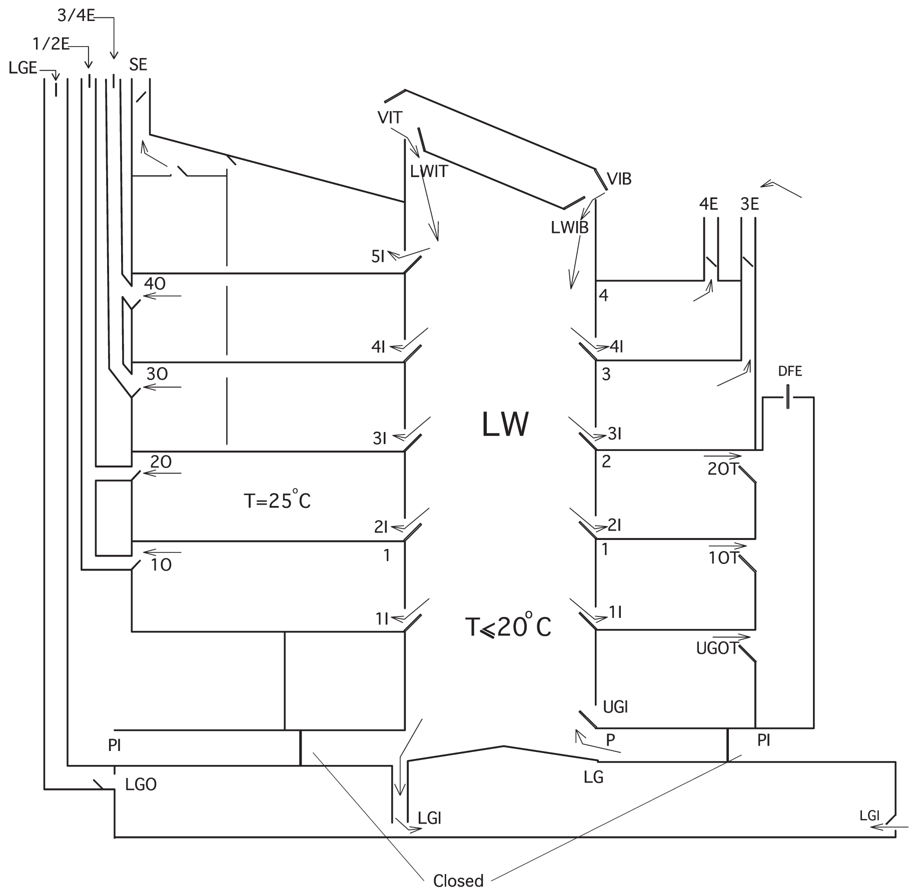


Figure 4 Settings for the dampers in passive downdraught cooling (PDC) mode. (For the key see Figure 2)

night ventilation, but commissioning experience would inform the decision about the slab set-point temperature selected.

Passive downdraught cooling (PDC)

- The settings for the dampers in PDC mode are shown in Figure 4. This mode was highly dependent on achieving airtight closure of the dampers at the base of the lightwell. A good seal would prevent cooled air draining out of the lightwell base, its natural tendency, short-circuiting the intended ventilation paths.

- All the actuated windows to the lightwell head and the dampers connecting the void within the lightwell head to the lightwell were to open on engaging this mode. Cooled water would be introduced into the cooling pipes below the inlet dampers. The volume flow of pre-cooled air to the occupied floors was to be controlled at the inlets to each floor from the lightwell.

The set point for PDC was taken as 25°C in any occupied space, but it was realized that commissioning experience should inform the selection of this critical control temperature. It was thought that by this stage the lightwell temperature would be 20°C or above, but that ambient external temperature would be higher, so that the stack-driven ‘ventilation cooling mode’ would eventually stall.

The procedure for introducing the PDC mode was rehearsed; the base of the lightwell was to be closed, the cooling coils switched on, the lightwell top opened and the inlets at each floor from the lightwell to be closed for a period to enable a head of pre-cooled air to develop, at say 20°C. It was thought this might take two to three minutes, at which point the lower inlet dampers to the tilted lightwell head should be closed. This was to avoid the development of an asymmetric supply of pre-cooled air to the south east side of the building which could have occurred due to unconnected town planning and conservation arrangements (Short *et al.*, 2004). However, maintaining the lightwell inlet bottom (LWIB) inlets to be open during charging of the lightwell would enable accumulated warmer air to escape. Waste heat from the chiller would be injected into the stack tops simultaneously.

Control in this mode would be driven by the average of the air and slab temperatures.

Contract controls specification

The Contract Specification for the controls, authored by the mechanical and electrical consultant (Environmental Design Consultancy (EDC), 2003), confirmed the design control propositions, but added further necessary preconditions to trigger the PDC mode:

- no heating demand anywhere within the building
- an ambient air temperature set point of 22°C and rising
- averaged structural slab temperatures to exceed 22°C
- averaged internal temperature to be at 26°C or greater, 1°C up on the design set point

The Specification also called for the higher lightwell temperature of 20°C in winter to rely less on heating at the points of entry to the floors. It recognized that it would be prudent to isolate the air volume of the front street side of the building, a circulating system in itself with lower stacks, from the rear. They are potentially connected, however, across the lightwell. It added an algorithm for minimizing penetration by heavy rain, instructing any window within a 20° margin of the wind direction to remain closed directed by wind speed and direction sensors.

The fire and smoke control strategy and its delivery to comply with Part B of the Building Regulations (The Stationary Office (TSO), 2000) are described by Short *et al.* (2006). The natural ventilation system was to be used to maintain smoke-free zones. This strategy was accepted by the London Fire Brigade.

The Contract Specification (EDC, 2003) for commissioning the environmental systems was worded as follows:

> **Post Contract commissioning/system fine tuning**
>
> Due to the interactive nature of the ventilation systems being employed, it is envisaged that the BEMS control system will need to be adjusted/fine tuned during the first 12 months of operation. In light of the above it is the Engineer's intention to hold periodic Post Contract meetings with the Representatives (end user feedback) to review system operations and to adjust/fine tune set points, proportional bands etc. accordingly.
>
> The Sub-Contractor together with his Controls Specialist will be required to attend 12 No. one day Post Contract controls meetings and consequently the costs for same shall be included within the Tender offer.

The tendered Specification, which became the Contract Specification without adjustment to the controls section, secured what was thought to be, by all parties, a more than adequate allowance for time and attendance on site to complete commissioning. The Specification continued:

> **Post Contract controls system stabilization/trouble shooting**
>
> The Sub-Contractor's Controls Specialist shall include for Post Contract Commissioning works to adjust/fine tune control systems, working closely with the Client's Facility Department and the Consulting Engineer. The works will generally involve multiple 'trend/history data logging' of various zones/plants/systems, data analysis and implementation of set point adjustments/control software adjustments *as necessary*.
>
> (added emphasis)

In practice, the data logging and analysis required to investigate equipment malfunction and establish the true cause of aberrant environmental conditions was prodigious. Table 1 gives some indication of the scope.

> The Controls Specialist will be required to maintain detailed post contract records of any system adjustments made, trend logs implemented etc. The records will ultimately be historic reference data and consequently it is imperative that same are chronological. Copies of all record information are to be distributed to the Client and the Consultant as and when generated.
>
> For the purpose of tendering the following minimum attendance shall be included at tender stage:
>
> i. For the 6 week period following Practical Completion, allow 2 man days site attendance per week.
>
> ii. For week 7 to week 52 following Practical Completion, allow 1 man day site attendance per week and daily monitoring via modem from a remote location.
>
> The Controls Specialist engineer in attendance for the above must be familiar with the system installed and be of a level able to effectively implement trend logs, analyse historic data and capable of implementing on site software changes.

The actual input was greater by an order of magnitude, virtually full time throughout this 20-month period, the controls subcontractor having recourse to the main contractor only for remuneration. As a domestic subcontractor, all payments were coupled to the satisfactory operation of the systems, a self-defeating and self-perpetuating loop.

Design performance predictions

Short *et al.* (2004) described the use of CIBSE Design Summer Year (DSY) data (CIBSE, 2002) as the climate file for computational simulations. The resulting year, 1989, had an absolute peak temperature of 33.68°C and 267 hours with a dry bulb temperature in excess of 25°C. The authors also described the thermal criteria used: the CIBSE suggestion that internal temperatures should not exceed 25°C for more than 5% of occupied hours (CIBSE, 2002). This criterion translates into a limit of 150 hours above 25°C, somewhat less than the number recorded by the Heathrow DSY at the outer edge of the London heat island. Even if the internal temperatures in a building within London could be maintained throughout at ambient during the peak summer period, the CIBSE comfort criterion could not be met, even discounting the considerable uplift in summer night temperatures measured in August 1998 (Watkins *et al.*, 2002).

Three modelling techniques were employed: two digital – computational fluid dynamics modelling of airflow, and dynamic thermal modelling of space temperatures through a full year. Physical models comprised the third technique, suspended in a water bath, the better to understand the dynamic complexities of the airflow, and to identify any different potential modes.

Modelling

Computational fluid dynamics

Due to the complexity of the building, three separate computational fluid dynamics (CFD) models were constructed: the first comprising upper ground and floors 1, 2, 3, and 4, the second comprising floor 5, thought to be vulnerable to summertime overheating, and the third comprising the lower ground floor, one step removed from the operation of the PDC within the lightwell. All three models were used to investigate the likely ventilation performance in passive mode and additionally, models 1 and 2 were used to predict the performance during mechanical cooling, including the heat inputs to the ventilation stacks to assist the natural ventilation outflow. All models predicted a healthy flow with warm air rising out of the building through the stacks, drawing in fresher air from the lightwell at low level (Figure 5) (Short & Associates *et al.*, 2007a).

In passive fresh air ventilation mode, the model suggested outside air at 24°C would enter the lightwell through the lantern base, as intended. In PDC mode, an

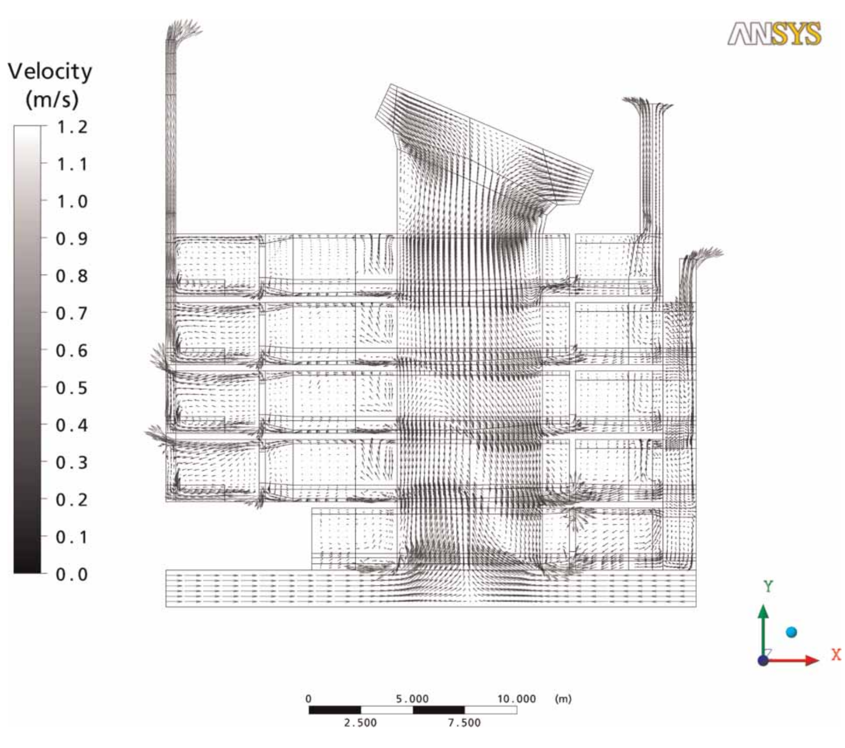


Figure 5 Computational fluid dynamics analysis: cross-section through the building in passive mode

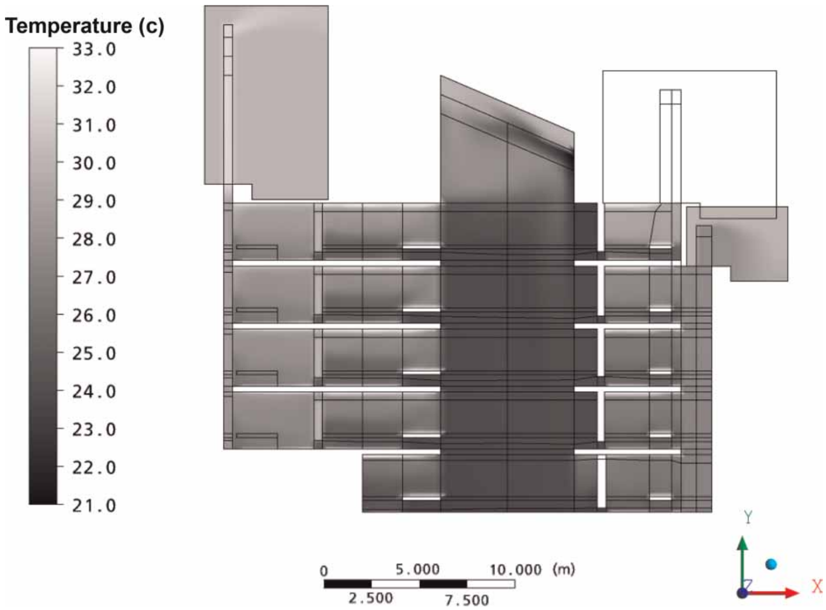
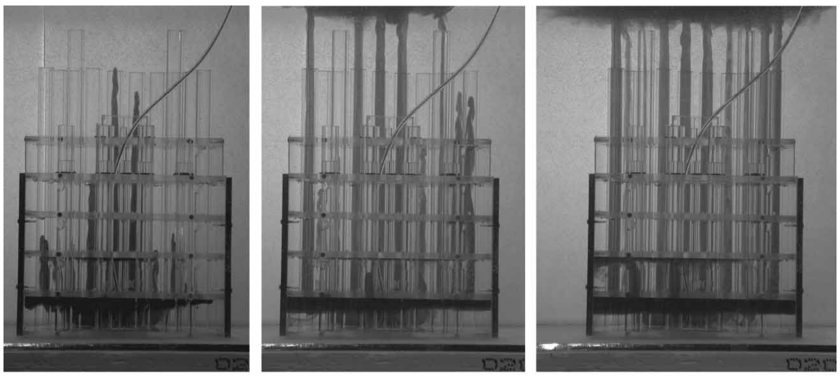


Figure 6 Predicted temperature distribution in the passive downdraught cooling (PDC) mode. Heat is injected into the higher stack tops to the left; flows are increased reducing temperatures in the occupied spaces. The ambient temperature is set at 30°C; stack temperatures rise to 32°C

ambient air temperature of 33°C was modelled, which, in the DSY weather data, is exceeded for only two hours of the year. In this case, all supply air entered the lightwell via its lantern top as intended, before passing through the cooling coils and descending into the lightwell. Predictions of airflow patterns showed clearly how the air entering onto each floor at low level should move across the core spaces surrounding the lightwell, and into perimeter spaces through acoustic labyrinths, where present. The model indicated how the air collected heat as it moved across the floor plate, causing some of the air to rise, flowing out of the core at high level into the perimeter spaces where it remained at high level before flowing out and into the ventilation stacks provided.

In both cooling and passive mode, the temperature of the air, as it flowed across the core spaces, rose by about 4°C; a further 2–3°C of heat 'pick-up' was predicted through the perimeter spaces. It should be noted that these air temperature predictions did not take into consideration radiant cooling effects created by the



1 2 3

Figure 7 Development of the non-uniform steady ventilation regime with different stacks building up flow at very different rates. Modelling of the design in its 'normal', 'bottom-up' ventilation mode. Fluid is introduced at the base of the atrium and out flows start to develop in some stacks 1, more stacks 2, and finally all stacks are relatively evenly distributed. Images show the development of the steady ventilation regime was non-uniform, with different stacks building up flow at very different rates, although eventually a well-ventilated space became established. Here the heat was supplied to the ground floor and the ventilation flow down the atrium, across the ground floor and up the stacks, is revealed

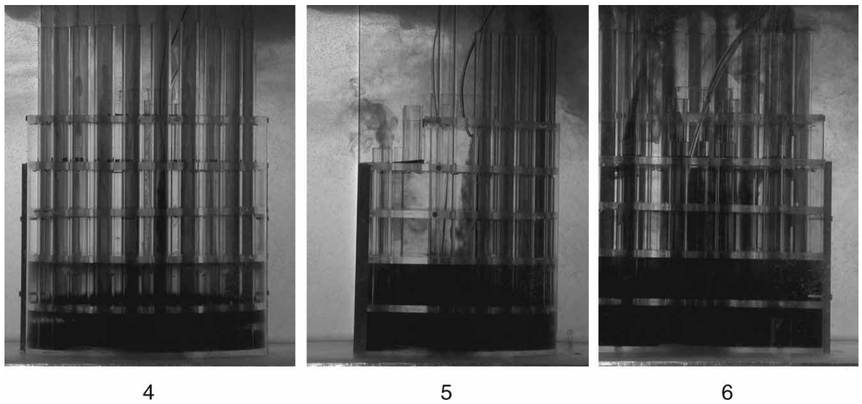


Figure 8 Ventilation flow in the case that pre-cooled (darker) fluid was supplied in the lightwell. The dense (darker) fluid filled the lower two floors, and this reduced but did not arrest the flow. As the flux of denser fluid increased however, relative to the buoyant (lighter tone) fluid, the ground floor fluid could become dense relative to the exterior, leading to some stalling. As may be seen in the side-photograph (centre) the different stacks were convecting either buoyant or dark denser fluid, so that the density of the fluid rising in different stacks from the same floor may be different, leading to temperature gradients across the floor space. This was related to the location of the source of the heating on each floor. In the last photograph of the series, the pre-cooling had by now really suppressed the flow and cooled the two lower floors substantially. They are shown to be, after some time, darker in tone and quite well-mixed. The introduction of heater batteries in the stacks was designed to overcome this loss of buoyancy

building structure following night-time cooling. These effects were modelled in the dynamic thermal simulation (see below).

Dynamic thermal modelling

The analysis was conducted for both a summer and a winter period. The model ESP-r (Energy Simulation Research Unit (ESRU), 1998) was used, modelling a segment cut through four floors of the building, linked by the lightwell and a stack. This was a combined airflow and thermal model. The airflows were driven by the differences between inside and outside temperature rather than being imposed. Simulations using the London (Heathrow) DSY (CIBSE, 2002) showed that there was a risk of exhaust air from floors 1 to 3 flowing back onto the fourth floor. Thus, it was recommended that the stacks venting the fourth floor should be separated from those exhausting the other floors. Stack separation was subsequently implemented throughout the building.

It was also observed that zones of high internal heat gain, such as the computer rooms, would overheat in summer, even with night ventilation and exposed thermal mass and therefore some form of assisted cooling would be needed. With a cooling system capable of reducing the lightwell temperature to below 23°C, the model predicted it would be possible to keep the spaces below 28°C under the conditions recorded in the DSY. It was noted that the effective operation of such a strategy was critically dependent on the successful operation of the dampers, particularly those delivering fresh air to the base of the lightwell.

The winter simulations predicted adequate fresh air ventilation. As a result of the predictions, it was suggested that perimeter heating of the building might not be necessary. However, it was decided to provide it in the built version to mitigate risk.

Experimental water-bath modelling

Physical models were used to investigate natural ventilation in a recirculation atrium-stack system. It was predicted that particular challenges for passive ventilation might arise when the external temperature was high, so that buoyant outflow may not readily develop. The work investigated how the pre-cooling designed for this building might overcome this problem.

The potential coupling of the flows from different floors, focusing on the case of a lower floor driving flow in an upper floor, and an upper floor driving flow in a lower floor, was also studied, and this analysis revealed conditions in which multiple ventilation regimes could develop, raising challenges for the control system.

Modelling approach

A series of simplified hydrostatic pressure profiles that could potentially develop in the lightwell and the outflow stacks was explored. Different possible flow regimes were identified. A more quantitative approach was developed to delineate these different possible regimes, and the different flows demonstrated using a series of laboratory experiments (Woods *et al.*, 2003a).

Laboratory experiments corroborated the principles described in the models. Although the actual flow regimes would be more complex than identified by the models (which assume the air is well mixed on each floor), they did identify the general principles which are supported by the experiments. The experiments were developed (1) to illustrate the principles, with simplified 'J'- and 'U'-tube geometries, to focus on the stack-stalling effect in high summer and the recirculation on higher floors induced by heat fluxes on a lower floor; and (2) to illustrate the complex coupling of floors and stacks in the real building. This latter programme of experiments was conducted in a small-scale Perspex model of the building which included the stacks on various floors and the central lightwell supplying (pre-cooled or pre-heated) air to the building. The experiments were visualized using various coloured dyes. The complex geometry of the model enabled observation of complex dynamic flow regimes.

Laboratory experiments

The physical modelling revealed the following:

- With moderate exterior temperature and a given inflow height to the lightwell, the flow became increasingly effective as the height of the opening in the outflow stack was increased, while the outflow temperature is in excess of the exterior temperature (winter, mid-season, and mild summer day mode).
- With high exterior temperatures (the peak mid-summer condition), and given inflow height to the lightwell, the flow increased as the height of the outflow vent in the outflow stack was lowered (in contrast to the above bullet point). The equivalent effect could be achieved by heating the stack to ambient.

Both the above are competing effects, and indicated that the 'U'-geometry for the building ventilation would be most effective when the exterior temperature is comparable with the desired temperature in the office space; mechanical heating of the stacks counters this effect (Woods, 2003b). The design was modified (in time to be included in the tender documentation) to avoid potential failures in the designed airflow regimes, more specifically:

- Heater batteries were indicated at the stack terminations to enable waste heat to be injected into the stacks to counter the stalling which could arise on an unusually hot day because the outflow stack was designed to be higher than the inflow stack.
- To counter reverse flow developing on upper floors connected to the same stack as a lower floor, the stacks were decoupled; serving two floors only at a time and the front of the building was decoupled from the rear by introducing full-height glazed screens to counter the effect of differential stack heights between front and rear.

Commissioning in practice

Table 1 refers only to controls and construction problems relating directly to the implementation of the environmental design strategy, more specifically:

- actuated windows and dampers
- the building management system (BMS) control system
- the heating circuits driven off the building owner's combined heat and power (CHP) circuit
- the lighting controls
- the 'passive downdraught cooling' (PDC) infrastructure
- the double ring of ethylene tetrafluoretrylene (ETFE) cushions forming the lightwell lantern at high level
- the chilled water circuit and the waste heat batteries raising the buoyancy forces in the exhaust stacks
- air tightness of construction, particularly the supply and exhaust plena

Predictably, the identification of defects tended to be seasonal: heating issues predominated in winter and cooling issues in midsummer. The client commenced occupation three months into commissioning. Although the occupants had been inducted into the broad principles of the control strategy, they found it difficult to recognize the symptoms of controls failure. For example, librarians reported not having seen any of their actuated windows move for three weeks, feeling it unlikely that, by then, changing weather and occupancies would not have triggered a reconfiguration. A log of complaints and occupant observations was maintained by the client's administrators and the mechanical and electrical consultants, to whom occupants reported directly. The twelve-month period defined in the contract documents was inadequate to deliver a fully functioning building.

The BMS sensors performed as intended. No significant failures were identified, but the BMS software was subject to regular close down, interference from incompatible software installed within the system, and external network attack. Low-level, elementary installation failures affected the performance of the heating, whilst low-level construction defects compromised the air-tightness of critical air supply and exhaust plena. However, throughout the 20-month post-completion period recorded here, the failure of

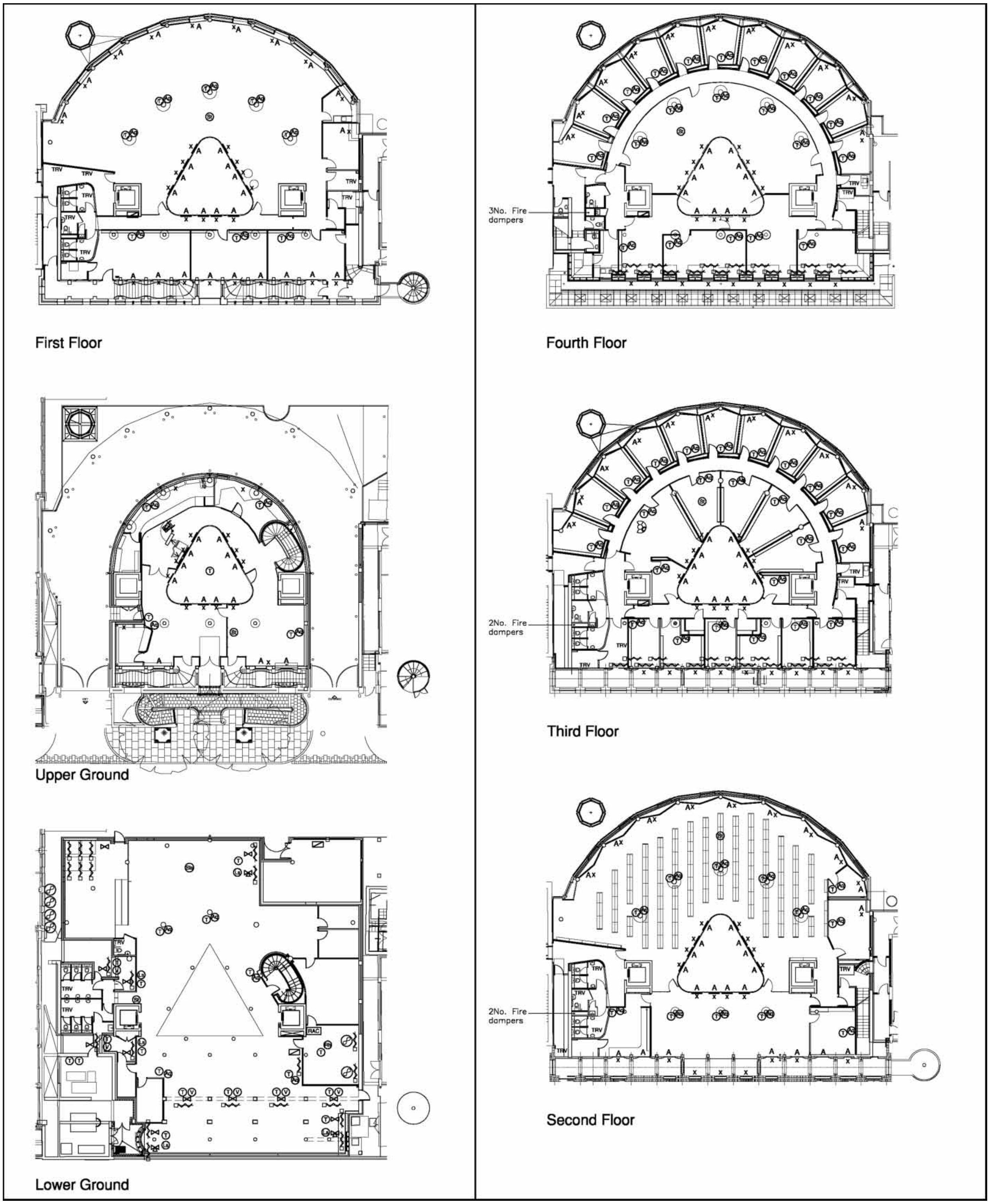


Figure 9 Layout of the BMS sensors installed in the building

simple motorized window actuators both physically and in their interface with the controls was detected continuously until the final few weeks. The design included 160 controls-actuated windows and 120 controlled dampers. Monitoring records, considered in the next section (Table 1), show clearly how their apparently random failure across the geography of the seven-storey building impaired its performance.

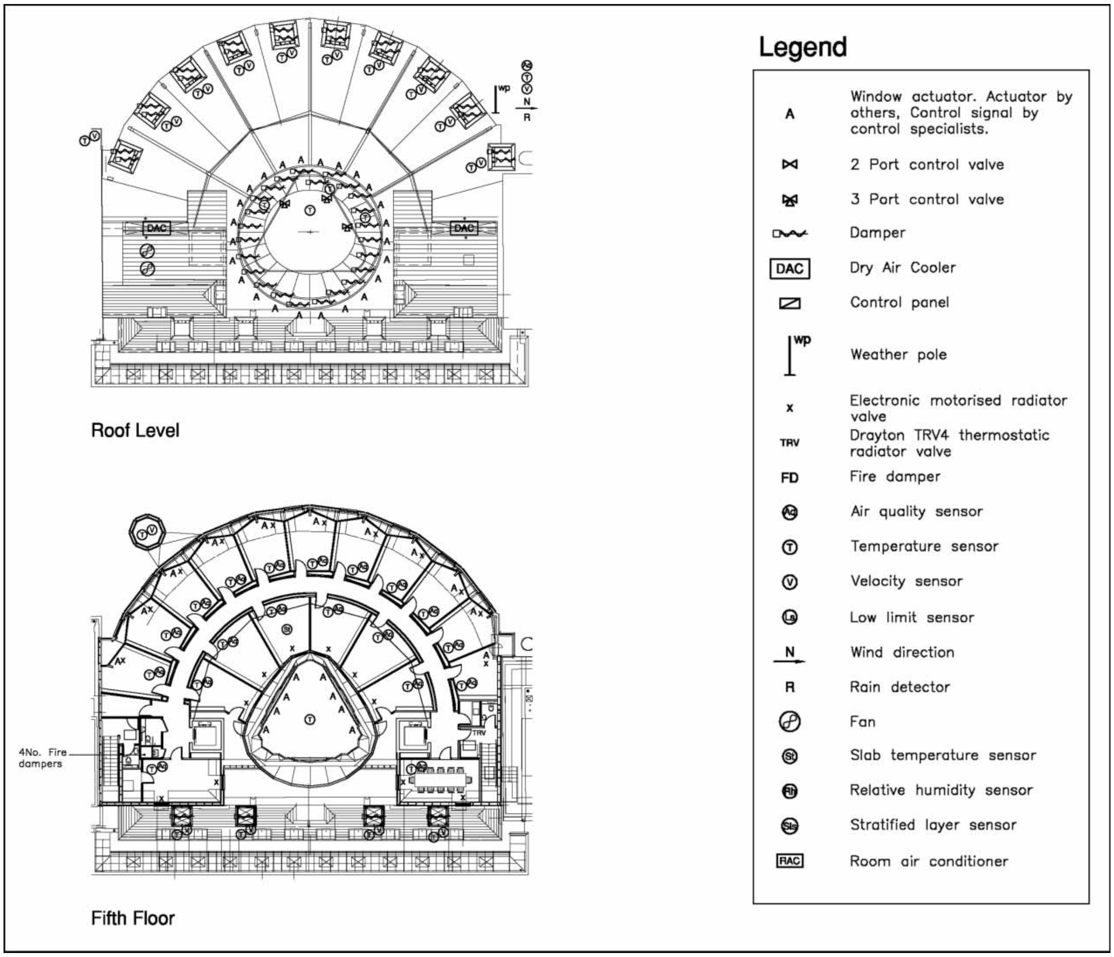


Figure 9 Continued

The twelve months' fine-tuning and commissioning period specified in the contract was used intensively to identify and resolve simple defects and prepare a methodology to resolve unanticipated environmental behaviours detected through testing. In summary:

- Monitoring evidence suggested the dampers and windows were originally programmed to open too wide, too quickly, allowing the building to over-ventilate, breaking up the vertical stratification and inhibiting the ventilation from working in displacement mode. Actual changes in mode were not modelled except for the engagement of PDC in the water bath laboratory work. Ventilation rates were subsequently slowed to all parts of the building. Stack-driven airflows were more vigorous than anticipated in some areas, perhaps as the result of wind effects.

- Delayed completion and commissioning of the daylight-linked occupancy-sensing lighting control system allowed excess heat gains to occur in the building, significant heat inputs beyond that modelled for the summer months, compounded by the inability of the controls to open the full free areas available.

- Repeated controls failures caused window vents to 'freeze' in position, allowing the building randomly to over-ventilate or be starved of air, depending on the fail position of each window.

- Ineffective night purge ventilation due to control failures allowed the structure to warm above design temperatures.

- Individual failed window actuators prevented windows from responding to 'healthy' controls signals, which, however, indicated the failed window had opened or closed, making remote operation of the controls unreliable.

- Frequent air-locking in radiators, heater batteries, cooling coils and the condenser water waste-heat

Table 1 Commissioning the UCL School of Slavonic and East European Studies (SSEES) building

	Window & damper actuators & controls	Building Management System			Heating		Lighting Sensors & controls	Passive Downdraught Cooling	Construction Defects (air tightness)
Date		BMS Sensors	BMS Software	BMS Hardware	Radiator Valves, Waterflow	CHP Interface		Chiller, Waste heat Batteries	
15 Aug **2005**	Partial occupation		Commissioning in progress			3 months before practical completion.			
11 Oct			No effective ventilation		No heating				
7 Nov								Tests show air supply plenum was leaking.	
24 Nov	- 10 actuators failed open (1st floor rear to exhaust stacks) - 3 actuators failed closed (1st floor front) - 1 actuator failed open (2nd floor lightwell supply).				- Water flow unbalanced (1st floor) - Sensors not calibrated (1st floor) - Sensors not calibrated (2nd floor)				
9 Dec			9 air temperature sensors failed (sensors generally reading +2°C)				'Several fittings not switching'.		
12 Dec	Practical completion								Leaking plenum flagged in defects list.

19 Jan **2006**					A number of radiator valves defective.				
25 Jan	Full test of all actuated windows, 7 windows fail open/closed								
30 Jan						- Plate heat exchanger failed (not cleaned on handover) - Heating pump repaired			
2 Feb						Heating pumps inadvertently disconnected (no heating)			
3 Feb	4 windows fail closed, upper ground floor lightwell								
7 Feb							Extensive list of lighting faults		
8 Feb					Pumps discovered to have been reconnected in reverse.				
13 Feb			Overheating of 2^{nd} floor, controls failure		Heater battery flow rates low, temperature low				
24 Feb		Temperature sensor identified as missing from downdraught cooler			Radiator circuit recorded as un-commissioned		Full commissioning of lighting system requested		Instruction to achieve air tightness in supply paths.
28 Feb						Excessive pressure drop across heat exchanger identified			
24 Mar	Various actuator failures reported by contractor		M&E defects list reissued						
3 Apr	Meeting to discuss continuing actuated window failures				Meeting to review progress on commissioning radiator heat exchanger and				

(Table continued)

Table 1 Continued

	Window & damper actuators & controls	Building Management System			Heating		Lighting Sensors & controls	Passive Downdraught Cooling	Construction Defects (air tightness)
Date		BMS Sensors	BMS Software	BMS Hardware	Radiator Valves, Waterflow circuit pump	CHP Interface		Chiller, Waste heat Batteries	
5 Apr **2006**				Meeting to review continuing window control failures M&E subcontractor & actuator supplier					
7 Apr			- Supplier advises software conflict, new software introduced - New software in conflict and removed, old software reloaded			Plate Heat Exchanger (PHE) inspected, blockage diagnosed	Re-commissioning of lighting controls overshoots 27 March target date		
11 Apr						CHP supplier requested to strip down and clean Plate Heat Exchanger (PHE). PHE isolated for cleaning on 18 August.			
15 Apr			Campus wide 'broadcast storm' badly affects BMS controls. Night venting not implemented						
27 Apr						PHE opened up, construction debris removed			
May		BMS controls software rebuilt. System down for 3-4 weeks. Building 'out of control' in failed control configuration, no night venting.							
6 Jun								Chiller as yet uncommissioned	
8 Jun			PDC dampers fail closed, night venting compromised.					-PDC activated for first time. Dampers above cooling coils remain locked closed (BMS failure) - Dampers activated but condenser water temperature set below design, activating dry air cooler prematurely, depriving waste heater batteries in stacks of heat	

								- Bypass valve left open diverting all chilled water from PDC cooling coils	
9 Jun **2006**			Report that further control re-settings resulting from 'broadcast storm' emerging. No night venting.						
19 Jun	Actuator physical failure to lightwell wheel window								
30 Jun	Actuator drive chains to first floor lightwell windows fail. Generally reduced opening by lightwell head actuators reported, restricting airflow.		Night venting compromised						
3 Jul			Status of night venting unclear, BMS record fails to correspond with on-site discussion.					Chiller failed, leak in pipework, waste heat batteries in 4 stacks not performing, air flows reduced	
4 Jul	On site full test of windows. 50% found to be not responding to control signals. All window functions restored by evening.		Slab temperatures indicated higher than design intent.						
6 Jul	10 physical failures to actuators reported.								
10 Jul	3 dampers failed to respond to signal.		Night venting compromised through July & August.					PDC is shut down until chilled water temperature is reset	
14 Jul								Cooling coils to lower ground floor failed mechanically	External rear lobby door sequencing found to disrupt building

(Table continued)

Table 1 Continued

Date	Window & damper actuators & controls	Building Management System: BMS Sensors	BMS Software	BMS Hardware	Heating: Radiator Valves, Waterflow	CHP Interface	Lighting Sensors & controls	Passive Downdraught Cooling: Chiller, Waste heat Batteries	Construction Defects (air tightness)
									airflows
20 Jul **2006**	Lightwell head actuator failed.							Air in chiller pipework reduces performance, heater batteries in 2 stacks failed	
11 Aug								Chiller reported to be fully functioning	
14 Aug	Window controls still problematic.								
18 Aug	Lightwell windows 4th floor failed to respond to controls. Library windows frozen in last activated position.					PHE isolated from system for cleaning			BPI monitor effect of front doors opening in tandem, clearly capable of reversing airflows across building at all levels
25 Aug	Rear elevation 2nd floor windows to stack failed to respond to controls. Library windows frozen.								
26 Aug	4 failed actuators. Windows failed to respond to controls.								
7 Sep	Library windows continued to be frozen in last actuated portion of mid August.								
11 Sep	Library windows still 'frozen'.		Building wide controls failure.						
13 Sep			'Enabling' SW programme identified as source of problem, part removed from BMS by controls subcontractor.						
15 Sep	All actuated windows reported to be fully functioning.		BMS controls reported as fully functioning. Removal of						

			enabling software completed 27/9/06.						
10 Oct **2006**	5 actuators failed.								
17 Oct	Proposition to supply more robust actuators for lightwell head. 5 physical failures.								
24 Oct	All actuated windows frozen.		Control of all actuators lost.						Inspection reveals defects remain
25 Oct	Window controls are reset.		Controls reset. Problem related to enabling S/W removed in September.						
2 Nov	Dampers fail open in 4th floor roof of plenum.				4th floor radiators air-locked				
3 Nov									(3 Nov) 4th floor plenum air tightness failures
8 Nov									Modifications to front entrance lobby door controls minimise full opening in tandem
18 Dec									Subcontractor completes front door controls modifications

(Table continued)

Table 1 Continued

	Window & damper actuators & controls	Building Management System			Heating		Lighting Sensors & controls	Passive Downdraught Cooling	Construction Defects (air tightness)
Date		**BMS Sensors**	**BMS Software**	**BMS Hardware**	**Radiator Valves, Waterflow**	**CHP Interface**		**Chiller, Waste heat Batteries**	
Jan **2007**									
Feb		BMS demonstrations for end-users.							
Mar									
14 Apr		Meetings to rehearse control strategies for summer 2007.							
May									
Jun									4^{th} floor roof plenum: remedial work failed to suppress air leakage
Jul									
7 Aug			BMS controls reviewed in preparation for testing of PDC.			Chiller failure repairs completed for planned PDC test			'Making good' of defects achieved
10 Aug	Actuators failed around lightwell lantern lower edge				Heating engaged unexpectedly briefly at 7.00 am after passive night venting		Lighting switched on despite zero occupancy	Full Building Smoke test established PDC performance, sufficient, all actuators, chiller, controls functioning	

batteries prevented effective heat exchange to occur. The building, starved of heating in these periods of failure, was inevitably cold.

- Blockage to the radiator circuit cross-plate heat-exchanger reduced the heat supply to the perimeter heating system, exacerbating the problems above.

- Regular chiller failure compromised the first attempts to operate the PDC installation. Chilled water flow temperatures were inadvertently lowered below the design intent by the subcontractor due to a communications failure. Too low a temperature setting induced condensation and a further period out of use whilst the controls were reset remotely.

- Excessive air infiltration as a consequence of the following:

  - Mechanically operated front doors. This was a particularly interesting discovery and most probably a common occurrence in contemporary buildings. The provisions of Part M of the Building Regulations (TSO, 2004) tend to increased opening periods for pairs of electronically operated doors, in this case adding 5 m^2 of unintended, untempered inflow, more than one-third of the designed free area at the base of the building. The modelling of the design certainly did not consider this possibility.

  - Incomplete sealing of, and insulation to, the fourth-floor roof plenum leading to excessive infiltration, undermining the control strategy for this area.

  - A smoke ventilation window at the top of the north stair remained open throughout (a disconnected actuator); introducing a new stack, short-circuiting airflows.

Relatively small clusters of defects had a disproportionate impact on performance. Certainly ten failed windows out of 280 actuated vents, 3.57% of the total, could seriously disrupt the environmental strategy in any mode across the building, raising questions of customary industry tolerances to defects, which may well be inadequate to realize advanced naturally ventilated buildings.

Measured performance

Fine-scale monitoring was conducted to map actual airflows through the building, establishing the direction and vigour of flow. These data were compared with the intended and predicted design performance. Monitoring was planned in three phases.

The objectives of the first phase (23 October 2006) were to monitor the building in its day-to-day running mode (which included changes requested by the mechanical and electrical design consultants). The purpose of the first phase was to compare existing BMS sensor readings with the new sensor readings and to collect data for use in determining further sensor positions for the second phase. Table 2 indicates the distribution of monitoring equipment.

Care was taken that the additional temporary monitoring sensors were hung over the installed BMS sensors in such a way so as not to impact on the operation of the existing sensors. Conditions were monitored continuously and logged every ten minutes. Comments from occupants relating to discomfort communicated directly to the design team and through the client administration were analysed and used to focus data gathering on particular areas.

Second phase of monitoring, week commencing 7 November 2006

During this phase data were downloaded from each sensor installed during the first phase. The sensors were left in place for further monitoring. The initial data obtained enabled some informed adjustments to the design environmental control strategies to be put in place.

Phase 2 was achieved by purchase of the controls subcontractor's '*supervisor*' software, enabling researchers to have remote access to all BMS data.

Third phase of monitoring

Smoke tests

A series of smoke tests was also carried out in the SSEES building on 11 December 2007 and filmed to assist the assessment of air supply and exhaust flows at different locations. An air current tester (Retrotec) was used to generate small puffs of smoke (titanium tetrachloride). By observing the movement of the emitted smoke, the direction and strength of the airflow at different points in the building were assessed qualitatively. Supply airflows were investigated outside the fourth-floor front offices and for two perimeter offices on the third floor. In the open-plan library space on the second floor both air supply from the lightwell and air exhaust flow into the ventilation stacks were tested.

The tests showed positive airflows into occupied spaces from the supply lightwell, into labyrinth air transfer ducts between core area and perimeter rooms, and out to exhaust stacks and stairwell/exhaust stacks through high level vents. These airflows were all

Table 2 Monitoring, Phase 1; distribution of equipment: first visit week commencing Monday 23 October 2006

Fifth floor	Two temperature sensors to rear perimeter offices Two temperature sensors in rear core offices
Fourth floor	Two temperature sensors in rear perimeter offices Two temperature sensors in rear core offices Two temperature sensors in front offices One temperature plus one CO_2 sensor in Director's office
Third floor	Two temperature sensors in rear perimeter offices Two temperature sensors in rear core offices Two-to-three temperature sensors in front offices
Second floor	Two temperature sensors in rear area Seen temperature sensors in front offices One temperature plus one CO_2 sensor in meeting room
First floor	Two temperature sensors in rear area Three temperature sensors in front offices (one each)
Upper ground floor	One temperature sensor in entrance foyer One temperature sensor on column opposite main door One temperature at reception desk One temperature sensor in reading area
Other	Four temperature sensors in double facade: one at the upper ground floor level one at the first floor level one at the second floor level (subject to access) one at the third floor level (subject to access) One external (shielded) temperature sensor on roof Five temperature sensors in lightwell (one per level)

observed to behave as the intended cross-ventilation of floors, from centre to edge, confirming the CFD model predictions.

Library first-floor front: measured performance mid-commissioning

The trace shows a period in which internal temperatures rose to 27°C or greater as peak external temperatures exceeded 38°C, unprecedented to that date (Figure 10). Controls were malfunctioning fundamentally through this very hot period, as Table 1 indicates. On 3 July very restricted window movement was identified, and on 7 July ten actuators were observed to have failed, revealing that the first floor had been sealed shut through late May/June. Night venting was recorded by the BMS as being in operation, but temperatures varied so little over 24 hours that it was very probable that this space was still, in effect, sealed shut at supply or exhaust or both, and not receiving the benefit of (albeit 50% reduced) downdraught cooling in the lightwell (Table 1). In effect, the graph depicts the performance of a heavyweight building without night ventilation or mechanical cooling assistance during an exceptionally hot summer period, behaving much as the DSY date suggested it would (CIBSE, 2002) by the CFD model run without PDC in peak conditions.

Internal temperatures rose to the end of the week, but recovered as external peak temperatures dropped to 25–26°C. During this period the controls were generally malfunctioning (Table 1). Windows were frozen open or closed. Night purging was not enabled, although night-time temperatures fell to 15°C. Downdraught cooling was engaged, although a number of windows in the lightwell lantern wheel were frozen open and closed. Some benefit was derived from the part-disabled PDC charging of the lightwell with cooler air, but results were disappointing compared with the CFD modelling of outside air temperature (OAT) at 30°C. Whole building testing of the fully functioning PDC mode a year later (Figure 12) showed a faster and very much more robust response to rising external temperatures.

Library first/second floors, 8–21 November 2006

Data for November 2006 (Figure 11) indicated that conditions were in line with the design intent, after a commissioning exercise in the early stages after which airflow rates were temporarily increased to counter occupant complaints of 'heavy' air and high temperatures. Increasing the supply failed to improve perceived conditions and, counter-intuitively, a reduced flow restored design temperatures by re-establishing the stable stratification of the intended displacement system. Inlet and exhaust air paths were balanced and equalized. The mid-period shown above indicates improving conditions. The commissioning history

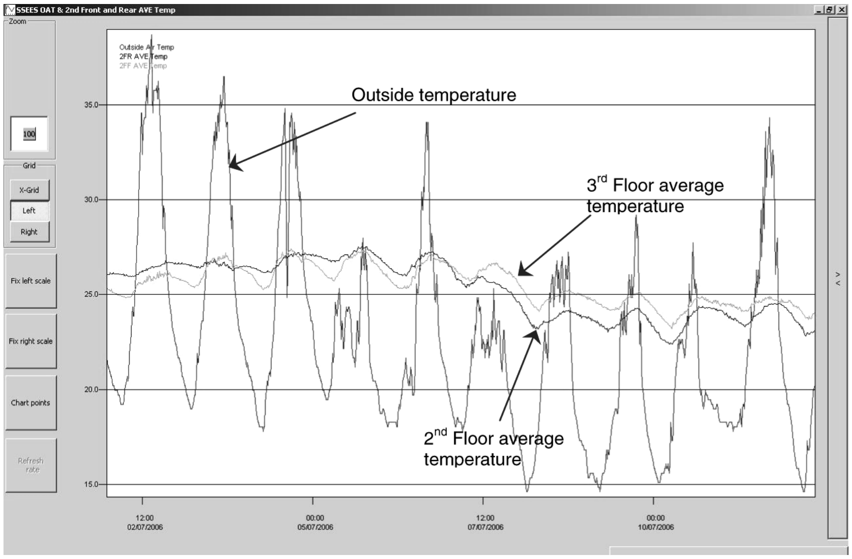


Figure 10 First floor front: measured performance, 2–10 July 2006

(Table 1) shows the controls were broadly functioning as intended in this period.

Smoke tests were carried out on 10 August 2007 to examine the efficiency of the PDC mode. Tests were undertaken on the lightwell wheel above the cooling coils, and at the top of the lightwell below the cooling coils.

Testing of the PDC mode with controls functioning on 9–10 August 2007

Cooling had been operational in the building for a four-hour period in the afternoon of 9 August and from 08.00 hours on 10 August (Figure 12). The building was cleared of occupants in the early afternoon and the smoke detection system disabled in agreement with the fire authority. Most of the building felt cool, pleasant and fresh to the researchers, despite a warm OAT in excess of 28°C and bright sunshine hitting the vertical windows at the upper face of the lightwell lantern. A graph showing typical inside and outside air temperatures at the time of the tests is shown in Figure 12 (Short & Associates *et al.*, 2007b).

The spike in the record for the Director's Office reveals that heating was triggered briefly by the controls. It was noted that a number of the windows at the lower end of the lightwell lantern wheel had failed closed, inhibiting natural cross-ventilation of the lantern to remove heat generated by solar gain. One lightwell lantern external window was observed to have failed open, despite the BMS reporting a 'closed' signal. At least two window mechanisms around the lightwell

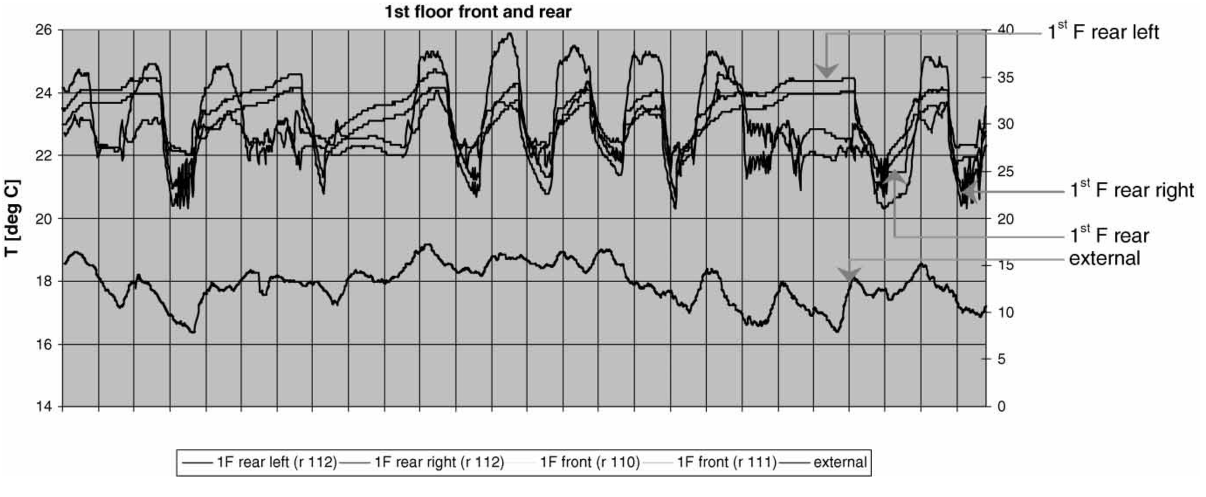


Figure 11 Library, first and second floors: recorded temperatures, 8–21 November 2006, mid-commissioning

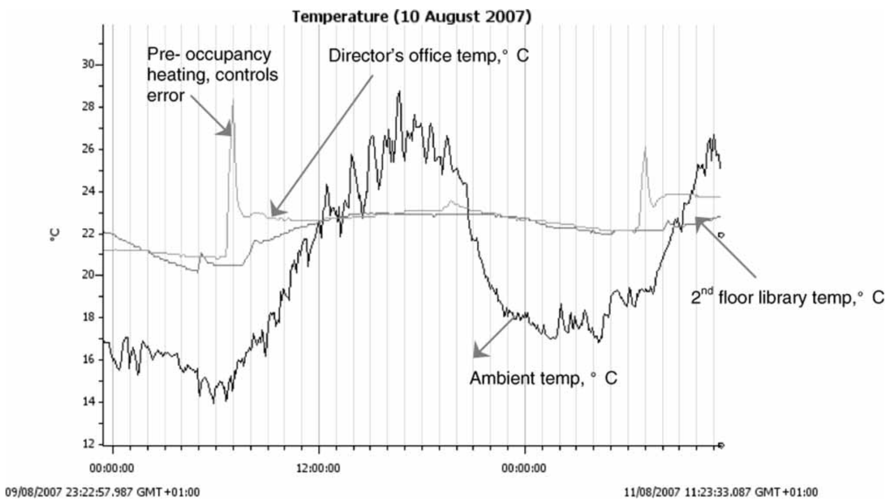


Figure 12 Temperatures in the second-floor library and in the fourth-floor director's office both maintained below a maximum of 23.5°C by passive downdraught cooling (PDC) as afternoon ambient external temperatures exceeded 28°C

wheel were malfunctioning. In one case the chain had sheared, in another the actuator motor was inoperable.

All windows connecting the lightwell to each floor were programmed to open from the commencement of the test. However, windows onto the first floor rear were closed throughout and upper ground floor windows were not open uniformly, suggesting a partial controls failure.

In addition, the lights were observed to be on within the second floor rear, the upper ground floor and parts of the lower ground floor, an unconnected controls failure. The lights remained on for extended periods and, on the first floor, appeared to switch on, part way through the evening, despite the floor being unoccupied throughout, contributing an unanticipated additional internal heat load.

Although the PDC coils were cold to touch, it was thought that a lower operating temperature would be beneficial, mindful of the risk of condensation. Chilled water operating conditions were set to 14.5°C to achieve a maximum temperature difference of 3.0°C. The design condition was for a flow temperature of 13.5°C with a temperature difference of 4.5°C. The flow temperature has been reduced to this operating condition since the test.

One of the isolation valves to one of the coils was found to be partially closed: this was rectified in time to conduct the test.

Smoke test 1: lightwell lantern wheel

Smoke injected into the lightwell lantern wheel at the head of the lightwell showed air movement from the lower to the upper end of wheel. On reaching the top there was some recirculation, much as predicted in the CFD analysis: smoke was observed flowing back along the top layer of ETFE, some was observed leaving through the windows at the top of the ring, thought to be due to wind, but was also observed moving down through the coils. Large quantities of smoke could clearly be seen from the fifth-floor walkway flowing downwards from the coils.

Vigorous cross-venting of the lightwell lantern wheel, which it was feared might starve the cooling batteries, was not observed. Use of the smoke pencil above the coils showed a clear but intermittent flow of air downwards and across the coils (Figures 13 and 14). The downward air movement was periodically disrupted by gusts of wind.

Figure 13 Lightwell wheel: smoke tracer following airflow down through open dampers and cooling coils

Figure 14 Beneath the cooling coils

Figure 15 Lightwell at the fifth floor: smoke injected at a high level descends with cooled air

The ambient temperature measured on the roof was 25.8°C. The temperature at the window opening at the top of the lantern wheel was 26.6°C, increasing to 28.4°C as the probe was moved further inwards.

Smoke was injected at the top of the lightwell beneath the coils from the walkway accessible from the fifth-floor office (Figure 15) and was clearly observed descending from beneath the coils, over the walkway and downwards into the lightwell.

This smoke was observed to descend quickly to the glass lens at the base of the lightwell. The smoke was estimated to take about 30 seconds to fall from the cooling coils to the base of the lightwell. This equates to a ventilation flow rate of approximately 18 m^3/s, which significantly exceeded the design flow rate of 12.76 m^3/s.

Some smoke was seen to re-circulate at the top of the lightwell flowing along the ETFE layer. This was particularly noticeable in regions away from the cooling coils, for example, beneath the inner ETFE layer and beneath the lower end of the doughnut wheel (where there are no cooling coils and where all dampers were closed). Such behaviour was also observed in the computer simulations and was not unexpected (Figures 6 and 7). In one case, smoke moved upwards. This seemed to coincide with an increase in wind speed. It may be possible that having windows open on only one side of the lightwell wheel (as a result of controls and mechanical failures) caused a net suction effect rather than neutralizing the wind effect. This effect requires further study.

The smoke tests demonstrated that the cooling coils produced effective PDC in the lightwell. Most of the spaces within the building felt cool as a result. This is supported by measured data (Figures 16, 17, 18 and 19).

It was particularly encouraging to observe the down-draught cooling despite the solar gain present at the top of the lightwell in early August (Figures 17–20). It is clear that the cooling action is slow and cooling mode should be engaged at the early commencement of the day to yield the optimal advantage. It may be beneficial to run the cooling mode through warm nights to assist night purging. The team had continuously monitored night venting of the building for some days before the test, establishing that the BMS was reporting correctly, and the functioning of the chiller, which was repaired specifically for the test. All other parts of the building appeared to be working well, but flows through the third- and fourth-floor front offices were less robust than the design modelling suggested. Subsequently, fans have been installed in the four stacks exhausting these areas.

Measured slab temperatures

The environmental design strategy is heavily dependent on exploiting the thermal mass of the concrete structure to stabilize internal temperatures, principally the floor slabs. The dynamic thermal modelling envisaged stable core slab temperatures of 21°C, the soffit being cooled below this by controlled night ventilation.

A sensor is embedded in each slab. The failure of the controls and the consequent non-implementation of the intended night cooling strategy allowed core structural temperatures to rise. Snapshots on 11 August 2006 (Figure 20) indicated temperatures between 21.7°C within the fourth-floor slab and 25°C within the third-floor slab. The commissioning history (Table 1) reveals that the night vent mode was either non-functional or heavily compromised during this period, delivering a significant 1–4°C disbenefit. The

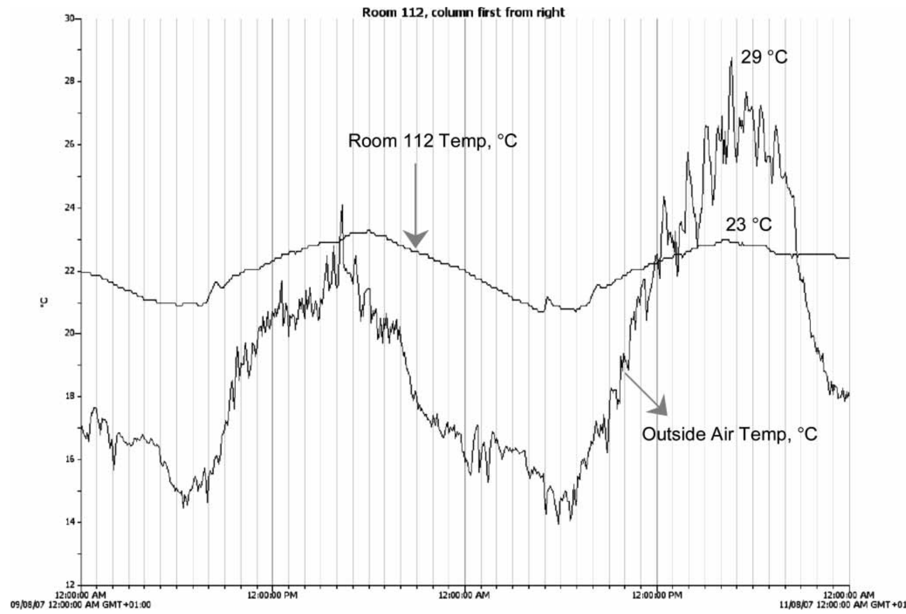


Figure 16 First-floor library (12:00 am 9 August – 12:00 am 11 August): stabilization of room air temperature on 10 August while outside air temperature (OAT) rose to over 28°C

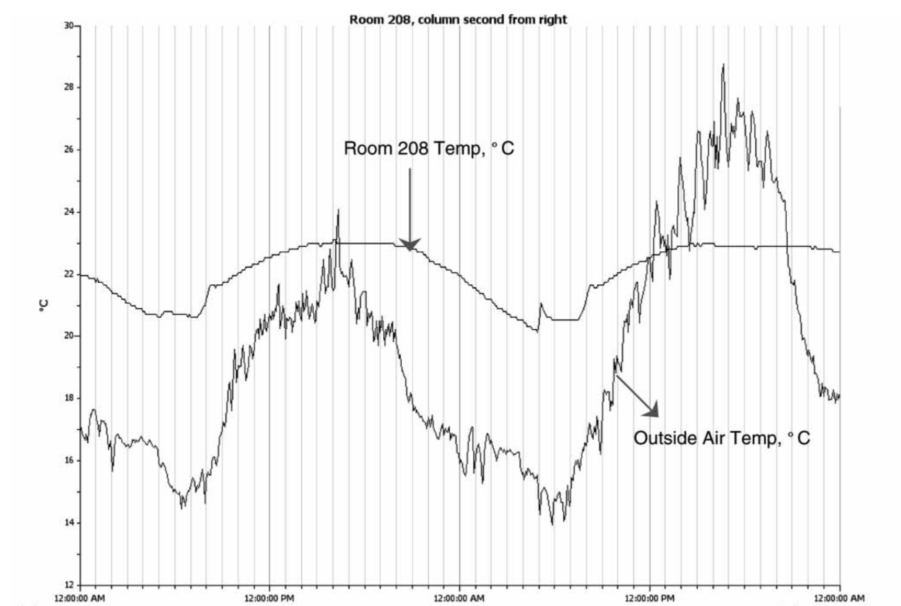


Figure 17 Second-floor library: first period of operation of cooling on 9 August between 15.30 and 20.00 hours; the internal temperature on 10 August was stabilized during a warm afternoon and evening

average air/slab temperature control parameter was weighted upwards, calling for more cooling.

Between 25 July and 1 August 2006, the first-floor slab temperatures were recorded as climbing to 27°C as external temperatures recorded by the building's sensor climbed to nearly 40°C, but, as ambient temperatures dropped, the slab temperature fell to 23–24°C. The data simply depict the thermal robustness of the shell without night venting.

There has been a long slow decline in the temperatures of the floor slabs from the commencement of regular night venting (from the time when daytime ambient

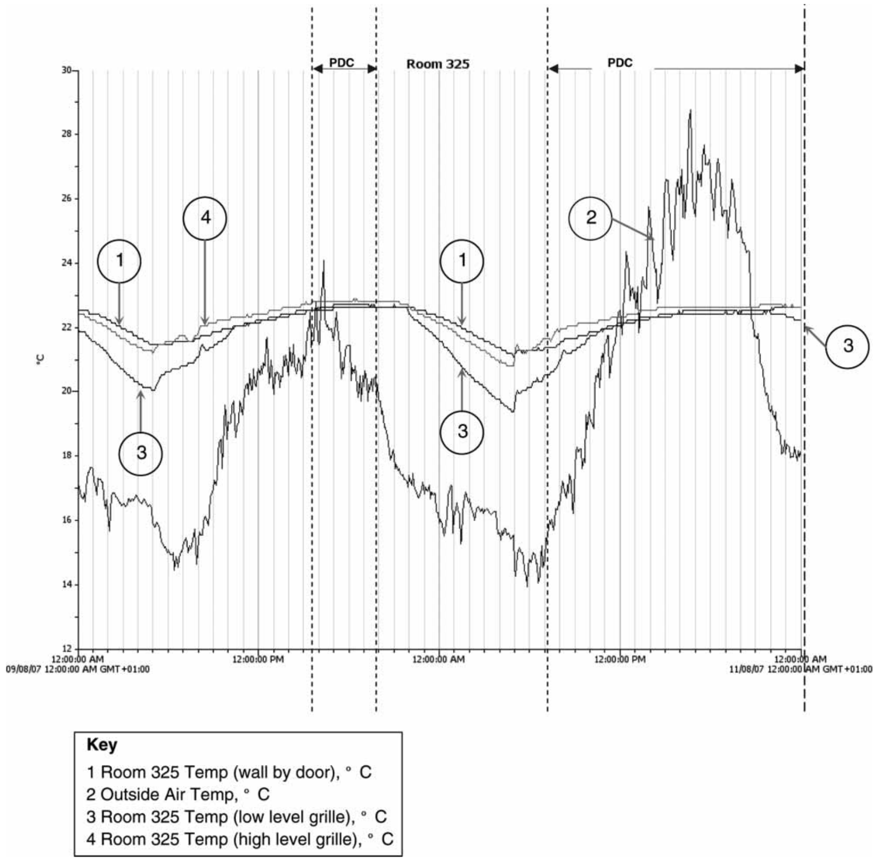


Figure 18 Rear academic room on the third floor: temperature rise arrested by passive downdraught cooling (PDC) as outside air temperature (OAT) peaked above 28°C

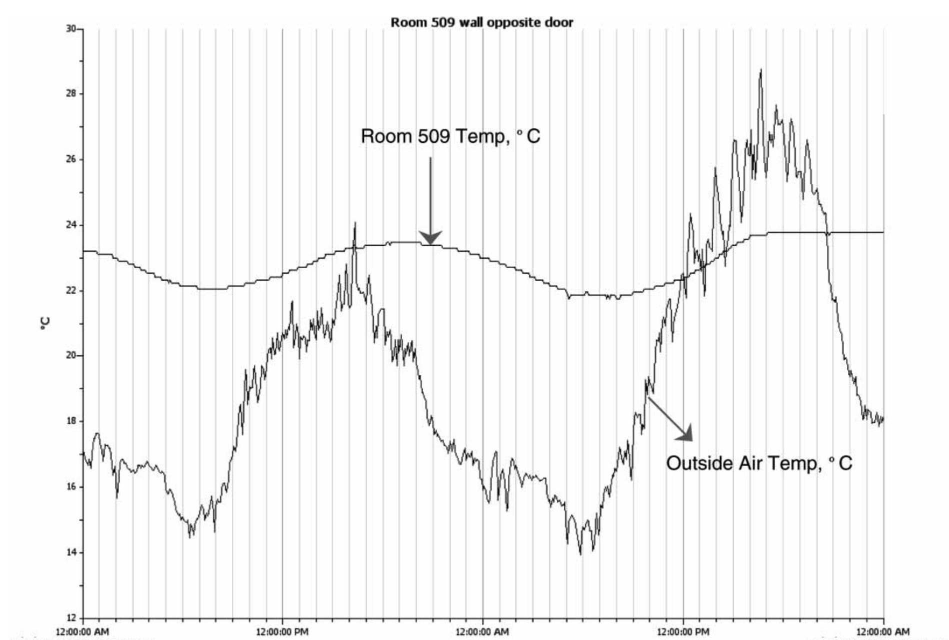


Figure 19 Rear academic room on the fifth floor. Similarly to rooms in lower floors, the internal temperature was 'capped' by passive downdraught cooling (PDC)

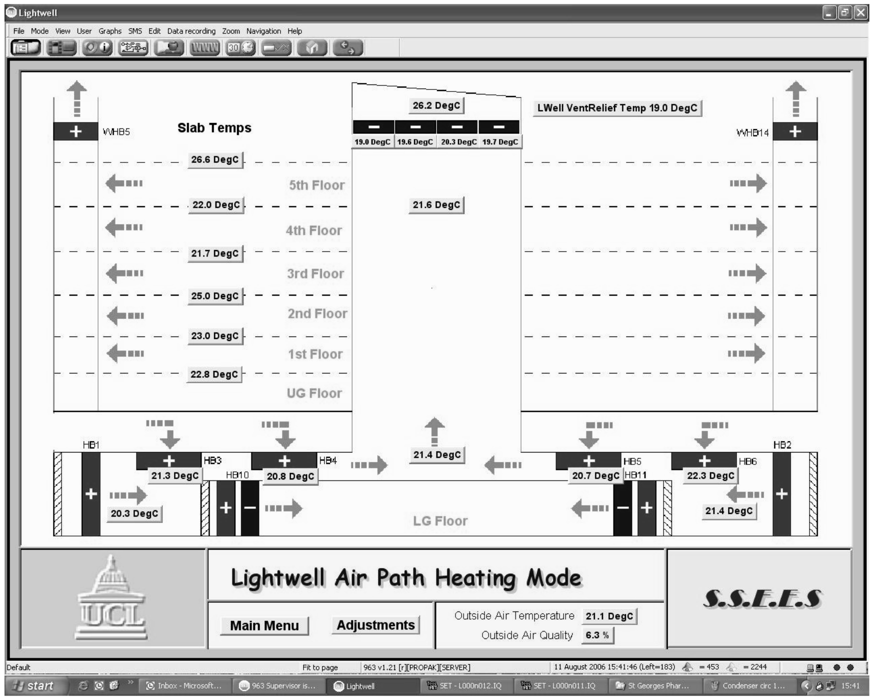


Figure 20 Recorded structural slab temperatures on 11 August 2006 indicate a range of temperatures between 21.7°C within the fourth-floor slab and 25°C within the third-floor slab

temperatures were sufficiently high such that only limited space heating was engaged).

Findings from the 20-month monitoring exercise

The design team and the controls subcontractor concluded that the following controls modifications would improve performance. These have been implemented incrementally:

- initiate night purge earlier, possibly even during occupation
- purge the head of the lightwell on commencement of night purging
- switch the control of the night purge away from lightwell temperatures to room temperatures, whilst maintaining frost protection via the heater batteries
- balance the area of openings from the air inlet to the building to the final controlled openings at the exhaust stacks
- initiate mechanical cooling early, almost on a predictive or forecasted high ambient temperature condition
- ensure that summer heating (operation of radiators) is inhibited

Conclusions

The UCL School of Slavonic and East European Studies (SSEES) building design received more modelling and analysis than is customary: the control modes were well rehearsed by the design team, reinforced by two academic research teams. The procurement was for full design services and full information under the aegis of the New Engineering Contract (NEC) (2007). There was no discontinuity in the delivery and detailed resolution of the design. It could be argued that these were optimal conditions for the delivery of an innovative design. However, the controls subcontractor was domestic to the main contractor so that communication with the designers was, at least theoretically, made indirectly through the main contractor, which is unviable in practice given the intricacy and rapidity of the responses required. The contractual allowance for input and attendance for the commissioning exercise from the contractor was thought to be generous, even a potential source of programme recovery. However, the actual commitment required was of a different order of magnitude sufficient to endanger viability (Table 1). For the mechanical and electrical subcontractor the physical demonstration that each window/damper actuator would function when powered up, which was the contractual requirement, was the beginning of the commissioning exercise, not the conclusion.

The experience reveals that control modes have to be checked in the appropriate season, in modelled conditions, determining at least a minimum viable commissioning period. Three months is clearly inadequate. Full building smoke testing was very illuminating in the exercise reported herein, but has implications for the building's continuing occupancy. Construction industry suppliers need to manufacture actuators that are robust and generally responsive to controls software with robust linkages to harmonize with all the likely combinations of software interfaces. The coupling of chains of fabricators and subcontractors compounds the problem especially if selected randomly by lowest tender. Pre-design assumptions become invalid as equipment is substituted. The commitment of the expanded design team propelled the commissioning exercise reported here to an eventual outcome close to the designed performance. This is not surprising given the commitment to the project, but the role of design consultants in the commissioning stage urgently needs to be recognized, quantified, and formalized within the various professions' appointment conditions.

Leaman and Bordass (2004) discuss building technology as being inextricably linked with manageability. They write of the 'learning curve' required by industry to master advanced naturally ventilated buildings. They comment on the relatively high incidence of failure in conventional control systems. These authors believe that these endemic but little reported issues should be made manifest and addressed directly and openly by the industry and its clients, much as other industries have in recent years engaged in comprehensive reforms, not least information technology, embodied in such standards as ISO 12207 (International Organization for Standardization (ISO), International Electrotechnical Commission (IEC), 1995), on software life cycle processes, and ISO 15504 (ISO/IEC, 1997), on software process improvement. The reform of the automotive industry, as an exemplar for construction, is referred to by Egan (1998). The present authors understand that the construction industry is different in character, a point made strongly by Way and Bordass (2005). A 'zero defects' approach in serial production may or may not be different to that applied to the making of one-off prototypes, but it could be argued that the building components, controls, and commissioning practices discussed herein are, in effect, serial in nature across this major industry, despite local variations in their precise configuration.

Set into an industry-wide context, Way and Bordass (2005) observe: 'tighter environmental regulation adds pressure for greater predictability of the end operation'. Four years earlier, Bordass *et al.* (2001b) urged the construction industry to establish 'no surprises industrial standards' over such construction tasks as minimizing air leakage.

The experiences of the SSEES commissioning and monitoring team support the Probe study findings (Lorch, 2001). Bordass *et al.* (2001a) point to endemic failures, what they term 'chronic' faults: gaps in the fabric allowing excessive infiltration of air-swamping control regimes, the recurring failures of motorized dampers and windows, and the unreliability of lighting control systems.

Excessive infiltration in reception areas due to the unexpected action and frequency of remotely actuated external doors is also logged. In their fourth paper in this series, Leaman and Bordass (2001) observe that the persistence of chronic problems may have a nonlinear outcome, the bad effects being out of proportion to the apparent scale of the defect. The consequences of the failure of 3–4% of actuated windows in the SSEES building demonstrates this. This experience is not confined to the UK. This team has recently reported on parallel experiences in the USA (Lomas *et al.*, 2008). Advanced naturally ventilated buildings need to be delivered to at least the more recent higher UK Regulation standards. They require more rather than less design and construction management input and designer involvement, and the products incorporated to enable their various control regimes need to be of a consistently higher quality.

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