Exploiting a hybrid environmental design strategy in a US continental climate

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Resistance to the widespread adoption of naturally ventilated buildings in North America derives from the exigencies of the ‘continental climate’ type: humid hot summers and cold, desiccating winters. The paper describes a proposed new hybrid strategy for conditioning the environment in the new library and faculty building for Judson College, Elgin, Illinois, US. The strategy exploits the significant mid-season opportunities for implementing natural buoyancy-driven displacement ventilation and passive cooling in the continental climate of the Chicago hinterland. Both the natural and mechanical modes of operation are described and put in the context of current thermal comfort criteria for wholly mechanical and wholly natural ventilation. Predictions are given of the annual duration of the various operating modes and the building’s likely overall energy performance using a standard reference year. Construction and energy costs are compared with those for a US Standard Building. An account is given of the various barriers encountered in introducing the innovations.

Keywords: alternative technology, design process, energy, environmental performance, ‘green’ building, innovation, natural ventilation, US

Introduction

Natural ventilation (NV), to maintain indoor air temperatures and thermal comfort, has the potential to reduce energy consumption (and energy costs) significantly compared with the use of mechanical ventilation and cooling (Bordass et al., 2001). Such buildings can be built at no additional first cost, but have reduced maintenance and repair cost. Improved indoor air quality, lower background noise levels and the potential for occupants to control their local environment...
are other cited advantages. These benefits accrue to the building owner and occupants. Concerns about global warming and the emission of greenhouse gases, together with renewed awareness of dwindling energy reserves and problems of energy security and supply, have also stimulated renewed interest in NV for non-domestic buildings, particularly in Europe.

Encouragingly, there is evidence of a growing interest in such buildings in the US, for example in the recent publications of Axley et al. (2002) and Emmerich et al. (2003), and real-world examples have also been described (e.g. Carrilho da Garaçá et al., 2004; Haves et al., 2004). The emergence, and growing profile, of the Leadership in Energy and Environmental Design (LEED) certification system (Green Building Council, 2001) supports the benefits of, and should stimulate interest in, NV buildings: they can reduce the energy cost compared with a 'pre-requisite standard', lead to improved ventilation effectiveness (e.g. through low-velocity displacement ventilation), provide good indoor air quality (e.g. through carbon dioxide (CO2) sensing), and enable occupant control of windows, space temperature and airflows.

Simple NV buildings tend to have an attenuated shallow plan form with perimeter openings, usually windows, providing the route for entry of ambient air. Such plan forms may not be possible on constrained sites or be optimal for the activities within the building. Deeper plan buildings become possible by the introduction of architectural devices (e.g. atria, lightwells and stacks), which, by using the natural buoyancy of warm air inside the building compared with that outside, can draw fresh air across deeper floor plates. These have been termed ‘advanced naturally ventilated’ (ANV) buildings (e.g. Bordass et al., 2001).

When the climate or local environmental conditions lead to elevated summertime temperatures, or when internal heat gains are particularly high, neither simple NV nor ANV buildings may render the indoor conditions comfortable and a hybrid strategy, blending NV or ANV with a mechanical system, which might incorporate summertime cooling, can be adopted. Such buildings pave the way for adopting the beneficial aspects of NV – even when the climate is severely cold or particularly hot during parts of the year. To be feasible, the mechanical and natural systems should be well integrated in order to avoid an accumulation of costly and space-consuming architectural features (for NV or ANV) as well as mechanical equipment (e.g. ducts, variable air volume (VAV) boxes, etc.), and to avoid duplication of dampers and controls.

The present authors have been responsible for the concept, design and realization of a number of ANV buildings and more recently a hybrid building in the UK (e.g. Cook and Short, 2005). Precedents for the building described in this paper are: first, the (ANV) Frederick Lanchester Library, for Coventry University, completed in 2000 (Cook et al., 1999a, b; Field, 2000; Pidwell, 2001); and, second, the School of Slavonic and East European Studies (SSEES), for University College London, completed in late 2005 (Short et al., 2004; Harbison, 2006), which is a hybrid design incorporating passive downdraught cooling.

Recognizing the benefits of environmentally conscious design, and wishing to demonstrate the commitment to environmental custodianship, the patrons of Judson College in Elgin, Illinois, US, launched a design competition in early 2001 for their new library and Division of Art, Design and Architecture (DADA) building. The competition brief asked:

in what ways may both digital and environmentally conscious technologies, issues of sustainability, and effective stewardship of resources become design positions in architecture in general and in these facilities in particular?

The competition was won by a team led by Short & Associates, supported by the Institute of Energy and Sustainable Development (IESD) at De Montfort University, Leicester, UK. The capital cost was subsidised by a US$7.5 million grant from the 2004 Federal Energy and Water Appropriations Bill, two grants totalling US$200 000 from the Illinois Clean Energy Community Foundation, and a Kresge Foundation matching grant for US$600 000 with an additional US$150 000 predicated upon the achievement of an LEED Silver rating or above.

This paper describes the building that resulted from the efforts of the design team (Table 1). It describes the way in which the climate influenced the design strategy and describes the construction and ventilation strategy for the building, outlining the various seasonal and daily modes of operation. The predicted energy performance of the building is presented along with the construction costs. These are compared with values for a more conventional, mechanically conditioned, building. A companion paper (Lomas et al., 2006) describes the thermal and airflow analysis that underpinned the evolution of the design. The building is due for completion in late 2006; construction commenced in the spring of 2003.

Table 1 Design team

| Short & Associates Architect – Architect |
| Burnidge Cassell & Associates – Architect of Record |
| Slaine Campbell – Landscape Architect |
| Institute of Energy & Sustainable Development – Energy Consultant |
| KJWW – Mechanical, Electrical & Structural Engineer |
The site and the brief

Judson College is 64 km (40 miles) north-west of central Chicago, close to the junction of the I-30 and I-90 Interstate Highways; the traffic noise is clearly audible on the college campus. The site (Figure 1) is close to the College entrance and stretching away to the south is the central green area, flanked by the Chapel at one end and halls of residence on either side (one of which is visible in Figure 1). The land drops away to a small river on the west of the site, and beyond is mature natural woodland. The new building will create the fourth side of a green quadrangle, which will be a focal point for campus gatherings (Figure 2).

The 1200 student college required a library with an open-access circulatory book collection growing to 100,000 volumes, a reference collection of 12,000 volumes, work space for 150 readers and 15 staff, with 30 computer workstations aggregated into a defined computing area. The DADA, which recruits 80 students per year, required accommodation for 20 staff (primarily in individual cellular offices) plus lecture rooms, teaching studios and peripheral specialist areas (i.e. model-making shop and photographic studio).

This brief led to two rather different sets of requirements. The library had to be spatially legible, open plan with limited-access points. It had to have a sealed facade (for security reasons and to limit the ingress of external noise) and an upper limit on humidity levels (to protect the book stocks). In contrast, the faculty building would be rather more vibrant, with numerous cellular spaces occupied, or controlled, by college staff keen to exercise personal control of their office environment and to maintain a close link between themselves and the surrounding green campus. Therefore, provision of heating and cooling controls, moveable shading devices, operable windows, and good acoustic separation were important. These differing environmental requirements manifested themselves explicitly in the form of the final building.

The climate

The National Renewable Energy Laboratory (NREL) database (Marion and Urban, 1995) contains Class A typical meteorological year (TMY2) weather data for two sites close to Elgin: Rockford Airport; and Chicago, for which the measurement site is Midway Airport. Elgin is roughly 64 km (40
miles) from each site and at a similar vertical elevation, approximately 200 m.

The two sets of data were compared with a view to selecting the most appropriate one. Chicago, as might be expected (in the urban fringe and close to Lake Michigan), tended to be a little warmer than Rockford, 28 and 67 hours, respectively, below 20°C; and 167 and 90 hours, respectively, above 30°C. There were no discernible differences in the diurnal temperature swings or the solar radiation data. In all the modelling work for the project the Chicago TMY2 data were used (Lomas et al., 2006).

Self-evidently, the extremely cold winters preclude the use of simple NV (e.g. by operable windows) and there is a need, in the interests of energy efficiency and thermal comfort, to employ heat recovery and possibly humidity control in the winter. The high summer temperatures are also likely to prevent the achievement of acceptably low internal temperatures using NV alone. These observations suggest that, in addition to NV, some form of mechanical cooling and heating is likely to be needed.

Looking in more detail at the hourly ambient temperatures and moisture content (Figures 3 and 4), the year seems to be divided into three periods. In winter (from the beginning of November to the end of March), peak daily ambient temperatures almost never exceed 15°C and the mean monthly daytime temperatures are below 4°C. During the summer period (from mid-May to mid-September), the peak daily temperatures invariably exceed 20°C.

The weather is susceptible to periodic swings at all times of year. In January, for example, daytime temperatures are between −22 and −14°C early in the month, then 3–10°C mid-month, and back to very cold conditions again at the month’s end. During the summer there is similar evidence of oscillating weather patterns, e.g. in July, the hottest month, there are two-to-five-day spells with warm, humid conditions, peaks of 30–35°C and a moisture content (MC) of 8–11 g/kg. The warm, humid spells coincide with south-westerly winds from the Gulf of Mexico, and the cooler dryer air with air streams originating from the north.

The diurnal temperature range is also variable, with swings of 15°K or more being reasonably common in April, May and September, yet on some days the swing is below 5°K. This suggests that even in these cooler months, when NV could be a satisfactory ventilation technique, night ventilation cooling might be an unreliable resource.

**Comfort criteria**

In the US, American National Standards Institute (ANSI)/American Society of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE) Standard 55-2004 places an upper limit on the allowable

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**Figure 3** Ambient temperature and moisture content for Chicago TMY2, October–March
operative temperature of about 28°C – although this decreases to about 27°C as the moisture content increases to the limiting value of 12 g/kg of dry air (ASHRAE, 2004a). An alternative approach, based on the adaptive model of human thermal comfort, is based on empirical data (De Dear and Brager, 1998) and applies to unconditioned buildings with operable windows. This method, applicable as it is to NV buildings, defines the acceptable range of indoor temperatures on the basis of the mean ambient temperature recorded each month; but it places no upper limit on the moisture content of the indoor air. In principle, therefore, this approach could extend the period of NV, reducing the time for which mechanical plant must operate.

The upper (and lower) limits of temperature for the 90 and 80% occupant satisfaction rates are plotted in Figure 5, along with the average temperature, for each month in the Chicago typical meteorological year, and the 95th percentile range of the hourly temperatures.

In the hottest month (July), which has a mean monthly temperature of 23.8°C, the alternative method suggests upper temperatures of 27.3 and 28.2°C for the 90 and 80% occupant acceptability rates, respectively. Two points are worth making. First, the acceptable temperatures are no higher than those permitted by the Standard 55-2004 comfort envelope; and second, that, in any case, there are around 300 hours per year for which the ambient temperature exceeds 28.2°C – the 80% acceptability rate temperature limit in July.

It is interesting to compare the US comfort standard with the other comfort criteria for NV design. In Europe, commonly used overheating criteria effectively limit the number of hours, recorded over a defined period, for which the internal temperature in an NV building may exceed some threshold value (Eppel and Lomas, 1992; Cohen et al., 1993). The UK Chartered Institute of Building Services Engineers (CIBSE) Guide J (Chartered Institute of Building Services Engineers (CIBSE), 2002) suggests a criterion of no more than 5% of occupied hours over a 25°C dry resultant temperature (DRT) to be applied in conjunction with a near extreme weather year (called a design summer year). In contrast, a more recent technical memorandum (Chartered Institute of Building Services Engineers (CIBSE), 2005) and Design Guide A (CIBSE, 2006) focuses on a limit of no more than 1% of occupied hours over a 28°C dry resultant temperature. Three groups of researchers (Eppel and Lomas, 1992; Cohen et al., 1993; Wright et al., 1999) have noted independently that the 5%/25°C criterion is harder to satisfy in the UK climate than the 1%/28°C criterion.

During the working day (08.00–18.00 hours) the Chicago TMY2 has more than 279 hours (7.6%) over 28°C and 577 hours (15.8%) over 25°C. In July, the hottest month, the ambient temperature exceeds 25°C for two-thirds of the working day and 28°C for over one-third of the working day (Figure 6). In fact, unless the internal dry resultant temperature could be maintained, some 5 K below
the ambient temperature, the 1%/28°C criterion could not be met. It is unlikely that a passive, NV college building could achieve this.

As a result of these analyses, the design of the building proceeded on the basis of meeting the indoor temperature targets of the Standard 55-2004 method, even in spaces with operable windows.

**Design strategy**

The design of the Judson College building was driven by the desire to meet the functional requirements for the library and faculty buildings, whilst at the same time making maximum use of the NV for both air quality and temperature control. This led to a design that permits controlled ventilation during both the day and at night in order to cool exposed thermal mass, which implies that ventilation is controlled by a central building management system (BMS), even if occupants have operable windows. Adequate solar shading and yet good daylighting associated with automatically dimming luminaires are important features of low-energy buildings.

Previous buildings, by the authors, have utilized stack-assisted, buoyancy-driven, natural-displacement ventilation in which the cooler ambient air is supplied at a low level with stale, warmer air exhausted at a high level. The system provides good air quality in the breathing zone, makes the best use of natural cooling, and enables ambient air to flow across relatively wide floor plates. In a hybrid building mechanical systems can also operate in displacement ventilation mode and benefit from increased floor-to-ceiling heights (e.g. Skistad, 2002).

The driving pressures in a buoyancy-driven NV system are much lower than those that are common in, and achievable by, mechanical systems. Therefore, to deliver a given volume of air, the cross-sectional area of the air supply and exhaust routes is much greater, and has a lower resistance, than in a typical mechanical air distribution system. By using the air paths of the NV system to distribute mechanically conditioned air, fan energy consumption can be reduced.

To reduce energy costs further, there was a desire to avoid the parasitic energy consumption associated with pumps, valves, small fans and other controllers necessary in distributed local cooling systems (fan coils, chill beams, etc.). Therefore, the aim was to develop a strategy in which virtually all the spaces1 in one part of the building (library or DADA wing) were operating either in passive (NV) mode or in mechanical mode. A central-conditioning unit would provide the heating or cooling with local temperature control based on adjusting the volume of air supplied – the control dampers being, in any case, an integral part of the NV system.

The hybrid ventilation strategy developed was strongly influenced by the experience gained from the Coventry...
University Library and SSEES buildings and refined based on the results of thermal and computational fluid dynamics (CFD) modelling. Very early in the design process, a simple dynamic thermal model was built using ESP-r (Energy Systems Research Unit (ESRU), 1998) to assess whether passive day- and night-time ventilation could offer energy-saving benefits. The present study showed that there were significant periods of the year, in the spring and the autumn, when passive daytime ventilation could produce comfortable conditions. The analysis also demonstrated that night-time passive ventilation associated with exposed thermal mass could extend the passive operating time and, in mid-summer, reduce the load on the air-conditioning system. More detailed simulations, which utilized a thermal and airflow model in order to predict reliably the buoyancy-driven ventilation rates, confirmed the value of the NV strategy, defined the times for which the NV system could operate, and guided the specification of the control strategy.

A simple CFD model was built using CFX5 software (ANSYS, 2005) to confirm that a displacement ventilation approach, in which air was delivered in the centre of a relatively deep-plan building, could deliver sufficient fresh air without causing drafts or local hot-spots. Ventilation cooling of the perimeter, which was subject to solar heat gains, was of particular concern and precipitated special attention to solar shading. A substantial CFD model covering one-half of the entire library building was built once the design was well advanced. The aim was to confirm that sufficient cooling air could be delivered to all open and cellular spaces so that, despite their differing internal heat gains, they would remain equally comfortable. The model incorporated the airflow resistances associated with the dampers, louvers and acoustic attenuators in the airflow paths.

Details of these modelling activities are discussed by Lomas et al. (2006).

The library
The library uses, primarily, a centre-in, edge-out (C-E) NV strategy (Lomas and Cook, 2005). With such a strategy, the fresh air is delivered to a centrally located air supply ‘shaft’ via a low-level plenum. The shaft, or multiple shafts in large buildings, penetrates through the building, delivering fresh air to each floor. Stacks, arranged around the perimeter, run the whole height of the building and exhaust the air to ambient, without any mechanical assistance. The strategy enables the building’s perimeter to be sealed, but the supplied air can be conditioned, most obviously by pre-warming it in winter, if necessary. In the Judson College library building, a central lightwell admits daylight into the core of the 32.9 × 32.9 m² floors and provides the primary route by which ambient air is supplied to each floor through low-level, automatically controlled, inlet dampers (Figure 7).
1. Low-level air intake sized to compensate for the loss of free area through insect mesh; 2. Air inlet plenum is insulated from building interior; 3. Air inlet with an open hospital radiator behind to provide reheat; 4. Air supply route to level one; 5. Lightwell and air supply plenum; 6. Acoustic attenuation in the air supply path of level four; 7. Ventilated buffer space between the air supply plenum and the exterior; 8. Extract air stacks from levels one, two, and three incorporated within the facade construction; 9. Insulated plenum within the depth of the roof construction; 10. Exhaust termination connected directly to the roof plenum, incorporating a rooflight. Outlet dampers behind belfry louvers; 11. Exhaust termination dedicated to level four incorporating a rooflight; 12. Air-handling plant; 13. Return air duct connecting the exhaust air plenum to the air-handling plant; 14. Mechanical supply to the air inlet plenum; 15. Air intake to cellular office with an acoustic attenuator box, damper and reheat; 16. High-level air exhaust via an attenuator box to minimize cross-talk between offices.
prevent conditioned air escaping when the building operates in mechanical mode (see below). Raked heating coils pre-warm the air before it passes deeper into the building. The plenum is well insulated to the line of the heating coils and more lightly insulated thereafter. Insulation is necessary because, in winter, the incoming air, even after pre-warming, is likely to be cooler than the temperatures of the spaces above and below. On summer days, the warm incoming air should not warm the night-cooled concrete floor of the space above or the ceiling of the floor below.

Since the air in the lightwell may be considerably warmer than ambient in winter, and cooler than ambient in summer, care over its design is essential. A glass lens spanning above the air inlets of level four creates an enclosed zone up to the double glazed pyramidal top. This upper ‘greenhouse’ has moveable shading curtains and is ventilated to remove summertime solar gains. In winter, the space is sealed, providing protection to the warm conditioned supply air below the horizontal lens (Figure 8). The lens also prevents a plug of static air accumulating below the top of the lightwell and helps to avoid transfer of noise from the studio, through the lightwell, to the library below.

An edge-in, edge-out (E-E) ventilation strategy is used for the perimeter offices (Lomas and Cook, 2005), i.e. fresh air is supplied from the building perimeter and exhausted by perimeter stacks. This strategy is suitable for relatively shallow plan spaces and when acoustic separation and individual environmental (temperature) control is required. The approach also means that the occupants of the offices can open perimeter windows without disturbing the balance of the ventilation system in the building as a whole. The direct air supply, via the up-feeds from the plenum, avoids the need for ‘transfer ducts’ to enable air from the library to pass into the offices. In the Judson College building, acoustic attenuators are used in the stacks to prevent ‘cross-talk’ between the perimeter offices and the library above (Figure 8).

There are two levels of airflow control on both the inlet and the exhaust routes. The dampers at the plenum inlet provide coarse control, whilst the dampers at the inlet to each floor provide fine control in response to air temperature, CO₂ and humidity sensors. Air entering any space is reheated to the final desired temperature by hospital radiators located after the inlet dampers. The flow of air up each of the 20 exhaust stacks is controlled by dampers at the point of inlet, which operate in tandem with the air inlet dampers under the control of the BMS. In the perimeter offices sensors relay the state of the windows to the BMS, which can then close the air inlet and outlet dampers, and thus avoid simultaneous passive (open window) and active (from air-handling unit) air supply, which could be energy inefficient.

In winter and summer the air-handling units, located on level one, condition ambient air and discharge it into the plenum. The inlet dampers at the perimeter of the plenum are closed. As in NV mode, the volume flow of air to each level of the library and to the cellular spaces is controlled by inlet and outlet dampers. Two vertical ducts return air from the roof top plenum back to the air-handling plant on level one. The junction between the stacks and the roof plenum (at the eaves) was carefully designed to maintain air tightness. Although shown schematically within the building in Figure 8, the return air ducts actually lie at the perimeter, appearing, architecturally, to be stacks. As the building is operating in mechanical mode, the return air ducts need only be about one-tenth of the cross-sectional area of the perimeter exhaust stacks.

The detailed wall section (Figure 9) shows some of the key features and illustrates how the perimeter stacks create a 1.2 m-deep recess, which naturally provides

Figure 9  Detailed library wall section: part plan and part elevation: 1. Belfry louver air intake; 2. Pre-cast hollow core floor planks; 3. Pre-cast wall panels, 3.07 m overall; 4. Deep facade, light steel frame holds shafts (9), and deep window reveals (5); 5. Glazing set back into the pre-cast panel; defended against solar gain by deep-white finish reveals; 6. Pre-cast soffit to level four; 7. Void of the roof exhaust plenum; 8. Lightweight-insulated roof deck; 9. Shaft housing air-extract stacks; 10. Prefabricated connection to the plenum at the eaves to ensure air-tightness at a vulnerable change in direction
lateral solar shading to the perimeter windows. This recess is fully exploited on the south-east and south-west facing elevations where horizontal shading is created above the vision and clerestory windows. The gloss white finish to the sills and reveals redirects and diffuses direct sunlight into the building, thereby lifting the daylight levels.

**Division of Art, Design and Architecture (DADA) wing**

The DADA building, like the library, is built on four levels, but has a radically different plan form. The 35.4 m long × 9.7 m wide wing houses staff offices and classrooms and is connected to the library by a bow-tie formed by lecture theatres, studios and a gallery (Figure 2). A central atrium accommodates circulation routes and the link across to the library.

The relatively shallow plan depth of the offices, approximately 4.6 m, the need for independent control in each one, and the desire to maintain acoustic privacy means that an E-E NV strategy was appropriate (Figure 10). The ventilation shafts are housed in the 1.2 m-deep south-facing facade, which also enables the necessary solar shading of the cellular offices, and the classrooms, that occupy the east and west end of the DADA wing. Thermal mass is introduced via the exposed pre-cast concrete ceilings and perimeter walls.

Vertical shafts rise from air supply plena, located between levels one and two, and supply fresh air to the offices at a low level, whilst separate shafts exhaust the air at a high level. Each office, therefore, has its own dedicated air supply and exhaust air route. A natural symmetry develops around this arrangement. As the volume of air being carried up the supply shafts diminishes floor by floor, the volume of air that is being carried by the exhaust shafts increases. Thus, the two separate shafts can be neatly interleaved, giving a composite vertical supply/exhaust route, which has a uniform depth and width all the way up the building (Figure 11).

The exhaust stacks connect into a roof plenum from where the stale air is exhausted to ambient. As in the library, the top floor rooms are separately ventilated in order to avoid the exhaust air in the stacks flowing back into the level four.

In a similar fashion, supply shafts rise from the plena and deliver air at a low level to the classrooms on each floor of the bow-tie building. Stale air is exhausted just below the ceiling level through stacks set in the 1.2 m outer walls. These discharge into a rooftop plenum, which exhausts to ambient through wind protected outlets at the ridge.

In NV mode the whole system is driven by the natural buoyancy of the warm air in the building, but in summer and winter the air-handling units, in the basement, drive the flow using the same air supply and exhaust plena and shafts as the NV system. To enable air recirculation, two shafts run down the building from the roof top plena to each of the two plant rooms.

**Air supply across floors**

The fall of land across the site means that half of level one is below ground level (Figure 12). This level, therefore, houses plant rooms, the library archive, expansion space, and, in the DADA wing, a photography
studio. These spaces tend to be less environmentally demanding, although in the case of the library archive the temperature stability offered by the subterranean location is advantageous. The central area receives daylight from the lightwell, brightening an otherwise gloomy interior. The cellular spaces are fed individually with fresh air from the plenum above and the area is exhausted through stacks on the north-east side.

The plenum above the basement spans the entire building, enabling the lightwell to be fed from all four sides and providing ample scope for feeding air down to level one and up to the offices on the south-east facade of level two (Figure 13). Branches from the main plenum channel air to the upfeeds supplying the offices on the south-west facade. The air inlets to the plenum reduce the impact of pressure differentials, created across the building due to the wind; this enables the BMS to operate the perimeter dampers such that warmed air is not blown out of the building.

Whereas the library is supplied by fresh air via a plenum, which is wide but shallow, thereby preserving head height in level one below, the DADA wing is ventilated via air corridors that are tall but of limited width. The corridors are tucked behind the DADA wing in the tow-tie section. They contain the air inlet dampers, fly screens and raked pre-heating coils (Figure 13). These feed plena, which run above the central plant rooms on level one and below the floor of the atrium. The plena feed air to the supply shafts in the south-facing wall and the side wall of the...
rooms in the bow-tie. Downfeed shafts supply air to the level one spaces (Figure 13). The air corridors also provide the route by which fresh air can enter the two plant rooms. An air corridor of this type was first used by the authors in the SSEES building.

On level two of the library (Figure 14) air flows freely across the floor plate, past the book shelves, to the perimeter stacks on the north-east and north-west facades. The shafts on the north-east and north-west facade are merely for exhausting air. Therefore, they are somewhat smaller than those on three other facades (which also supply perimeter offices), enabling a more open aspect to the orientations from which there is little direct solar radiation. The classroom on the north corner has its own independent supply from the plenum below.

The thickened walls around the studios, galleries, and teaching spaces of the bow-tie enable air supply and exhaust shafts to be incorporated, just as they are in the south-facing facade of the DADA wing (Figure 14).

The level four studio (Figure 15) is completely open-plan, as is level three below it, which enables the free passage of air from the central lightwell across the floor plates to the perimeter stacks. In contrast, level four of the DADA wing and bow-tie has a similar plan to the levels below and, therefore, adopt a similar air supply and exhaust route. However, whereas the spaces on the lower floors discharge into the exhaust stacks, the level four spaces have their own dedicated exhaust route (Figures 8 and 10).

The roof-top plenum of the library (Figure 16) occupies the whole of the pitched roof volume and is exhausted by the eight louvered termination devices. These are divided into four separate compartments.
that enable the louvers in the compartments facing down-wind to be opened, while those facing into the wind can be closed. Five of the terminations exhaust the rooftop plenum, whilst three directly exhaust level four. Similar terminations exhaust the atria in the DADA wing.

**Building control strategy**

There are three broad modes of operation for the building: mechanical heating and humidification (MHH), primarily in winter; mechanical cooling and dehumidification (MCD), particularly in summer; and, in mid-season, passive heating and ventilating (PHV), which can provide passive daytime cooling and passive night-time cooling of exposed thermal mass. Although these are labelled as seasonal operation strategies, it is quite possible, given the variability of the climate, for the building to change operation from one mode to another, and back again, within a single day.

The control strategy needs to fulfil the following criteria: maintain the interior, as far as possible, within the ASHRAE Standard 55-2004 (ASHRAE, 2004) comfort envelope; be as energy efficient as possible; enable a seamless transition between the various operating modes; avoid frequent switches between operating modes (hunting); and be based on a realistic sensor resolution and calibration. Additionally, the relative humidity levels in the library must not exceed 70% for prolonged periods.

The control strategy for the library is presented here in outline as an aid to understanding how the building will operate. Therefore, details (such as dead-bands between on and off switching, etc.) have been ignored in the interests of clarity. The various modes of operation are illustrated using a part section through the library in Figures 17–19.

![Diagram of building control strategy](image)
Winter operating modes (MHH)

The MHH operation would be initiated in response to measured ambient temperature or moisture content. If the ambient air temperature drops below a certain value, it will be more economical to run the mechanical equipment (and thereby recover heat, even at the expense of the fan energy) than to let heated air ventilate freely to ambient. Although the ASHRAE Standard 55-2004 comfort envelope specifies no minimum moisture content, at low humidity levels occupants may experience a dry throat and nose, and static electricity can build up. Thus, it is prudent to prevent the relative humidity dropping too low. Therefore, one might postulate the following conditions for initiating MHH:

\[ T_0 \leq 6.0^\circ \text{C} \quad \text{or} \quad \text{MC}_0 \leq 3.0 \quad \text{g/kg} \]

where \( T_0 \) is the outside temperature and \( \text{MC}_0 \) is the outside moisture content. Both set point values are estimates and so are shown in italics to indicate that they would finally be chosen, through practical experience, when operating the building; this convention is continued below.

Whilst operating in MHH mode, the occupants will be clad in warmer clothes, so in the interests of energy efficiency, interior temperatures should be maintained towards the lower end of the ASHRAE Standard 55-2004 envelope:

\[ T_i \geq 20.0^\circ \text{C} \]

where \( T_i \) is the internal air temperature. No lower limit of moisture content is set because an active humidification plant is not planned. The values achieved will
therefore be above the set point for moisture content, noted above, and dependent on the effectiveness of the moisture recovery plant (enthalpy wheel) in the air-handling equipment and on the rates of the internal moisture generation.

Fresh air will be supplied at a sufficient rate to prevent CO₂ levels rising unacceptably high, which, using LEED as a guide, would be:

\[ \text{CO}_2^i < \text{CO}_2^o + 530 \text{ ppm} \]

where \( \text{CO}_2^i \) is the internal CO₂ level (ppm) and \( \text{CO}_2^o \) is the outside CO₂ level (ppm).

Four modes of MHH operation might be identified. At night (mode one) the heating elements (radiators) around the perimeter and lightwell operate to stop the interior temperature dropping too low, e.g. not below 12°C. Likewise, the plenum and lightwell can be warmed by the raked pre-heating coils in the plenum. Before occupancy (mode two) the interior space will be heated to bring the temperature up to 20.0°C. The air-handling plant will not run during operating modes one and two.

On winter days (mode three) the mechanical plant will operate to maintain the plenum and lightwell at a small positive pressure, and at an air temperature of around 17°C. Air will be re-circulated from the roof plenum so that heat and moisture can be recovered. During this phase of operation, the CO₂ in the spaces will be maintained within acceptable limits by controlling the volume flow of air from the lightwell, through the spaces, to the exhaust stacks, using the dampers at the inlet and outlet.
The supply air will be warmed, as needed, by the reheat coils at the air inlet to provide a minimum supply air temperature \((T_s)\), which is 2°C, or so, below the target air temperature. This ensures that air flows across the floor plates in displacement ventilation mode. If spaces start to become too warm, e.g. \(T_i \approx 23^\circ\text{C}\), then the perimeter heating will switch off. Should the temperature continue to rise, then control of the airflow would revert (from CO2) to temperature and dampers would be opened to increase the volume flow of air. Air inlets have been sized to enable up to about eight air changes per hour without excessive local air speeds.

A fourth mode can be anticipated in which space temperatures continue to rise above an unacceptable upper limit for MHH operation, say \(T_i > 23^\circ\text{C}\). In this case the preheating of the supply air would be diminished, eventually enabling air from the lightwell to enter the occupied spaces freely.

During the MHH operating mode, the enclosed greenhouse at the top of the lightwell may not be shaded or ventilated. The dampers in the louvered roof outlets would be closed so that the air in the roof plenum would be returned to the plant room via the two return air ducts.

**Mid-season operating modes (PHV)**

The building will switch to passive heating and ventilation (PHV) when the ambient temperatures and moisture content fulfil a condition such that:

\[
T_o > 6.0^\circ\text{C} \text{ and } 12\text{kg} > MC_o > 3.0\text{g/kg}
\]

In the passive operating modes, the air-handling unit ceases to operate and airflow is driven purely by internal heat generation. The aim is to hold the interior conditions during the occupancy period to within the ASHRAE Standard 55-2004 comfort envelope, for example:

\[
20.0^\circ\text{C} \leq T_i \leq 27^\circ\text{C} \text{ and } MC_i < 12\text{g/kg}
\]

The LEED CO2 condition should also be met, but, in practice, at these warmer ambient temperatures, maintenance of the internal temperature, rather than CO2 levels, is likely to determine airflow rates.

There are ‘five modes’ of PHV operation. Night setback (mode one) and preheating before occupancy (mode two) are the same as those for MHH operation (Figure 17, levels one and two). On cool days (mode three), \(T_o < 17^\circ\text{C}\), daytime temperature and CO2 control of spaces will follow the method adopted for the MHH mode of operation, but the air entering the lightwell will be supplied passively to the plenum (rather than from the mechanical plant) and preheated by the coils at the plenum inlet (to a temperature of, say, 17°C). On warmer days (mode four) air will be supplied via the plenum, without heating, and so the lightwell will be filled with ambient air. Air inlet and outlet dampers will operate to restrain the rise in internal temperature until, under the warmest conditions, or with high internal occupancy, the inlet and outlet dampers will be fully open and the internal temperature will drift towards the upper acceptable limit for thermal comfort.

During the nights following warm days, the building will be passively ventilated to cool the exposed thermal mass of the ceilings and walls (mode five). Alternative night venting strategies have been evaluated and a suggested strategy is proposed by Martin and Banyard (1998).

During the PHV modes of operation, the greenhouse at the top of the lightwell will be shaded and ventilated if necessary during the day (and if night venting is initiated, also at night) to prevent its temperature rising, which would cause heating of the air in the lightwell by conduction through the glass lens.

**Summertime operation (MCD)**

The building will switch into the MCD modes of operation when the daytime internal conditions threaten to exceed the upper limits of the ASHRAE Standard 55-2004 comfort envelope:

\[
T_i \geq 27^\circ\text{C} \text{ or } MC_i \geq 12\text{g/kg}
\]

In the library spaces, switching may also be triggered if the relative humidity (RH) exceeds the recommended limit:

\[
\text{RH}_i \geq 70\%
\]

On switching from PHV operation to MCD operation, the dampers at the inlet to the plenum and in the exhaust outlets on the roof will close and the return air ducts from the roof plenum to the plant room will open up.

In the MCD mode, the mechanical plant will supply air to keep the plenum and the lightwell at a positive pressure and at a temperature of around, say, 21°C. That is about 6°C below the upper limit for space temperatures – which is, probably, the limiting temperature differential (between the supply air and the
The building could switch back to PHV operation when:

\[ T_o \leq 23^\circ\text{C} \quad \text{and} \quad MC_o \leq 12\text{g/kg} \]

but, in practice, these values might be set a little lower to avoid hunting between the MCD and PHV modes.

When operating in MCD mode, the greenhouse at the top of the lightwell is likely to be shaded and ventilated to remove solar heat. The internal heating elements will, of course, be switched off.

Three modes of operation might be identified (Figure 19). Immediately before occupancy, mode one, the building will be sealed with space temperatures in the range 20–26°C. This could be achieved by night-time passive ventilation.

During occupancy (mode two) the flow of air from the lightwell will be controlled by modulating the air inlet dampers to achieve the desired space temperatures. In mode three, when the space temperatures are at their highest acceptable value (e.g. 26°C), the supply dampers will be fully open and, if necessary, the mechanical plant will supply the peak volume of cooled air. In both modes two and three, air is re-circulated back to the air-handling unit from the roof plenum.

**Estimated energy performance**

To assess the likely energy savings, and energy cost reductions, which might result from the Judson College design rather than from a more conventional approach, predicted simulations were undertaken using the dynamic thermal simulation program ESP-r (Energy Systems Research Unit (ESRU), 1998) and the Chicago TMY2. This is a widely used program that offers the option of incorporating a zonal airflow model, thereby making it well suited to assist with the design of passively ventilated and hybrid buildings.

The program was used to assist with the design of the building, i.e. to predict likely internal temperatures resulting from different stack sizes, ventilation opening areas and window shading strategies. The same geometrical model as that used for the design analyses on the library was used for the energy use and cost estimates produced here. The analysis is not, therefore, intended to provide a fully LEED-compliant energy cost evaluation. Rather the purpose is to illustrate the differences between the Judson College approach to controlling the thermal environment and the approach more commonly used in US buildings.

The geometrical model consisted of one-quarter of one floor plate of the library building, defined by the north-west-facing facade and diagonals radiating from the centre of the lightwell to the corners of the building. This quadrant had a floor area of 273 m², a floor-to-ceiling height of 3.61 m² and a facade area of 123 m². The space was occupied from 08.00–18.00 hours on every day of the year and unoccupied outside of these times.² On weekdays the heat gain during the occupied period was 34 W/m², but at weekends it was only 60% of this figure.

Comparisons between the Judson College building and a US Standard Building (with alternative cooling set points) was undertaken to illustrate the magnitude and origin of the energy savings possible (rather than for the purposes of LEED assessment). The standard building had the same basic geometry as the Judson College building, representing one south-west-facing quadrant of level three of the library. It was built to ANSI/ASHRAE/IESNA Standard 90.1–2001 (ASHRAE, 2001) minimum requirements for inoperable windows and walls (Table 2) and was assumed to have a lightweight false ceiling, with all the daytime heating and cooling being provided by a central air handler, supplying air to meet the fresh air requirements. One version of the standard building had a cooling set point of 24°C, which might be seen as a rather conventional value, but the other had a cooling set point of 26°C, which is the value proposed for the Judson College building. This enabled the differences in energy use and cost arising due to the building and environmental design to be assessed without the difference in the cooling set point clouding the result. In fact, the change in cooling set point had little affect on the conclusions reached.

The Judson College building, in contrast, was modelled to match that of the library design described above (Table 2). Thus, the facade was somewhat different from the standard US approach and the ventilation was provided passively (when ambient air temperatures exceeded 6°C, and no cooling was required) and at a variable rate in order to maintain a thermally comfortable interior. In the model, night ventilation was based on the temperature of the internal ceiling...
slab (i.e. night ventilation was enabled between 18.00 and 08.00 hours when the ceiling slab temperature was greater than 23°C). This proved easier to model and control than night ventilation based on the space air temperature. The passive ventilation ducts have very low airflow resistance and so the specific fan energy in the Judson College building is much lower than would be needed in a more conventional US building (i.e. 1.1 compared with 2.4 kW/m³/s).

The ESP-r program calculated temperatures, ventilation flow rates, and heating and cooling loads. To convert these loads into delivered energy and cost, the following values were used: heating efficiency, 0.91; chiller coefficient of performance (COP), 3.0; hot water circuit pump, 0.09 kW; cooling pump, 0.02 kW; gas cost, 3.2 c/kWh; and electricity price, 8.5 c/kWh.

The energy demand and energy cost predictions ignore lighting (functional, decorative and security), plug loads (computers and other office equipment), catering, mechanical ventilation extract (e.g. woodworking shop and toilets), parasitic loads (e.g. actuators, indicator lights, trace heating), etc. They, therefore, relate purely to the energy for thermal conditioning of the modelled space.

As a result of the night-time ventilation, coupled with exposed thermal mass and solar shading, the summer-time cooling energy loads in the Judson College building are less than half those in the US Standard Buildings (Figure 20). The period for which cooling energy is needed decreases from around seven months (April–October) in the US Standard Buildings to around just three months (June–August) in the Judson College building. The higher insulation levels reduce the mid-winter (December–February) heating energy loads by about 29%. However, during spring (March–April) and autumn (October–November) the Judson College building actually demands more heating energy because the window shading excludes useful solar gain (Figure 20).

---

### Table 2 Description of a model of Standard US buildings and Judson College building used in the energy use analyses

<table>
<thead>
<tr>
<th></th>
<th>Standard US (24°C)</th>
<th>Standard US (26°C)</th>
<th>Judson College building</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floor area (m²)</td>
<td>272</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Floor-to-ceiling height (m)</td>
<td>3.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Facade area (m²)</td>
<td></td>
<td>123</td>
<td></td>
</tr>
<tr>
<td>Window area (m²)¹</td>
<td>49.2</td>
<td>15.2</td>
<td></td>
</tr>
<tr>
<td>Occupancy²</td>
<td>08.00–18.00 hours, weekdays, 34.0 W/m²</td>
<td>08.00–18.00 hours, weekends, 20.4 W/m²</td>
<td></td>
</tr>
<tr>
<td>Wall U-value (W/m²K)</td>
<td>0.70</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>Window U-value³ (W/m²K)</td>
<td>3.20</td>
<td>1.85</td>
<td></td>
</tr>
<tr>
<td>SHGC⁴</td>
<td>0.39</td>
<td>0.68</td>
<td></td>
</tr>
<tr>
<td>Shading⁵</td>
<td>No</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Ceiling</td>
<td>Lightweight⁶</td>
<td>Heavyweight⁷</td>
<td></td>
</tr>
<tr>
<td>Infiltration (m³/h)</td>
<td>190</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ventilation rate (m³/h)</td>
<td>1200⁸</td>
<td>1200²</td>
<td></td>
</tr>
<tr>
<td>Fan energy (kW/m³/s)</td>
<td>2.4</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>Heating set point (°C)</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cooling set point (°C)</td>
<td>24</td>
<td>26</td>
<td>26</td>
</tr>
</tbody>
</table>

Notes: ¹Orientation south-west. ²No heat gains 18.00 to 08.00 hours, on any day. ³Centre pane value. ⁴Solar heat gain coefficient (the Judson College value varies with solar incidence angle). ⁵Shading for Judson College as per actual building. ⁶Twelve-millimetre fibreboard, air gap and a concrete ceiling panel. ⁷Exposed concrete panel. ⁸During occupancy, at night infiltration only. ⁹During occupancy in mechanical mode; variable in passive mode and at night.
The costs for delivering energy are greater in the US Standard Buildings than in the Judson College building during every month of the year (Figure 21). This is because in the US Standard Buildings significant amounts of energy are consumed by the fans, whereas in the Judson College building fresh air is often delivered passively.

The substantial reduction in the time for which mechanical systems must operate in the Judson College building, compared with the US Standard Buildings, is illustrated in Figure 22. The US Standard Buildings require mechanical ventilation during all occupied hours and for fewer than 4% of these is it possible to neither heat nor cool. In contrast, in the Judson College building the mechanical air-handling plant is needed for only 48% of occupied hours. Passive ventilation with neither heating nor cooling is possible for 29% of these occupied hours and for 23% of such hours ventilation pre-heating is required.

The consequence of these performance differences is that the predicted annual energy cost for space conditioning the model segment is about 47% less in the Judson College building than in the US Standard Building (24), and 43% less than in the US Standard Building (26) (Figure 23).

**Barriers to innovation**

**Maintaining design integrity through the procurement process**

The UK design team’s earlier NV and hybrid buildings were procured through ‘traditional’ routes in which the design in its entirety was completed before the construction contract was let (e.g. for the SSEES building, see Short et al., 2004, and Harbison, 2006). The contractor plays little role in the design and any contribution made or expected is precisely defined within the contract. The procurement method is thus characterized by rigidly sequential plans of work (Royal Institute of British Architects (RIBA), 2000) and so is not without its difficulties (Kagioglou et al., 2000).

The Judson College Academic Centre is, however, being procured through a management contracting
Figure 21  Comparison of monthly heating, cooling and fan energy costs: (a) US standard (24 °C) and (b) Judson College

Figure 22  Percentage of occupied hours for which buildings operate in various modes: mechanical ventilation and heating (MV + H); mechanical cooling (MV + C); mechanical ventilation only (MV); passive ventilation and heating (PV + H); and passive ventilation (PV)
process in which the American Institute of Architects (AIA) scheme design, which is equivalent to the Royal Institute of British Architects (RIBA) Stage E, is disaggregated into discrete packages of work, bid and let sequentially. In practice this route has quite different implications for the sequencing of design decisions. It is particularly suitable for designs assembled from contained sets of components: frame, curtain wall, interior partitions, hung ceilings, air-conditioning plant and ductwork, and so on. It encourages a particularly high degree of fluidity in the choices of materials and construction method through the construction drawing and specification phase, driven by value-engineering goals and perceived practicability. Coherence through sequences of packages is, in a sense, contrary to the spirit of the highly collaborative process.

The eventual selection of structural pre-cast concrete panels, as the most economic solution for all external walls, was ultimately beneficial to the strategy but unanticipated during the detail design phase. The precise coordination of the heating, ventilation and air-conditioning (HVAC) systems and the architecture, e.g. in the location and sizing of openings in the concrete for ducts and dampers, becomes critical. In practice, many rapid iterations and checks against the original computer simulations were required as the reinforcement within the panels constrained the zones of permissible puncture, and these zones varied from the bidding fabricators’ stock designs. The programme to finalize the pre-cast element shop drawings drove the detailed resolution of the environmental strategy at this point.

The Judson College design is highly integrated, and the exploration of more economic or buildable alternatives for one component cannot be usefully considered out of context for fear of destabilizing the environmental design strategy. For a local team of contractors and implementation consultants ‘of record’, this is demanding, certainly more so than the standard conditions of engagement for the various disciplines envisaged. The design team was appointed under the AIA Agreements of 1992 and 1997 (AIA, 1992, 1997); subsequent versions do not appear to envisage more design iterations requiring more programme time and remuneration.

There were a number of difficult problems to resolve. The fabric U-values proposed for the Judson College buildings are substantially lower than those recommended by ASHRAE Standard 90.1–2001 (ASHRAE, 2001) (Table 2). The wall and roof U-values were relatively easily attained, however, achieving details to avoid cold-bridging around apertures and at the perimeter, commensurate with the lower U-values, required some effort: the standard details produced unacceptable heat bridging. Overcoming ingrained practice in the design of HVAC systems was also challenging, in particular: to encourage systems with energy-efficient features that, in Europe, would be considered standard practice; and to transpose the proposed hybrid control strategy into a BMS protocol. In retrospect, the Illinois State award to fund further detailed design enquiry was invaluable.

Although fire and smoke control issues have proved to be major determinants of environmental design decision-making for the authors in their UK projects (Short et al., 2006), in Illinois, with code officers perhaps more familiar with less prescriptive, evidence-based routes to compliance, agreement was reached relatively rapidly, despite the incorporation of three- and four-storey voids through the plans.

**Costs**

Although value engineering opportunities were keenly pursued by the management contractor, there is a premium on the capital cost of the building relative to the equivalent notional US Standard Building. The Judson College building will cost in the order of US$2115/m², as compared with a lightweight US Standard Building, weighted to reflect Illinois pricing, of US$1854/m² (Dodge Reports, 2005). However, there is a more fundamental redistribution of costs: certainly more investment in superstructure and controls; less in
Table 3 Comparative constructional costs for the Judson College building and a US Standard Building

<table>
<thead>
<tr>
<th>Element</th>
<th>Description</th>
<th>Judson College¹</th>
<th>US Standard Building²</th>
<th>Judson College additional cost and percentage increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Site work</td>
<td>Excavation, site utilities, landscape and retaining structures</td>
<td>144 ³ 6.8 102 5.5 42 (40%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Substructure</td>
<td>Site concrete</td>
<td>21 ¹ 10.0 16 0.9 5 (31%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Concrete</td>
<td>Above ground</td>
<td>107 5.1 81 4.4 26 (33%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Structure</td>
<td>(1) Pre-cast concrete</td>
<td>237 355 5 16.7 161 8.7 33 (10%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(2) Structural steel including fire proofing</td>
<td>118  161 8.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Roofing</td>
<td>Metal roof build-up and coverings</td>
<td>172 5 8.1 161 8.7 11 (7%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Internal partitions</td>
<td>Framing and drywall</td>
<td>140 7 6.6 118 6.4 22 (18%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. Glass and glazing</td>
<td>Glass, glazing, lightwells, skylights and windows</td>
<td>137 3 6.5 140 7.5 –3 (~19%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. Moveable shading</td>
<td>Shade at the top of the light well</td>
<td>3 0.2 Not typical 0.0 3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9. External walls</td>
<td>Masonry and cladding (for Judson College incorporating deep window reveals and a return)</td>
<td>162 7 129 7.0 33 (25%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10. Heating, ventilation and air-conditioning (HVAC)</td>
<td>HVAC controls</td>
<td>410 10 19.4 301 16.2 109 (36%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11. Other HVAC</td>
<td>Plumbing, alarms, phones, data, elevations, sprinklers</td>
<td>297 14.0 323 17.4 –26 (~8%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12. Finishes</td>
<td>Painting</td>
<td>145 6.9 140 7.5 5 (4%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13. All other construction</td>
<td>Doors, general trades, toilet cubicles, flooring, fire shutters</td>
<td>22 1.0 21 1.1 1 (1%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Totals</td>
<td></td>
<td>2115 11 100 1854 100 261 (14%)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes: ¹Judson College building costs (unpublished) are supplied by Shales McNutt Construction (2005). ²US Standard Building costs are assembled from contemporary Dodge Reports (2005). ³Site works: additional cost includes the forming of detention ponds, the Fenland landscape, to provide a sustainable drainage scheme; US$319 000 for the import of additional fill/soil to remedy poor site conditions. Excavated fill is used to form Fenland. Site utilities and retaining structures are assumed to be equivalent for both schemes. ⁴Substructure: some additional complexity relates to plan geometry, the orientation of the Division of Art, Design and Architecture (DADA) wing and air intakes; the structural solution of the pre-cast load-bearing wall elements increases the design strength of the perimeter retaining walls; the weight of steel reinforcement rises. ⁵Structure: pre-cast panels are more costly; there is an increased number and pattern of openings in pre-cast panels relating to airflow routes; there is increased sub-contractor engineering input and increased labour content in manufacture. Overall, structural steel content is somewhat lower, whilst the pre-cast concrete element is higher than for a US Standard Building. There is a 10% premium rate on the more complex external wall construction to accommodate the advanced environmental strategy. ⁶Economies of scale deliver a fairly complex roof form at Judson College for almost the standard rate. ⁷Internal partitions: additional cost relates entirely to increased ceiling heights, which are beneficial to a passive air flow strategy, accommodating temperature stratification. ⁸Glass and glazing costs are almost equivalent; the window shapes and expected performance sizes are standard to US suppliers. ⁹External walls: the additional cost includes for the light structure and preformed ductwork forming the double facade; all the returns and deep reveals and copper shingle external covering. However, a high degree of repetition enables serial prefabrication off-site in 10 and 12 feet, three-sided elements, lifted into place. This cost is offset, in part, against the full internal ductwork of the Standard Building with conventional HVAC. ¹⁰HVAC: US prices for non-standard controls are high, US$500 000 as compared with US$150 000 for the US Standard Building. (The highest quoted reception was of the order of US$1 million.) However, there are 1500 sensor points in the Judson College building; the US Standard Building envisages only 500; there are more moving elements, actuated dampers and windows, and a requirement for a full three-month commissioning period. ¹¹In summary of the additional US$261/m², a 14% increase in the overall cost of a US Standard Building, additional costs specifically associated with the hybrid environmental strategy emerge as US$175/m², equivalent to a 9.38% premium rate on a US Standard Building costs, made up as follows: US$33/m² premium on structure; US$33/m² on external wall construction; and US$109/m² for controls. In the case of the Judson College building, approximately US$86/m² of the over-cost derives from specific site conditions and client requirements.

applied finishes and hung ceilings; less in conventional ductwork; more in the physical construction of the building to make the air distribution infrastructure; and more in the insulation of the envelope, and in the external shading of the glazing (Table 3). Standardized off-the-shelf controls packages in the US are significantly more economic than in Europe, whilst bespoke, custom-designed controls, such as those required to operate the Judson College building, are relatively more expensive, accentuating the premium. Some of this additional cost, approximately US$85/m², relates to site-specific conditions and particular client requirements, so the additional cost directly attributed to the hybrid environmental strategy is US$175/m² made up of: structure, US$33/m²; external wall construction, US$33/m²; and controls, US$109/m². Overall, therefore, the items associated with the LEED certification credits appear to be adding some 9% to the total cost. Inevitably, the payback period is not insignificant.
Following the standard formula for a 60-year building life expectancy:

\[
\text{Difference in cost including equipment replacement costs/energy saving} = \text{payback period}
\]

The estimated equipment costs over 60 years, assuming other maintenance costs are equivalent, arise for the US Standard Building, from replacing the chillers every 20 years at US$64,500 and the air-handling units every 15 years at US$132,000. For the Judson College building it was assumed that the chillers are replaced every 35 years at US$64,500 and the air-handling units every 30 years at US$132,000.

Using the difference in construction cost (US$175/m² \times 7810 m² = US$1,366,600) gives:

\[
\frac{[1366600 - 3 \times 64500 - 4 \times 132000 + 64500 + 2 \times 132000]/15800 = 62 \text{ year payback}}{}
\]

The payback is in excess of the building’s life. However, if energy costs were 25% higher in Illinois, the cost saving would become US$19,800 per annum and the payback period 49 years; if energy costs rose almost immediately by 50%, the payback period reduces to 41 years.

The net present value (NPV) analysis of capital and running costs for the Judson College building compared with the base case is equally revealing. The methodology is derived from CIBSE Guide No. B18, Owning and Operating Costs (CIBSE, 1986). Investments are generally assumed to be viable if the NPV is zero at the appropriate discount rate.

The analysis (Table 4) is set in the more commercial context of 25- and 50-year periods and uses both a 5.0% discount rate (as advised by the College Vice-President, Business Affairs) and a 3.5% discount rate as recommended for UK public-sector investment. The discount rates are real rates and all costs are considered in real terms, ignoring inflationary rises. Capital cost at year zero is not discounted.

It can be seen that the NPVs are always negative and the running costs multiplier (K) to achieve an NPV of zero is between 5.3 and 7.6, although the US Federal Government’s advice is that fuel costs will remain stable in the long-term. The non-energy benefits of the building are, however, substantial and around the minimum that the College anticipates achieving through additional student enrolment (the academic fee is US$18,250 per annum), staff retention, enhanced reputation and profile.

The College would not have proceeded on energy-saving grounds alone. As Ellingham and Fawcett (2006) explain, uncertainty, irreversibility and the use of options, explicitly or implicitly, in decision-making make managers more cautious about energy-saving measures than other capital items. They describe this phenomenon as the ‘energy paradox’ and refer to the intense frustration it causes energy conservation advocates. In the Judson College context, however, the required additional benefits to achieve a zero NPV are relatively containable on an annual basis relative to, say, its annual turnover of between US$17.5 million (2003/04) and US$18.7 million (2004/05).

### Table 4 Net present value (NPV) analysis under the four scenarios

<table>
<thead>
<tr>
<th>Period of analysis</th>
<th>50 years</th>
<th>50 years</th>
<th>25 years</th>
<th>25 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPV discount rate</td>
<td>5% per year</td>
<td>3.5% per year</td>
<td>5% per year</td>
<td>3.5% per year</td>
</tr>
<tr>
<td>NPV²</td>
<td>US$1,693,000</td>
<td>US$1,591,000</td>
<td>US$1,746,000</td>
<td>US$1,685,000</td>
</tr>
<tr>
<td>Multiplier K²</td>
<td>6.9</td>
<td>5.3</td>
<td>90</td>
<td>76</td>
</tr>
<tr>
<td>Price rise U³</td>
<td>8.8% per year</td>
<td>7.2% per year</td>
<td>18.3% per year</td>
<td>16.4% per year</td>
</tr>
<tr>
<td>Non-energy benefits B⁴</td>
<td>US$93,200/year</td>
<td>US$68,349/year</td>
<td>US$126,500/year</td>
<td>US$105,000/year</td>
</tr>
</tbody>
</table>

Notes: ¹NPV’s with data given in text.
²Value for multiplier (K) that would achieve a zero NPV; all running costs are multiplied by K. This is equivalent to a rise in the cost of energy cost.
³Value for real price rise (U) that would achieve a zero NPV; all running costs are taken to be U times the previous year’s energy costs, starting with current costs in Year 0. This factor leads to extremely high energy costs in later years.
⁴Non-energy benefit (B) that would achieve a zero NPV; B is added to the energy cost savings for every year from Year 1. This might be made up of educational, promotional or other benefits.

### Anticipating behaviours in a hybrid building

The environmental control strategy was evolved in discussion with the clients, through observation of their current working and learning environments, and with the very helpful guidance of the local consultant team on the management of expectations. Comfort expectations and variance from the US national comfort standards were deemed simply to be non-negotiable
in terms of client expectation and the relevance of the project as a potential model. The guidance was useful, setting the conditions to be met as the building passes through its various modes of operation, but it raised some questions with regard to the expectations of the occupants in the different operating modes. Will they maintain their apparently more tolerant behaviour when the building passes from an unassisted natural mode towards a full mechanical mode, and perhaps, more importantly, during the reverse process?

The mutually exclusive guidance on comfort criteria offered by ASHRAE Standard 55–2004 (ASHRAE, 2004), for passively ventilated buildings and for those that include mechanical systems, raises a number of interesting questions that might benefit from further research. For example, what upper and lower temperature bands are appropriate in hybrid buildings which may have both mechanical cooling and operable windows? Would occupants of hybrid buildings adjust their expectations depending on the mode in which the building is operating? Would expectations differ depending on whether occupants are made aware of the mode in which the building is operated? Should there, therefore, be an ASHRAE Standard 55–2004 optional method for hybrid buildings?

Whilst building costs are accurately known, the energy use and internal environment produced can only be predicted at the design stage. The design team and the client are interested in conducting a post-occupancy evaluation to gain evidence about the actual in-use performance and occupant satisfaction. Such studies are, regrettably, rarely conducted but are the key to improving building design and for promoting the wider uptake of low-energy building designs.

Conclusions

The ambient temperature and humidity in Chicago frequently lie above the limits permissible by the ASHRAE Standard 55–2004 thermal comfort envelope. The alternative Standard 55 method, applicable to buildings with operable windows and no mechanical cooling, is, for the climate of Judson College, more restrictive on the indoor summertime temperature than the standard method. A hybrid ventilation strategy was therefore adopted, blending mechanical ventilation with heating, cooling and passive ventilation. Target internal conditions were defined by the Standard 55 comfort envelope.

The Judson College design strategy closely integrated the airflow distribution and collection infrastructure for the naturally driven and mechanically supplied displacement ventilation. This was essential to save space and capital cost and to avoid duplication of mechanical and natural systems. The building, therefore, has a true hybrid strategy. This necessarily integrated design approach has implications for the procurement of construction materials and alternative options have to be reviewed quickly in the context of the whole design strategy. This requires an unusually full understanding on the part of the construction management team.

An internal temperature, moisture content and CO₂ control strategy has been proposed that enables a seamless transition between the three basic seasonal operating modes: winter mechanical heating; passive heating and ventilating in the mid-season; and summertime mechanical cooling and dehumidification.

Thermal simulations indicated that, as a result of the night-time ventilation, coupled with exposed thermal mass and solar shading, the summertime cooling energy loads in the Judson College building were less than half those in a US Standard Building. The period for which mechanical cooling is needed decreased from seven months to around three months. The hybrid design meant that the mechanical air-handling plant was needed for only 48% of the occupied hours in the year. The predicted annual energy cost for heating, cooling and ventilating the modelled segment of Judson College library were about 43% less than those for a US Standard Building. This benefit is not in itself viable. Paybacks are lengthy, energy costs are notoriously volatile, and the net present value calculation is negative. However, the additional quantifiable benefits required to achieve viability are not unrealistic for the college.

Hybrid ventilation strategies would appear to have substantial energy and cost benefits, even in a severe continental climate. The Judson College buildings show one route by which building design can contribute to reducing CO₂ emissions, improving the security of the US energy supply, and reducing summertime electrical energy loads.

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References

Hybrid environmental design strategy in a US continental climate


Endnotes

1 A small number of spaces with special environmental requirements, or particularly high heat gain, would need local conditioning.

2 In hindsight, perhaps some heat gain (e.g. from computers) should have been modelled outside occupied hours. However, night ventilation could easily remove this low-level heat input, whereas the gains would add to the cooling load (on the subsequent day) in the mechanically cooled buildings. Thus, the absence of the gains acts to underplay the energy benefits of the hybrid strategy.
Exploiting a hybrid environmental design strategy in a US continental climate

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