IEA

INTERNATIONAL ENERGY AGENCY
ENERGY CONSERVATION IN BUILDINGS AND COMMUNITY SYSTEMS

Pilot study report:

# WIlkinson Building

The University of Sydney, Sydney, Australia

Photo David Rowe

View of Wilkinson Building from the south. The study area is in this wing. Level 2 is at the bottom of the picture and level 5 is at the top. The 600 mm wide horizontal overhangs can be seen above hinged hopper type windows.

Photo David Rowe

View to east showing study areas on levels 4 and 5 and supplementary reverse cycle refrigeration equipment on the roof over level 3.

Photo John Fraser-Mifsud

View from southeast of the central access core and atrium which provide some stack effect for ventilation. The study area is in the wing at the right of the picture.

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# 1 GENERAL INFORMATION

1.1.1 *Report date* January 2002

1.1.2 *Principal researchers* David Rowe, Honorary Senior Lecturer, Architectural and Environmental Science Group, Faculty of Architecture, the University of Sydney.

1.1.3 *Other participants* None.

1.1.4 *Project title* Hybrid Ventilation and Indoor Climate Control in Staff Offices in the Wilkinson Building.

1.1.5 *Principal objectives*

- Definition of relationship between energy consumed by the on-demand, occupant controlled climate control system and outdoor weather in a suite of naturally ventilated cellular offices provided with supplementary refrigerated cooling/heating equipment in a moderate climate.
- Definition of relationship between occupant controlled indoor temperatures and outdoor temperature.
- Definition of relationship between mean clothing insulation values and outdoor weather.
- Comparison of occupant subjective perceptions of thermal comfort and air quality with those of occupants of other buildings.
- Comparison of prevalence of symptoms of "sick building syndrome" with those of occupants of other buildings.
- Periodic sampling of $CO_2$, particulates, VOCs and microbiological contaminants of indoor air.

1.1.6 *Start date / End date* 1 August 2000 to 31 December 2001

1.1.7 *Number of man-hours* Very approximately 800.

1.1.8 *Project approach* This is a retrofit project. The Wilkinson Building houses the Faculty of Architecture at the University of Sydney. The building was constructed in stages beginning in 1960. The final stage was completed in 1978. The whole building is an example of hybrid ventilation. It accommodates teaching studios, tutorial rooms, lecture theatres, a library, various laboratories including several computer laboratories, workshops and cellular offices for staff and graduate students. Lecture theatres, library and computer laboratories are air-conditioned. Teaching studios, workshops and cellular offices are naturally ventilated through operable windows and doors. The ventilation of deep teaching spaces is supplemented by a centralised mechanical ventilation system with hot water coils for winter warming. A central gas fired boiler plant provides hot water, which is circulated to the heating coils in air conditioning and mechanical ventilation systems and wall mounted panel radiators in offices. This project focuses on a particular study area comprising a suite of 25 naturally ventilated cellular offices for staff which were provided with an occupant controlled supplementary Variable Refrigerant Flow (VRF) cooling/heating system that was put into service in November 1997. The extent of the study was curtailed by the level of funding available. However the following activities have taken place:-

- Energy consumption of the supplementary cooling/heating equipment in the study area has been monitored continuously and recorded at half hourly intervals since the beginning of December 1997.
- Indoor temperature and occupancy status of each room in the study area has been monitored and recorded since 1 October 2000. Some monitoring equipment problems have resulted in incomplete records. Nevertheless sufficient are available to provide a representative sampling through a full range of outdoor climatic conditions for Sydney.
- Occupants' subjective perceptions of thermal comfort and air quality were sampled in August 1997 (before installation of the supplementary equipment), in September 1998 and again in July 2001 when sampling was also carried out in a group of similar rooms in the building that do not have the

supplementary cooling/heating equipment. Responses are compared with those from 34 other Australian office settings.

- During an investigation in September 2001 concentrations of CO2 and fine particulates were measured, and insulative value of occupants' clothing and their metabolic rates were estimated. Similar measurements were made at approximately the same time in two air-conditioned buildings.

### 1.1.9 *Building selection* The availability of the supplementary cooling/heating equipment donated by Daikin Australia Pty. Ltd. for experimental purposes and convenience of location were the catalysts for the project selection. Earlier sampling of occupant perceptions of thermal comfort and air quality in other buildings had suggested that satisfaction levels were likely to be high and energy consumption low in comparison with conventionally air-conditioned premises.

### 1.1.10 *References*


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### 1.1.11 *Comments*

- Energy consumption of the supplementary cooling/heating equipment in the study area is less than a quarter of the estimated amount that would be used by a well designed conventional air conditioning system with mechanical ventilation, cooling and heating for the same spaces, year on year.
- Average monthly energy consumption has a strong binomial relationship with monthly mean outdoor temperature.

- Indoor temperatures in occupied rooms are considered to be acceptable because of the wide variety of change options available. Average indoor temperature in occupied rooms is quite strongly related to daily outdoor temperature. There is, however, a considerable difference in acceptable temperatures between individuals on any one day and in individuals through the course of a day. There are also differences in levels of mechanical intervention between individuals across the seasons.
- There is a strong tendency to limit indoor temperatures to a maximum of 27 $^{o}$C to 28 $^{o}$C. This appears to be associated with intervention by use of mechanical cooling when daily minimum outdoor temperatures exceed about 17 $^{o}$C and daily maximum temperatures exceed about 26 $^{o}$C. Above these outdoor temperatures the mean indoor temperature in occupied rooms was observed to be approximately constant at about 25 $^{o}$C as indicated in figure 11(ii).
- Funding limitations prevented the development of a relationship between insulative values of clothing and outdoor weather. However it was noted that in winter clo values were approximately 0.1 clo higher than in air-conditioned premises indicating use of heavier clothing as an adaptive strategy.
- Mean scores for thermal comfort and perceived air quality were among the highest observed in a sampling of 38 office environments, a majority of them air conditioned. It is believed that the capability for individuals to adjust conditions to suit personal requirements has a major influence.
- Prevalence of eight symptoms commonly associated in the literature with "sick building syndrome" was significantly low in comparison with air-conditioned buildings. It is noted that symptom prevalence in other naturally ventilated and hybrid examples is generally in the lower 50 percentile of the 38 settings sampled. This finding is in accordance with others from the northern hemisphere, e.g. Finnegan, Pickering and Burge (1984).
- $CO_2$ concentrations were measured in ten locations in July 2001 yielding an average of 930 ppm. Concentrations of fine particulates were similarly sampled resulting in an average count of 1.10E+06 particles of 0.5µ or larger per $m^3$. This was about five times higher than counts in two air-conditioned buildings sampled at about the same time. The high counts are probably due to the location of the building on a busy main highway. Nevertheless the setting achieved a very high rating for perceived air quality. It is believed that this score is strongly influenced by availability of operable windows and means for personal control of the thermal environment.
- It seems likely that much of the success of this project in terms of energy consumption and perceptions of thermal comfort and air quality is due to the availability of operable windows and doors supported by independent control of the supplementary cooling/heating equipment in cellular accommodation which permits individuals or very small groups to control the ventilation and thermal environment in accordance with personal desires.
- Although energy is consumed by the supplementary mechanical equipment, it is much less than would be expected if the space were conventionally air-conditioned. The payback, in comparison with similar settings that do not carry the cost of the supplementary equipment, is considerable improvement in occupant comfort, satisfaction and productivity.
- The supplementary cooling/heating plant has a sophisticated microprocessor based control system to monitor and control relevant functions of the refrigeration system. It operates in the background to allow individuals to adjust their personal environments without interference or confusion while maintaining good efficiency over a wide operating range. The controls available to the occupants are simple and effective with rapid and clearly detectable response when action is taken. The results suggest that control systems should support individual user intervention without frustrating it. A good analogy is the power steering system in a modern motorcar, which supports user requirements effectively but unobtrusively.

# 2 TEST SITE DESCRIPTION

## 2.1 Geographic information

*2.1.1* *Location* Sydney, Australia. Longitude 151 deg. E; latitude 33 deg. S.

*2.1.2* *Elevation (height above sea level)* 90 metres.

*2.1.3* *Terrain* Suburban, low-rise buildings and parkland, fronting a major highway.

*2.1.4* *Orientation* South, southeast and northwest.

*2.1.5* *Comments* Cooling and heating loads are perimeter dominated in all spaces.

## 2.2 Climate information (Summary)

A Typical Reference Year real hour by hour climate data file for Sydney 1981 is available and was used for the reference energy simulation. A file of main climate data as recorded by the Australian Bureau of Meteorology has been maintained by the author since the beginning of year 2000.

2.2.1 *Location of meteorological station* Australian Bureau of Meteorology Sydney Observatory less than 5 km from the site. Latitude, longitude and elevation same as site.

*2.2.2* *% Frequency wind speed versus wind direction* Wind speed mean for year 11.6 km/hr. Mean for January 12.3 km/hr. For June 11.6 km/hr. Winds are mainly from the north to east in summer and from south to west in winter.

2.2.3 *Air temperatures* January mean maximum 25.7 °C, mean minimum 18.8 °C. June mean maximum 18.8, mean minimum 9.6 °C. Mean temperature for year 18 °C.

Design summer condition 31.5 °C dry bulb, 23 °C wet bulb. Winter 7 °C dry bulb, 80% RH. Figure 1 below shows monthly mean temperatures for the years 2000 and 2001. Inner bars represent one standard deviation and outer bars represent two standard deviations.

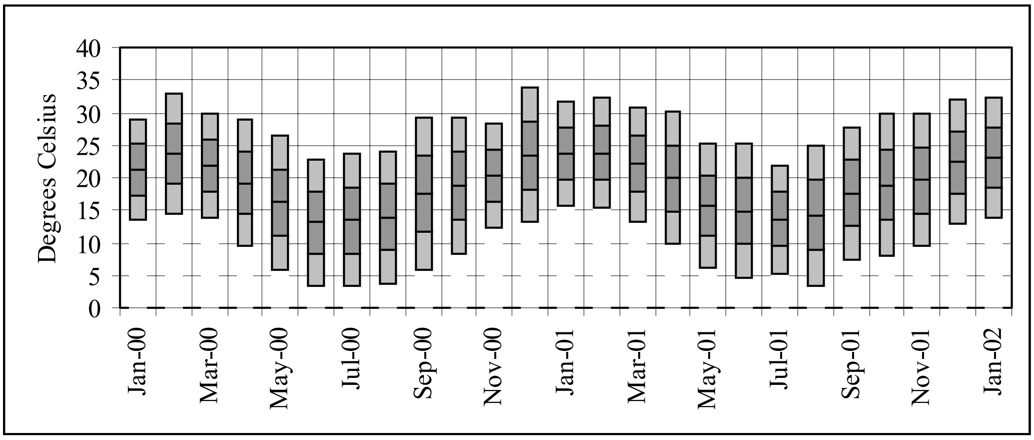


Figure 1. Monthly mean temperatures for years 2000 and 2001 shown by centres of bars. Inner bars represent one standard deviation, outer bars two standard deviations.

*2.2.4* *Degree day information* Heating degree days, 18 °C base: 642

Cooling degree days, 26 °C base: 3

Solar excess degree hours: 8,677

Cooling degree-days as quoted do not reflect the requirement for latent cooling in summer. Most designers would use a lower base temperature if data were available.

2.2.5 *Daylight / insolation* Mean insolation January 6,539 Wh/m$^2$; June 2,456 Wh/m$^2$.

Mean hours sunshine per day: January 7.2, June 5.2.

2.2.6 *Cloud factor* Mean daily hours cloud cover: January 5.9; June 5.0.

2.2.7 *Relative humidity & precipitation* Design RH during summer 47% (31.5 °C dry bulb, 23 °C wet bulb). Mean annual rainfall 1,216 mm. Mean annual rain days 139.

2.2.8 *Barometric pressure* Range 1005 to 1017 Hpascals at sea level.

2.2.9 *Soil temperature* No data.

2.2.10 *Other meteorological parameters* Prevailing humid NE to SE winds in summer (December, January, February) and early autumn. Cold, dry westerly winds in winter with westerly airflow continuing but warming in spring.

2.2.11 *Comments* Warm humid weather in summer is a difficult adaptive challenge in an office environment where dress codes may limit ability to reduce clothing insulation.

# 3 BUILDING DESCRIPTION

## 3.1 General description

3.1.1 *Building name* Wilkinson Building

3.1.2 *Building type* Tertiary education (Faculty of Architecture)

3.1.3 *History*

The building was constructed in stages from 1960 to 1978. The section in which the study area is located was the last completed. The 25 offices on which the study is focused are naturally ventilated through operable windows and doors. They were fitted out with supplementary cooling and reverse cycle heating equipment at the end of 1997. The offices are also centrally heated with manually controlled wall panel radiators provided as part of the original design.

3.1.4 *Design philosophy for IAQ and thermal comfort, energy efficiency and other issues of concern*

The design philosophy was based on the laissez faire principle that room occupants are the best sensors of thermal comfort and air quality. The Sydney climate is such that for much of the year people can achieve indoor comfort by passive means by way of adaptive behaviours such as adjustment of windows, garment change or change of position. This can however be difficult in the warm to hot summer months of December, January and February. In fact several staff members in rooms without mechanical cooling will admit to adjourning to work in the air conditioned library on hot afternoons; a striking example of behavioural adaptation. The intention behind the design was therefore to allow individuals as much freedom as possible to make decisions and take control action to alter an unsatisfactory condition if required. It was believed that the selected supplementary cooling/heating system would provide an additional degree of freedom but would use less energy than a conventional air conditioning system with centrally controlled temperature operating in an environment of sealed windows because it would be called into use only when considered necessary. A primary requirement of the refrigeration plant was that it has a sophisticated output control system that would act unobtrusively in the background to produce high efficiency across a wide range of loads.

The natural ventilation system in the study area is mainly wind driven through top hinged hopper or awning type windows and internal doors to corridors. Size of windows is based on the rule of thumb principle in the Building Code of Australia that area of operable openings in a room should have a total area equal to 5 percent of the floor area of the room served. Limited stack effect is available by way of narrow high-level windows in some of the rooms. Additional stack driven ventilation is available to offices on levels 2 and 4 through corridors to a small atrium and open stairway extending from ground level to level 5 in the central access core. Night cooling is not available. The system works well at most times of the year without mechanical intervention. Room occupants can operate windows and doors and, when they consider it necessary, can switch on or off the refrigerated reverse cycle fan coil unit(s) and adjust temperature set point, fan speed and direction of air flow in their personal space.

A previous small pilot study had indicated that the system would tend to default to “off”; i.e. if conditions in a room are acceptable then the system is not turned on. It had also shown that energy consumption was likely to be much less than for a conventional mechanical cooling, heating and ventilating system. Ventilation can be said to be "demand controlled" inasmuch as occupants' open or close windows as they see fit to maintain necessary ventilation. In practice, many of them prefer to open windows and doors in pleasant weather but close them when hot dry or warm humid winds occur in summer or on the colder days in winter.

The supplementary cooling/heating system was designed to handle cooling and heating loads with indoor temperatures held at 24 °C (summer) and 20 °C (winter) under Sydney outdoor design conditions of 31.5 °C dry bulb, 23 °C wet bulb in summer and 7 °C dry bulb, 80 percent RH in winter. Cooling loads were estimated using CAMEL (Carrier Air-conditioning Method of Estimating Loads)[1] cooling and heating load estimation software. Hour by hour energy simulation was performed using Beaver/ESP[2] software to estimate energy consumption that would be expected if the spaces were mechanically heated, cooled and ventilated. Results of this simulation are compared with actual month by month energy consumption as indicated in figure 4.

### *3.1.5 Comments*

Results to date indicate that occupants perceive thermal comfort and air quality better than reported by people in 36 other (mainly air conditioned) settings. Energy consumption over four years has averaged about a quarter of what would be expected if the spaces were conventionally air conditioned with mechanical heating, cooling and ventilation.

## 3.2 Building geometry & materials

### *3.2.1 Plan*

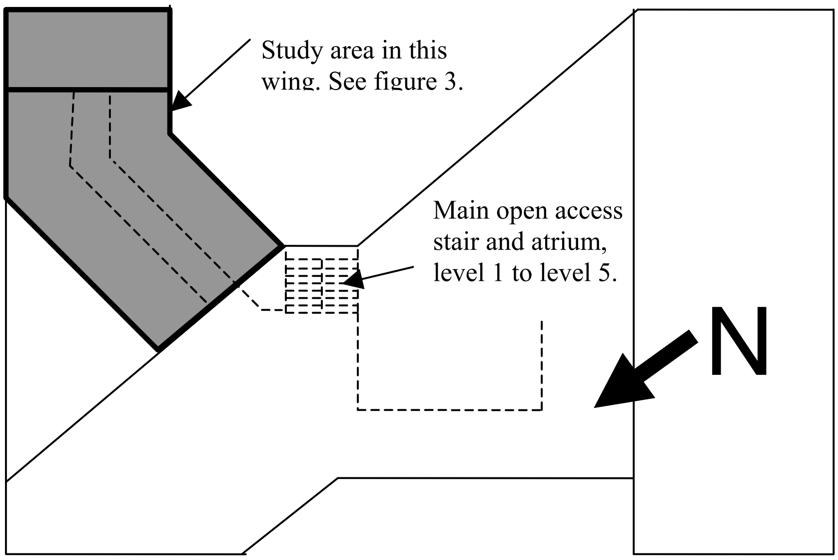


Figure 2. Block plan showing relationship of study area to the whole building and the central access stair and atrium. Not to scale.

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[1] Sourced from ACADS/BSG Ltd. High Street, Glen Iris, Victoria.

[2] Ibid.

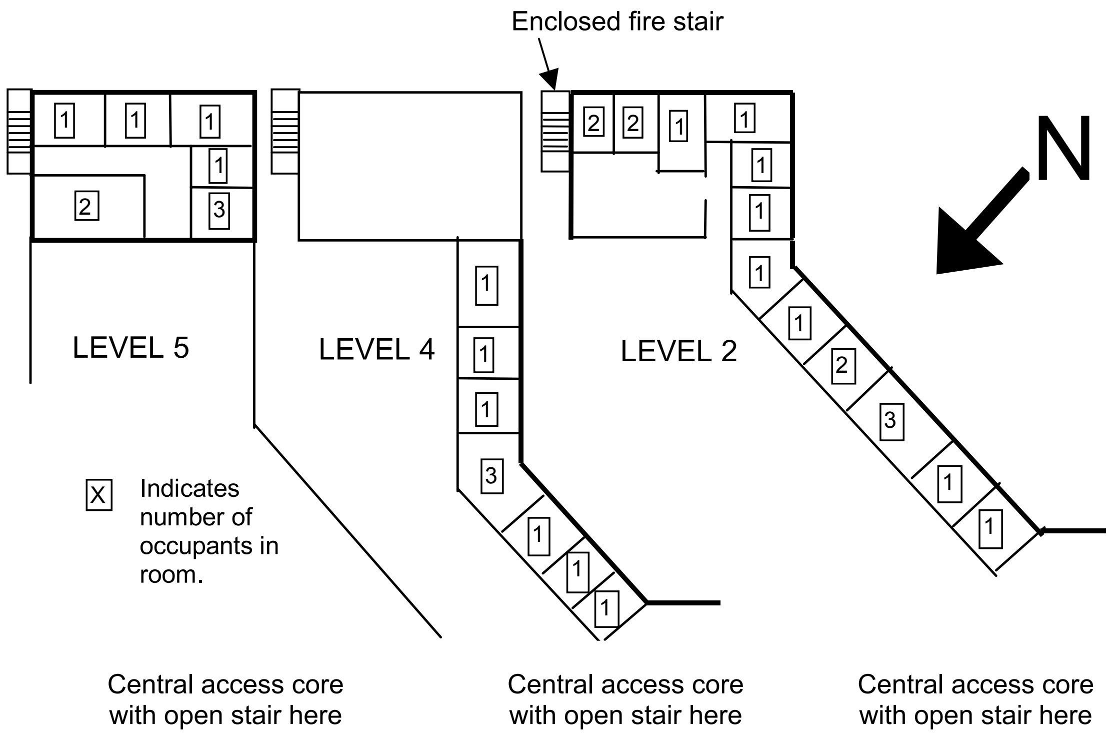



Figure 3. Plan of study areas on levels 2, 4 and 5.

Not to scale.

3.2.2 *Elevation* Not available but please see photographs for typical details.

3.2.3 *Building form* Total building height 20 metres with five levels. The retrofit study areas are on levels 2, 4 and 5 as indicated in figures 2 and 3. The building has flat roofs of reinforced concrete with three wings radiating from a central service and access core containing the main stairwell, single lift and a small atrium extending from level 1 to level 5 as shown in figure 2

3.2.4 *Volume The volume of the whole building is approximately 12,000 m$^3$. Effective volume of the retrofit area is 1,290 m$^3$. The air-cooled condensing unit for the supplementary VRF cooling/heating system is mounted on the roof over level 4 of the northeast-southwest wing and occupies no internal space. Refrigerant and condensate piping runs are surface mounted above head height in corridors and rooms. Droppers between floors are enclosed in existing service ducts. Fan coil evaporators are wall mounted in the rooms. Condensate is drained to existing drains or onto roofs. A small switchboard is located in an existing electrical cupboard on level 4 and a central indicator and control panel is wall mounted in a level 4 corridors. Internal volume occupied by the installation is negligible.*

3.2.5 *Floor area & materials*

Gross floor area of the pilot project is 430 m$^2$. This does not include access corridors or passages.

Net useable floor area (NFA) is the same as the gross floor area.

Floors are of 150 mm thick reinforced concrete with underfelt and carpet. U-value 1.08 W/m$^2$K.

3.2.6 *Ceiling height:* Varies from 2,700 to 3,500 mm.

Roof over level 4 is of 150 mm reinforced concrete with waterproof membrane, 50 mm expanded polystyrene insulation and 50 mm coarse gravel with ceiling of timber boarding below a 100 mm. air space. U-value is 0.322 W/m$^2$K. Area is 75 m$^2$.

The roof over level 5 is of 150 mm unlined reinforced concrete with waterproof membrane. U-value is 1.094 W/m$^2$K. Area is 108 m$^2$.

### 3.2.7 Facades (external walls)

Level 5

- Southeast: total area 48 $m^2$. Spandrel of double brick with area 10.8 $m^2$, U-value 2.02 $W/m^2K$. Glazed area above spandrel including operable windows with total glass area 37.2 $m^2$, U-value 5.9 $W/m^2K$.
- Southwest: total area 36 $m^2$. Spandrel of double brick with area 8.1 $m^2$, U-value 2.02 $W/m^2K$. Glazed area above spandrel including operable windows with total glass area 27.9 $m^2$, U-value 5.9 $W/m^2K$.
- Northwest: total area 48 $m^2$. Spandrel of double brick with area 6.3 $m^2$, U-value 2.02 $W/m^2K$. Glazed area including operable windows with total glass area 41.7 $m^2$, U-value 5.9 $W/m^2K$.

Level 4

- Southwest: total area 48 $m^2$. Spandrel of double brick with area 8.1 $m^2$, U-value 2.02 $W/m^2K$. Glazed area above spandrel including operable windows with total glass area 39.9 $m^2$, U-value 5.9 $W/m^2K$.
- South: total area 48 $m^2$. Spandrel of double brick with area 8.7 $m^2$, U-value 2.02 $W/m^2K$. Glazed area above spandrel including operable windows and doors to courtyard on roof over level 3 with total glass area 39.3 $m^2$, U-value 5.9 $W/m^2K$.

Level 2

- Southeast: total area 48 $m^2$. Spandrel of double brick with area 6.3 $m^2$, U-value 2.02 $W/m^2K$. Glazed area including operable windows with total glass area 41.7 $m^2$, U-value 5.9 $W/m^2K$.
- Southwest: total area 44 $m^2$. Spandrel of double brick with area 9.9 $m^2$, U-value 2.02 $W/m^2K$. Glazed area above spandrel including operable windows with total glass area 34.1 $m^2$, U-value 5.9 $W/m^2K$.
- South: total area 88 $m^2$. Spandrel of double brick with area 19.8 $m^2$, U-value 2.02 $W/m^2K$. Glazed area above spandrel including operable windows with total glass area 68.2 $m^2$, U-value 5.9 $W/m^2K$.

### 3.2.8 Windows

Level 5

- Southeast: total area 5.4 $m^2$ (included in glass wall described above). Six operable hopper or awning type windows of 1,000 by 600 mm set in metal frames above spandrel with six smaller hopper windows above a metal head rail. Operable windows have flexible seal around edges for tight closure. U-value 5.9 $W/m^2K$. External shading from roof overhang 600 mm wide.
- Southwest: total area 3.6 $m^2$ (included in glass wall described above). Four operable hopper or awning type windows of 1,000 by 600 mm set in metal frames above spandrel with four smaller hopper windows above a metal head rail. Operable windows have flexible seal around edges for tight closure. U-value 5.9 $W/m^2K$. External shading from roof overhang 600 mm wide.
- Northwest: total area 3.6 $m^2$ (included in glass wall described above). Four operable hopper or awning type windows of 1,000 by 600 mm set in metal frames above spandrel with four smaller hopper windows above a metal head rail. Operable windows have flexible seal around edges for tight closure. U-value 5.9 $W/m^2K$. External shading from roof overhang 600 mm wide.

Level 4

- Southwest: total area 4.8 $m^2$ (included in glass wall described above). Eight operable hopper or awning type windows of 1,000 by 600 mm set in metal frames above spandrel. Operable windows have flexible seal around edges for tight closure. U-value 5.9 $W/m^2K$. Horizontal external shading by concrete overhang 600 mm wide.
- South: total area 3.6 $m^2$ (included in glass wall described above, plus with an external door to each of the four rooms, leading to a courtyard, described in item 3.2.9 below). Four operable hopper or awning type windows of 1,000 by 600 mm set in metal frames above spandrel with four smaller hopper windows above a metal head rail. Operable windows have flexible seal around edges for tight closure. U-value 5.9 $W/m^2K$. Horizontal external shading by concrete overhang 600 mm wide.

Level 2

- Southeast: total area 4.8 $m^2$. (included in glass wall described above). Eight operable hopper or awning type windows of 1,000 by 600 mm set in metal frames above spandrel. Operable windows have flexible seal around edges for tight closure. U-value 5.9 $W/m^2K$. No external shading.
- Southwest: total area 3.6 $m^2$. (included in glass wall described above). Six operable hopper or awning type windows of 1,000 by 600 mm set in metal frames above spandrel. Operable windows have flexible seal around edges for tight closure. U-value 5.9 $W/m^2K$. Some external shading from adjacent trees.
- South: total area 5.4 $m^2$ (included in glass wall described above). Six operable hopper or awning type windows of 1,000 by 600 mm set in metal frames above spandrel with four smaller hopper windows above a metal head rail. Operable windows have flexible seal around edges for tight closure. U-value 5.9 $W/m^2K$. Some external shading from adjacent trees.

### 3.2.9 External doors or hatches

Level 4

- South: total area 7.0 $m^2$ (one door to each of four rooms included in glass wall described above, leading to a courtyard on roof over level 3). The doors are metal framed and fully glazed. They have weather strips and flexible seals around edges for tight closure. U-value 5.9 $W/m^2K$. Horizontal external shading by concrete overhang 600 mm wide.

### 3.2.10 Number, volume and layout of rooms

25 rooms used as offices for academic and administrative staff. Total volume 1,290 cubic metres. Layout as shown in figure 3.

### 3.2.11 Attic, basement, crawlspace

None.

### 3.2.12 Interior walls, including moveable partitions

All internal partitions are of unrendered single brick 110 mm thick. U-value 3.06.

### 3.2.13 Interior doors and devices

Each room has an interior door leading to an access corridor.

### 3.2.14 Stairwells

The study area is served by an open stairway in the central core area and an enclosed fire safe stair at the east wing of the building as indicated on plan, figures 2 and 3.

### 3.2.15 Service risers

One elevator shaft in central access core with ventilation opening in roof of motor room. Several risers are grouped in the central core for electrical mains, fire and hydraulic service pipes and ducts for mechanical ventilation to tutorial studios. They are blocked at each floor with concrete slabs.

### 3.2.16 Comments

The building is of heavyweight construction with double brick or precast concrete panel outer walls, single brick interior partitions and reinforced concrete floors and ceilings. The roof over level 4 offices is insulated with 50 mm polystyrene with coarse gravel overlay. The concrete roof slab over level 5 offices is uninsulated. This produces a significant radiant heat load, which is uncomfortable in summer but welcome in winter. Ceilings on levels 2 and 4 are lined with timber boarding with natural finish. Building materials are mostly natural timber, brick and concrete with wool carpet on floors. Most indoor brickwork is not painted. Furnishing materials are mostly manmade of with desks of particle board and chairs upholstered with plastic materials. Most shelving is fabricated from steel. Ceiling heights vary from 2700 mm to 3500 mm. The fan coil units provide air movement with very low noise levels. The building is located on a busy highway but the rooms in the study area are oriented away from the road. Security risk due to the ventilation system is low as most windows are well above ground level and are usually closed at night for protection from rain.

## 3.3 Air leakage data (type, location and crack length for each component)

### *3.3.1 Doors* No data but external doors are metal framed and fitted with flexible seals and weatherstrips.

### *3.3.2 Windows* No data. Metal framed and fitted with flexible seals.

### *3.3.3 Ventilation openings & stacks* No data

### *3.3.4 Chimneys & flues* No data

### *3.3.5 Communicating walls, such as cavity walls* No data but fairly high leakage would be expected through walls, which are not rendered internally or externally.

### *3.3.6 Structural joints: sole-plate, ceilings, corners, skirting boards, vapour and air barrier treatments* No data

### *3.3.7 Service routes: plumbing outlets, drains, electrical outlets, etc.* No data

### *3.3.8 Other air leakage zones such as stairwells & service risers* No data

### *3.3.9 Background leakage* No data

### *3.3.10 Neutral pressure level* Not known

### *3.3.11 Comments*

No data available but it would seem that leakage is quite high because the average concentration of $CO_2$ measured in July 2001 was 930 ppm although windows were not open in any of the rooms sampled.

## 3.4 Wind pressure coefficients Not known.

## 3.5 Space heating

Background heating is available in the study area by way of manually controlled wall panel radiators served from a natural gas fired central hot water heating system. Supplementary heating for offices in the study area is available from the reverse cycle refrigerated supplementary cooling/heating system. When a detailed thermal comfort survey was conducted in July 2001 (mid winter) none of the rooms sampled was using either the background or supplementary systems.

Capacity of the supplementary refrigeration system for the rooms in the study area is 87 kW cooling. The condensing set is air-cooled. The system was installed in November 1997 and circulates refrigerant R22 to the rooms on the system. The equipment is now available with zero ozone depletion refrigerants but these were not available when the equipment was manufactured.

A natural gas fired central heating boiler supplies hot water to panel radiators in most of the cellular offices in the building and to heating coils in the mechanical ventilation systems in the tutorial studios. Three lecture theatres, several computer laboratories and the library are air-conditioned

## 3.6 Ventilation

### *3.6.1 Ventilation principle*

Ventilation of rooms in the study area is mainly wind driven cross flow from windows through doors to corridors. Stack effect is also available for the rooms on levels 2 and 4 via internal doors, corridors and the open stairway and atrium from level 1 to level 5. Doors on level 5 leading to the roof are kept open on fine days providing a clear path to outdoors. Windows are the main source of ventilation throughout the year.

### *3.6.2 Components*

On levels 2 and 4 airflow is through windows, across rooms to corridors and along corridors to central stair and atrium and through an external door leading to the roof over level 4. On level 5 flow is through windows and internal doors to corridor and through an external door to the roof over level 4.

*3.6.2.1 Fresh air inlets*

Hinged awning or hopper type windows operated by room occupants to provide ventilation as described in 3.6.1.

*3.6.2.2 Fans*

No fan assistance provided for ventilation in study area offices. Cooling system performance could possibly be improved by installing small thermostatically controlled propeller fans in windows to operate for nighttime cooling of the structure.

*3.6.2.3 Heat recovery* No heat recovery equipment.

*3.6.2.4 Filtration* No filtration of outdoor air. Fan coil units have coarse washable panel filters operating on recirculated room air.

*3.6.2.5 Ducts*

No ducts.

*3.6.2.6 Room supply & extract devices*

Windows and doors as described in 3.6.1.

*3.6.2.7 Air exhaust outlets*

Doors on levels 4 and 5.

### 3.6.3 *Frequency of operation, duration of operating cycle:* Fan coil units in rooms are operated as required by occupants. The supplementary cooling/heating system is disabled at 9 pm and midnight each day to save operation after rooms are vacated. The system is however immediately available for re-start if required in any room.

### 3.6.4 *Balancing report*

No balancing required.

### 3.6.5 *Ventilation rate (outdoor airflow supplied by system):* Variable depending of adjustment of windows but average $CO_2$ concentration of 930 ppm measured in winter when most windows were closed suggests a rate of more than 7.5 l/s. per person.

### 3.6.6 *Any recirculation between rooms due to HVAC system:* No.

### 3.6.7 *Space cooling*

Space cooling is available on demand from the supplementary system as described herein. Night "free" cooling is not available but could be provided quite easily by installing a window mounted, thermostatically controlled propeller fan in each room to circulate cool air at night.

### 3.6.8 *Comments:* Surveys of occupants have shown that they are well satisfied with air quality, please see figure 6 (ii). It seems likely that their perception of it is influenced by their ability to adjust windows and limit temperature rise in rooms as desired.

## 3.7 Internal loads

### 3.7.1 *Pattern of occupancy*

The building is open from 8 am to 9 pm during autumn and spring semesters of 16 weeks each and from 8 am to 6 pm at other times. Staff have key card access to the building at all times Rooms can be unoccupied for lengthy periods when members of staff are absent on recreation or study leave. Average occupancy is estimated at 70 percent. Numbers of occupants in rooms are indicated in figure 3. Average space per person is 14 $m^2$.

### 3.7.2 *Lighting*

Lighting gain approximately 20 watts/ $m^2$; Electric lights are controlled manually by switches in each room. Because each room has large windows it is not unusual to find electric lights off with occupants relying on daylight during daytime.

### 3.7.3 *Other internal gains*

Each room has at least one computer with estimated heat output of 200 watts.

## 3.8 Control system and control strategy for ventilation and space conditioning

*3.8.1 Type of system:* Semi-automatic. Each occupant can manually adjust windows and doors to suit personal requirements; and can manually switch on or off the supplementary cooling/heating system as required. When in use the refrigeration cycle in the supplementary system is under the control of a proprietary system, which monitors system pressures and adjusts refrigerant flow to suit the current load. The condensing unit consists of six interconnected modules. One of these has an inverter variable speed drive. This module starts first and its speed increases till it is fully loaded. On further load increase a fixed speed module starts and the variable speed module returns to its lowest speed. This cycle is repeated as the load increases until all modules are operating. When a fan coil unit in a room is in use its output is controlled by at thermostat sensing temperature of air either in the return air stream or at the room control unit and controlling the operation of a modulating refrigerant flow control valve. The occupant of a room is able to adjust room temperature set point manually and also to select one of two fan speeds and the direction of airflow from the unit. Fan coil units are disabled by the proprietary central control system at 9 pm and again at midnight as an energy saving measure. Availability is restored immediately to enable after hours use if required.

### *3.8.2 Parameters monitored*

Ventilation rate is controlled manually by adjustment of windows and doors by occupants as required. When the supplementary system is in use its operation is under the control of a dry bulb room air thermostat.

### *3.8.3 Sensors*

Daikin proprietary temperature sensors are located in the return air path in fan coil units and in the room controllers. Either can be selected to suit room geometry.

### *3.8.4 Control strategy & internal design conditions*

The control strategy is laissez faire; occupants are at liberty to use windows, doors, window blinds and supplementary cooling or heating within each room as they see fit. Thus operating temperature in a room is at the discretion of the room occupant(s). Ventilation supply temperature is not controlled but depends entirely on outdoor conditions. Ventilation rate varies depending on adjustment of windows and doors as perceived necessary by occupants.

### *3.8.5 Lessons Learned*

- The system is simple and easily comprehended by occupants who, for the most part, tend to use the supplementary cooling/heating as a facility of last resort. Occupants have rated thermal comfort, air quality, overall comfort and effect on performance of work highly in comparison with 36 other office settings. Prevalence of symptoms commonly associated with "sick building syndrome" is low by comparison. More details of these findings will be provided in section 3.13. Energy consumption is about a quarter of what would be expected in the same space if it were conventionally air conditioned with fixed windows.
- Some difficulties were experienced with the heating mode because factory settings resulted in refrigerant supply to fan coil units being reduced to a minimum when set point was satisfied. At the same time the circulating fan in the unit stopped and the air flow direction control blade parked in the horizontal position. When under the control of the return air thermostat in a room with a high ceiling this resulted in stratification of the air with a pool of very warm air near the ceiling maintaining temperature above the set point while the air was too cool at floor level. This was corrected by an adjustment to the control software to park the air directional blade in the vertical position and keep the fan running.
- The proprietary control system allows selection of a control mode that will maintain the same set point temperature in all rooms that are using the cooling/heating system. This mode was not selected as previous experience with a smaller but similar system had shown that comfort temperatures vary between individuals and from time to time for an individual. This can lead to a need for compromise when more than one person is using the room. The central set point mode

was chosen in a similar installation in another institution and occupant rating for thermal comfort in it was significantly lower than in this project although the rating for air quality was similar.

- It is firmly believed that the high ratings for comfort and air quality achieved in this setting depend on the simplicity of the control system and level of personal control available to occupants. This in turn depends on single occupancy of most of the rooms. Achievement of such results would be more difficult in open planned space typical of much modern office accommodation.
- The tuning period was negligible. Ten minutes explanation was sufficient to enable the people to use the system effectively and efficiently. The system tends to default to "off" because when one enters a room and finds conditions acceptable one does not then go to a switch to modify them. And when a change is desired the first resort for most people is to adjust a window.

## 3.9 Pollutant sources

*3.9.1 Interior sources* Particle board in desks; manmade upholstery materials for chairs.

*3.9.2 Exterior sources:* The building stands on City Road, the a six lane road which is one of the main routes from the city and northern suburbs to southern suburbs and the south coast, carrying heavy traffic throughout the day and evening. It is therefore exposed to considerable volumes of motor vehicle exhaust gases and ultrafine particulates.

## 3.10 Furniture, interior fittings:

Rooms are furnished with desks, chairs and sometimes occasional tables typical of modern commercial furniture i.e. constructed of manmade materials such as particle board and upholstery materials. Bookshelves are usually of unitary steel construction.

## 3.11 Costs

*3.11.1 Building:* Actual costs are not available for this existing building. The estimated current cost for a building of this type would be in the order of E750 per $m^2$.

*3.11.2 Plant: Value of plant including cost of installation when built in 1997 was approximately E68,000. A dedicated electricity submain was installed from the main switchboard on level 1 to a system distribution board on level 4, which provides supply to the condensing unit and to fan coil units in all rooms on all floors at an additional cost of E8, 550. This was necessary to capture all the energy used by the cooling/heating system. A further E2, 000 was expended on a recording meter to measure all electrical energy consumed by it.*

3.11.3 *Control system: Cost* of the proprietary control system is not know as a separate item but is included in Plant Cost at item 3.11.2. Cost of supply and installation of motion detectors for monitoring room temperatures and occupancy status in each room in the study was E2, 280. This included cost of installation of a temperature sensor in each room and connection to the monitoring system but did not include cost of the sensors digital and analogue data gathering boards or microprocessors required to connect the system to an existing computer which were donated by Honeywell Ltd. Cost of these items is estimated at E3, 800.

## 3.12 Monitoring programme

- **Energy** consumed by the cooling/heating system has been monitored continuously and recorded at half-hourly intervals by a digital recording instrument since the system commenced operation at the beginning of December 1997.
- **Occupant perceptions of comfort and satisfaction** were sampled in August 1997 before the supplementary system was commissioned and again in September 1998 after some 10 months of use. They were again sampled in July 2001, after nearly three years of use. It might be argued that the results of the September 1998 sampling reflected the "Hawthorne" effect. However the July 2001 results are very similar to the set taken nearly three years previously giving confidence that the improvement is genuine.

These surveys were part of a larger work where subjective responses of occupants of 38 office settings were measured. The surveys were based heavily on a methodology described by Vischer (1989)[3]. The survey protocol is attached in appendix A.

- **Health effects.** Concurrently with the surveys of comfort and satisfaction participants were asked to indicate frequency of experience of eight symptoms of malaise or minor ill health. The symptoms listed were sore eyes, headache, runny nose, dry throat, dry skin, lethargy, dizziness and nausea which are commonly associated in the literature with "sick building syndrome".
- **Outdoor weather conditions** used are as recorded by the Australian Weather Bureau at the Sydney Observatory in the Sydney CBD. The observatory is about 5 km from the study site and the microclimates at both places are very similar.
- **Indoor space temperatures** in all rooms in the study area are monitored continuously by a Honeywell Excel 500 building monitoring system and have been recorded on disc since 1 October 2000. Thermocouples in plastic housings are located under desktops to shield them from drafts and direct solar gains and to ensure that the temperatures are measured close to the bodies of seated occupants. This report is based on temperatures in rooms at 3 pm to provide a close approximation of steady state conditions. It is believed that temperatures in occupied rooms must be regarded as acceptable to the occupant(s), given the wide range of adaptive mechanisms available including mechanical intervention. Unfortunately due to a remnant Y2k problem with the recording system some records were lost but recording was recommenced from 31 August 2001 and complete records are available from that date. Sufficient records are available to provide a representative sample covering a full range of temperatures experienced in the moderate Sydney climate throughout the year.
- **Occupancy status** Motion detectors are placed in all rooms in the study area and continuous records have been kept since October 2000. The records are incomplete for the same reason that some indoor temperature records are missing but the remainder match the indoor temperature records referred to above. Where no motion was recorded between 9 am and 3 pm on any day, the room is treated as unoccupied.
- **Use of supplementary cooling/heating system** Room units in use are indicated on the central control panel on level 4. Manual records of status were noted intermittently in sufficient number to enable a relationship with outdoor temperature to be detected.
- **Carbon dioxide concentrations** were measured in ten rooms in the study area in July 2001. Measurement was carried out with a Drager air pump and detector tubes. Funding constraints prevented more frequent sampling.
- **Particulate concentrations** in the size range >0.3μ were measured in ten rooms in the study area in July 2001. The instrument used was a MetOne laser particle counter. Funding constraints prevented more frequent sampling.
- **Volatile organic compounds and microbiological organisms** could not be sampled as intended due to funding constraints.

## 3.13 Results from monitoring programme

- **Energy consumption per annum** for the supplementary cooling/heating system has varied between 21,131 and 22,550 kWh per annum during each of the four years of operation. This is compared with an estimated consumption of 97,017 kWh for a conventional air conditioning system for the same space. The estimate was computed by dynamic simulation using hour-by-hour real weather file for TRY Sydney 1981. Occupancy of the study area is estimated to be 70 percent and this was applied to the simulation as an occupancy diversity factor. Month by month consumption is illustrated in figure 4 below. A serious effort was made to ensure that the estimate is conservative. The computational model was designed to provide a variable air volume air distribution system with outdoor air economy cycles to apply full outdoor air when outdoor dry bulb temperature falls below 21°C. Dead band control of indoor temperatures is applied to limit availability of cooling to occasions when indoor temperatures are above 24 °C and to limit heating availability to occasions when indoor temperatures are below 20

[3] Vischer, J. (1989): “Environmental Quality in Offices”. Van Nostrand, New York.

°C. The model also provides for conditioned air to be supplied from three separate air handling units for north east, north west and south/south west zones. Despite these precautions it cannot be guaranteed that the simulation is an accurate representation of reality. However it is clear that considerable savings have been achieved in comparison with performance of conventional air conditioning plant in conjunction with mechanical ventilation and fixed windows. Monthly energy consumption and cost for the typical year 2001 are shown in table 1 below.

Table 1. Month by month energy consumption of the supplementary cooling/heating system for year 2001

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Energy/mth kWh | 2715 | 2901 | 2468 | 1440 | 1058 | 1509 | 1941 | 1628 | 839 | 1049 | 1252 | 1799 |
| Cost/mth Euro | 143 | 160 | 129 | 84 | 86 | 103 | 113 | 99 | 62 | 58 | 74 | 92 |

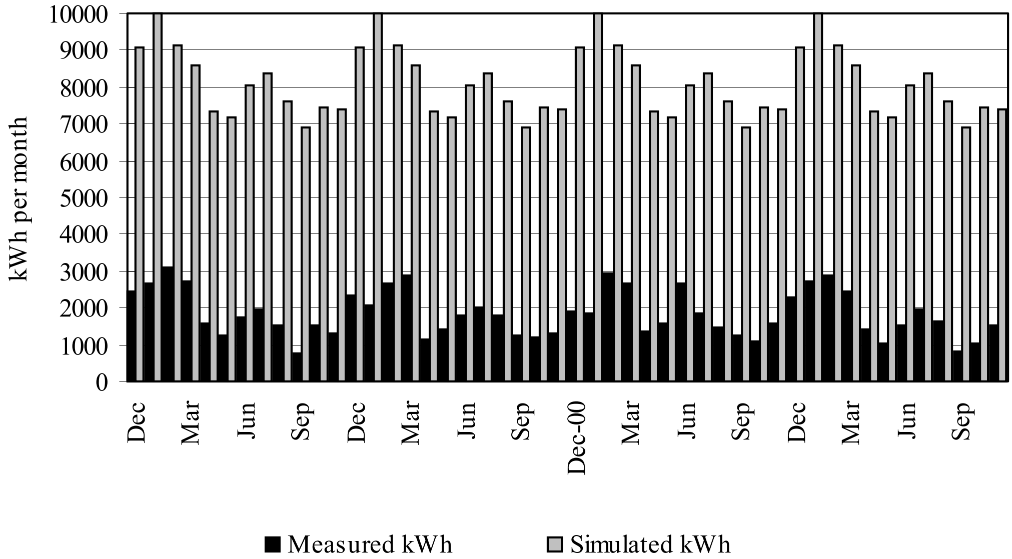



Figure 4. Month by month energy consumption of the supplementary cooling/heating system from December 1997 to November 2001 compared with estimated consumption for a conventional air conditioning system for the same spaces with fixed windows.

A strong binomial relationship is detectable between monthly energy consumption for the supplementary cooling/heating system and outdoor mean monthly temperature. This relationship is illustrated in figure 5 below.

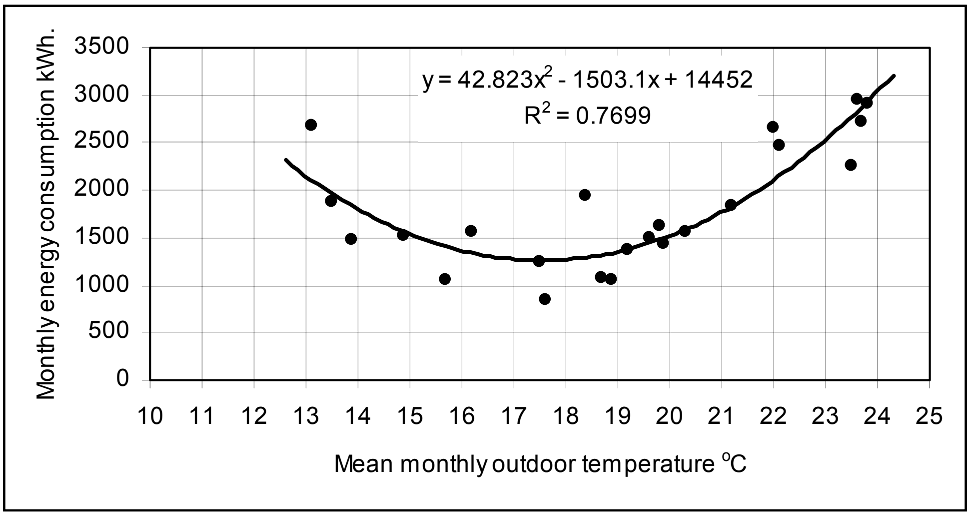
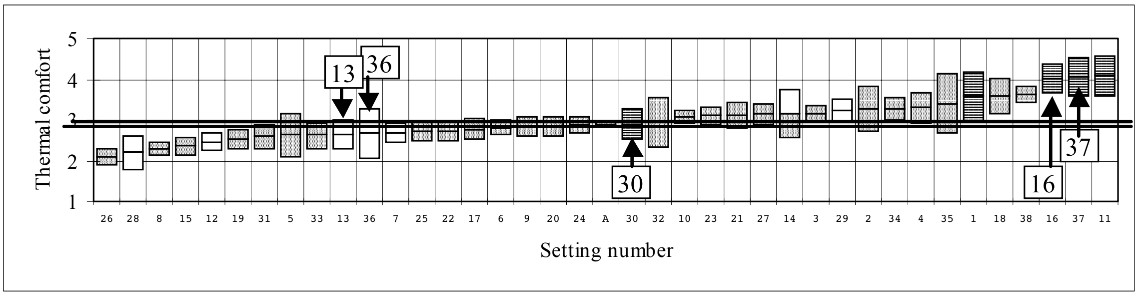



Figure 5. Relationship between monthly energy consumption and mean monthly outdoor temperature.

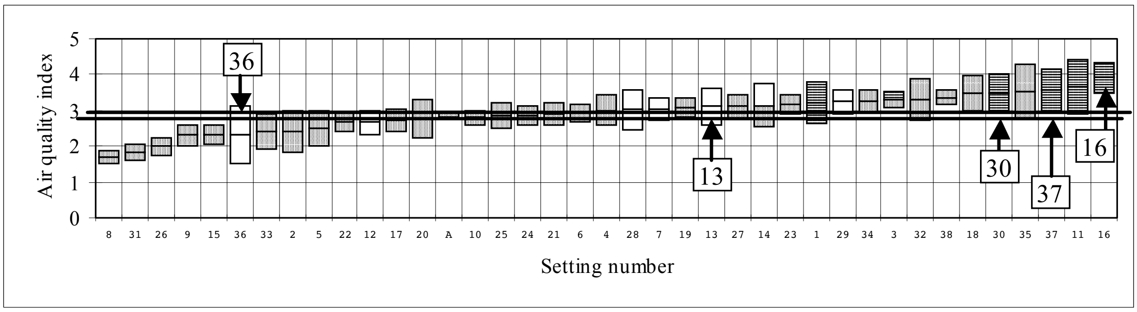
- **Occupant perceptions of comfort and satisfaction** Surveys of occupant comfort and satisfaction in the workplace have been carried out. Participants indicate on scales from 1 to 5 their perceptions of 23 factors relating to their experience of seven vectors as defined by weighted factor analysis by Vischer (1989) where 1 = bad or equivalent and 5 = good or equivalent. The seven vectors are "thermal comfort"; "air quality"; "activity related noise"; "spatial comfort"; "privacy"; "lighting"; and "external or building related noise". The survey also includes two additional stand-alone factors called "overall comfort and satisfaction" and "effect on performance of work". These survey results are used to compute building scores for each vector. Scores are computed by adding the scores for each factor in a vector for each individual and averaging the totals for the group. They are then normalised to a range of 1 to 5. The average of vector scores for the whole population can be regarded as a benchmark if the database is sufficiently representative of the building stock. The factors used to define thermal comfort are "temperature comfort"; "how cold it gets"; "how hot it gets"; and "temperature shifts". For the air quality vector, the factors are "ventilation comfort"; "air freshness"; and "air movement".

  Results of the surveys showing comparison of scores for thermal comfort, air quality, overall comfort and satisfaction and effect of the workspace on performance of work for 38 settings in 33 different buildings are illustrated in figures 6 below. In these illustrations 95 percent confidence intervals are shown as bars and the mean scores are shown as the centres of the bars. The sample includes air conditioned settings shown as grey filled bars, some that are naturally ventilated, shown as open bars and hybrid or mixed mode settings similar to the pilot study setting, shown as bars filled with horizontal hatching. 95 percent confidence intervals for mean scores for the whole sample population of more than 1,500 respondents are shown as heavy horizontal lines.

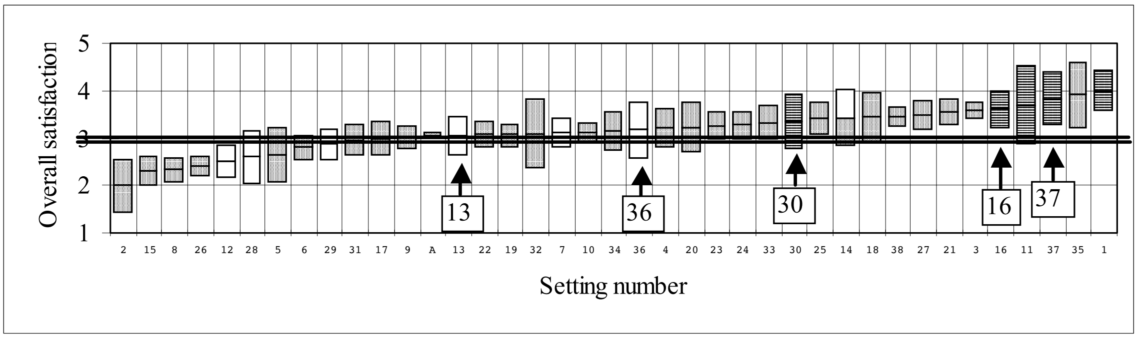
  It can be observed that scores grade smoothly from lowest to highest. If different bar shading were not applied it would be difficult to distinguish air-conditioned examples from hybrid or naturally ventilated. However it is noteworthy that thermal comfort in settings numbers 1, 16, 37 and 11 which are naturally ventilated with supplementary on-demand occupant controlled cooling/heating systems all stand high in the rating spectrum. Setting 30 which has a climate control system very similar to that in the study project number 37 but has centrally set common winter (22 °C) and summer (24 °C ) temperatures is not rated as highly for thermal comfort but stands high in the air quality spectrum. The ratings for thermal comfort and air quality in the study area are significantly above the whole population average at the 95 percent confidence level. It should be noted that most of the rooms in the subject setting have only one occupant who is therefore able to select control settings to suit personal requirements without consideration of the needs of others.



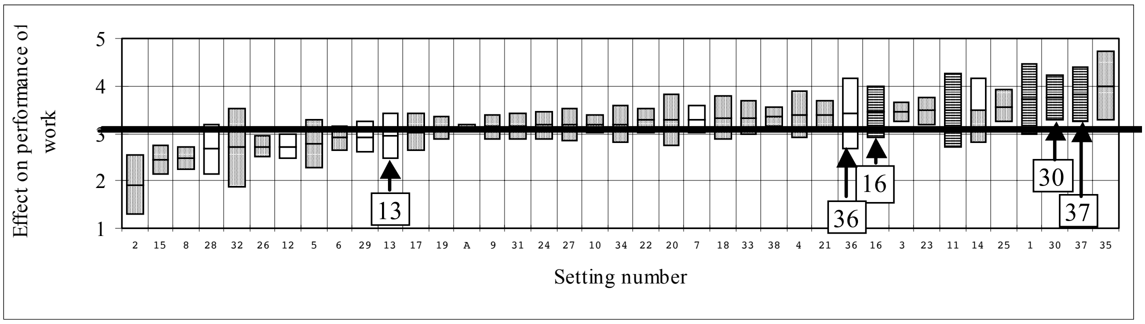

(i) Thermal comfort




(ii) Air quality




(iii) Overall comfort




(iv) Effect on performance of work

Figure 6. Comparison of ratings for some comfort vectors between the study setting and those from a representative sample of Australian buildings.

Please note the differences between scores for settings 16 (September 1998) and 37 (July 2001) which are from the study area and 13 (August 1997) and 36 (July 2001), which are from similar areas in the Wilkinson building but lack supplementary cooling/heating.

Regression analysis was performed to investigate relationships between some of the comfort and health vectors comfort and the relationships are illustrated in figure 7 below.

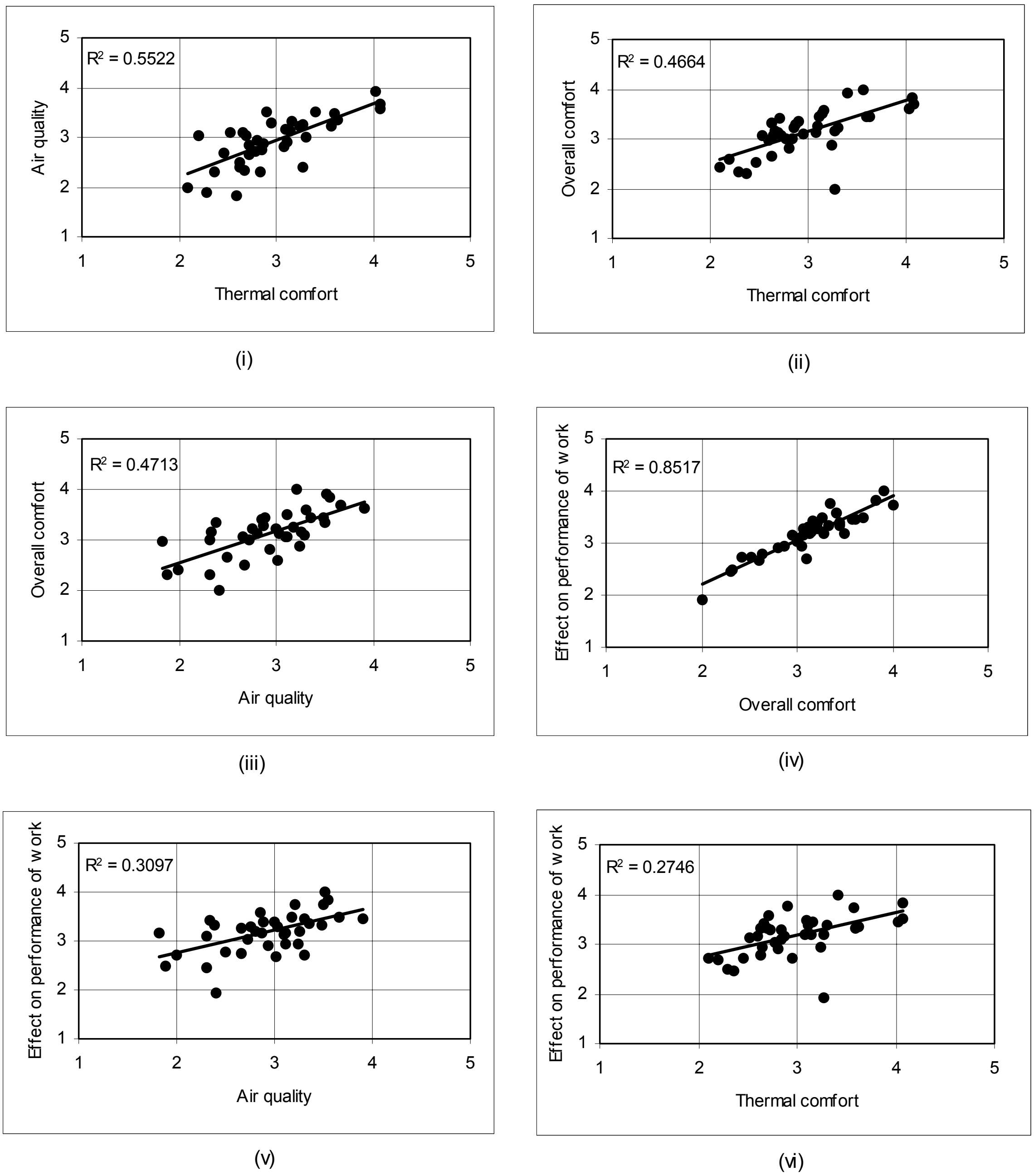



Figure 7. Relationships of varying strength are detectable between thermal comfort, air quality, overall comfort and effect on performance of work.

Figure 7 indicates a strong relationship between perceptions of overall comfort and satisfaction and self-reported effect of the space on performance of work as would be expected. Influence of perceptions of the correlated thermal comfort and air quality on overall comfort and performance of work are weaker and are diluted by other vectors such as spatial comfort, privacy and activity related noise. Nevertheless it would seem that perceptions of thermal comfort and air quality have a real influence and attention to them could be expected to produce worthwhile improvement in productivity.

- **Health effects** Combined rating for prevalence of eight symptoms of malaise or minor ill health often associated in the literature with "sick building syndrome" as self-reported by occupants of 38 office settings are shown in figure 8 below. Prevalence is reported on a scale from 1 to 5 where 1 = never experienced; 2 = rarely; 3 = once per week; 4 = twice per week; and 5 = daily. Scores for each person are totalled and the total for the setting is averaged and normalised to a range of 1 to 5 as for the comfort scores. Results are illustrated in figure 8 below. As in figure 6 mean scores are at centres of bars with ends of bars indicating upper and lower 95 percent confidence limits. Heavy horizontal lines represent the 95 percent confidence limits for the whole population mean. Inspection shows that settings 16 and 37 are among the lowest. It is noteworthy that mean prevalence scores for hybrid and naturally ventilated settings are all below the whole population average. Scores for many of the air conditioned examples are at the higher end of the spectrum although if the definition of SBS is taken to include excessive symptom prevalence in relation to the whole population only settings 8 and 26 would warrant further investigation with ratings significantly higher than the population average at the 95 percent confidence level.

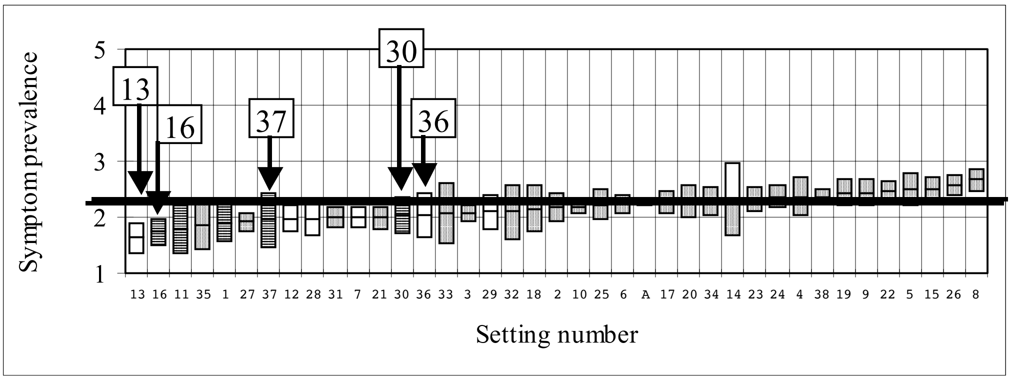
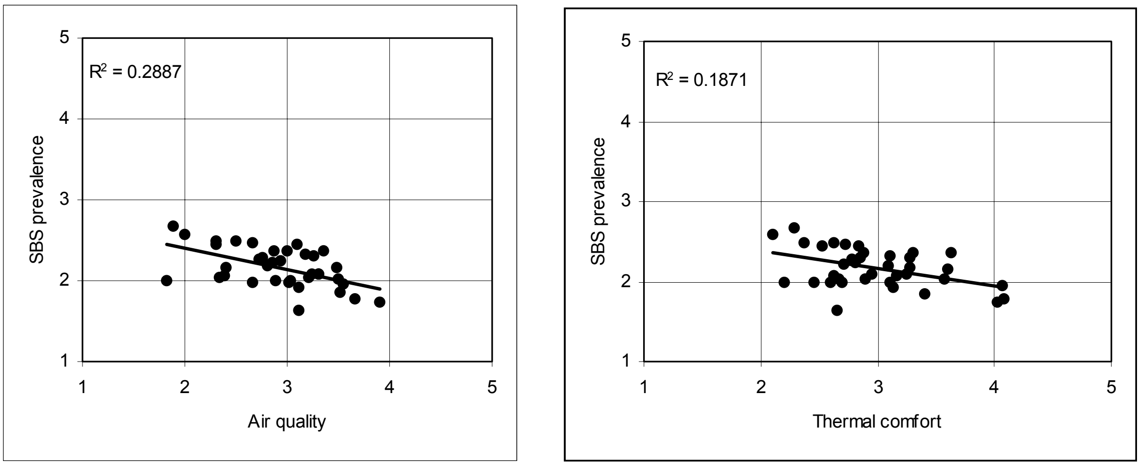



Figure 8. Comparison of ratings for prevalence of SBS symptoms between the study setting and those from a representative sample of Australian buildings.

Regression analysis has been applied to examine the relationship, if any, between symptom prevalence and perceptions of air quality and thermal comfort. Results are shown in figure 9 below. Associations are detectable but are weak, particularly in the case of thermal comfort.

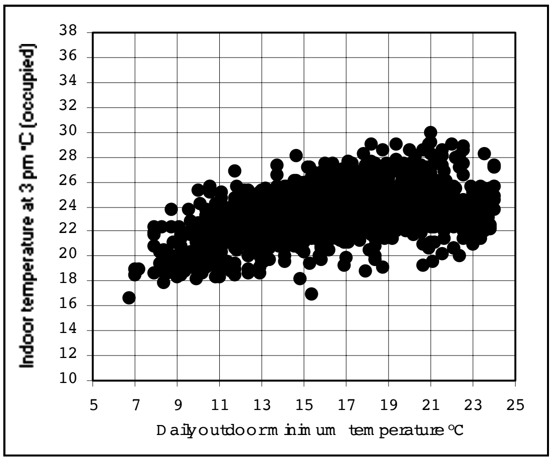



(i) SBS/air quality

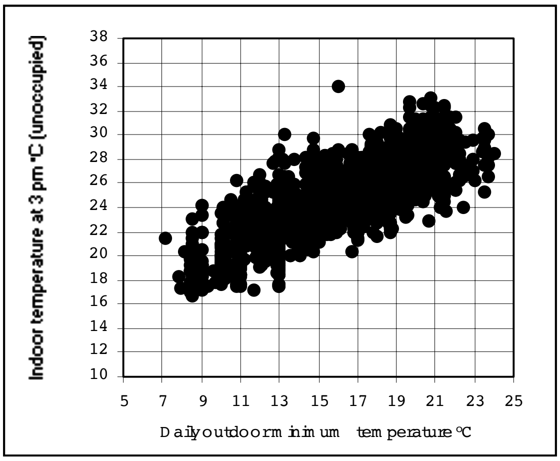
(ii) SBS/thermal comfort

Figure 9. Relationships between SBS symptom prevalence and perceived air quality and thermal comfort.

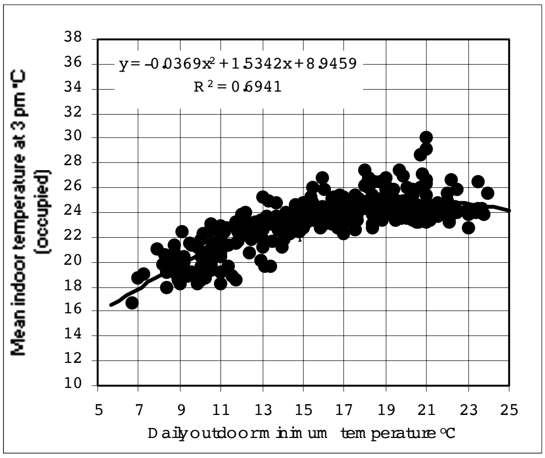
- **Indoor space temperatures** are strongly related to outdoor temperatures as illustrated in figure 10 below.



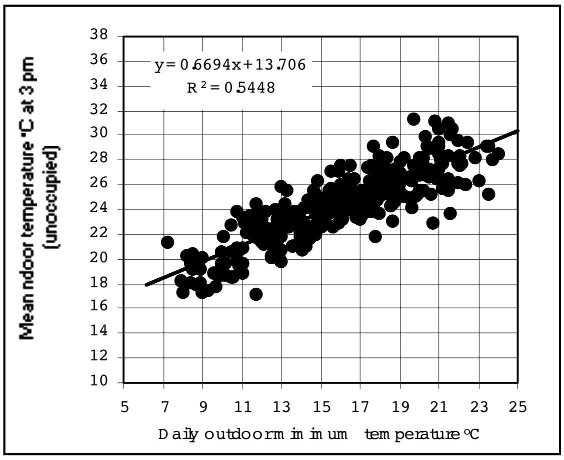

(i) Indoor temperatures in occupied rooms at 3 pm.



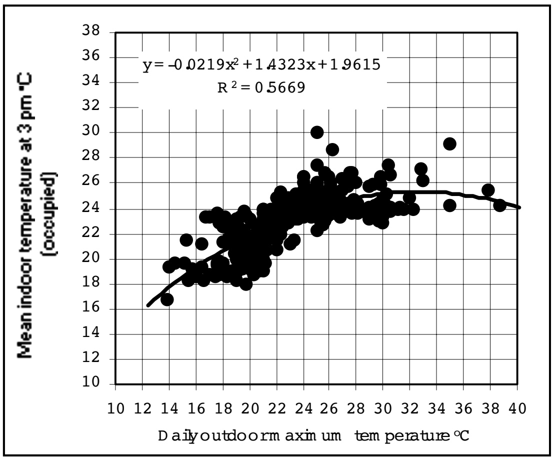

(ii) Indoor temperatures in unoccupied rooms at 3 pm.



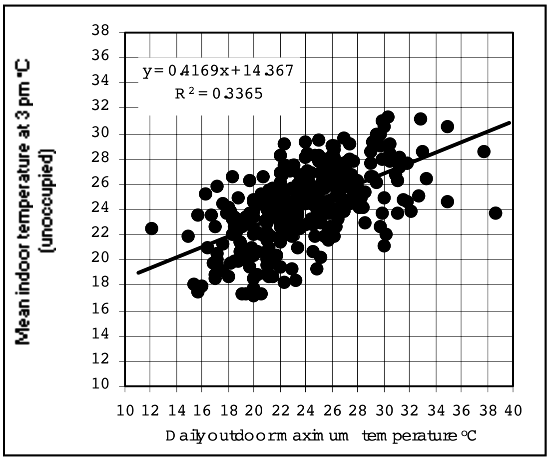

(iii) Mean indoor temperatures in occupied rooms at 3 pm.




(iv) Mean indoor temperatures in unoccupied rooms at 3 pm.




(v) Mean indoor temperatures in occupied rooms at 3 pm.



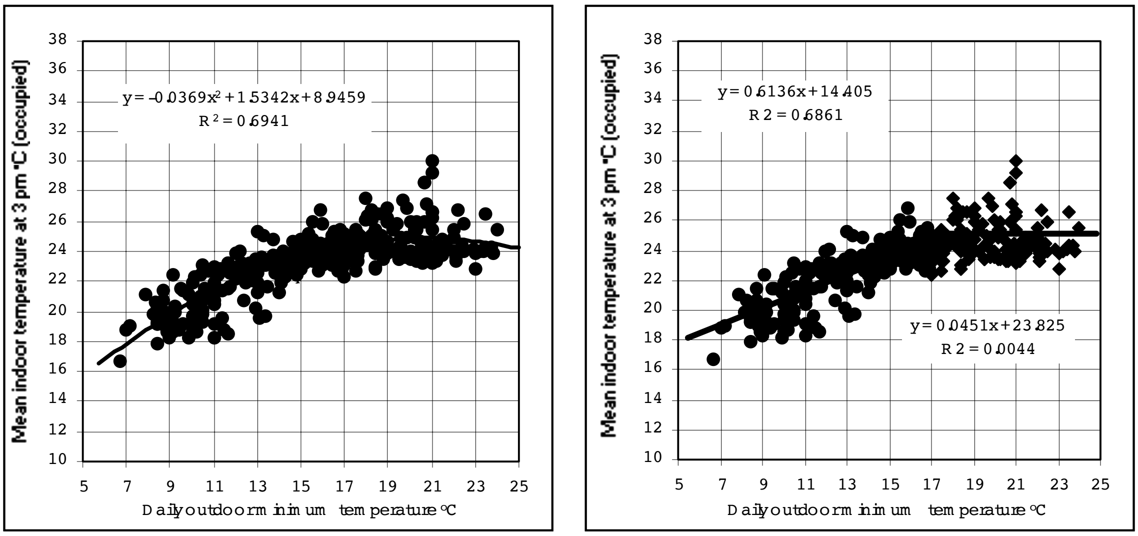

(vi) Mean indoor temperatures in unoccupied rooms at 3 pm.

Figure 10. Associations between indoor and outdoor temperatures in occupied and unoccupied rooms.

As would be expected, warmer outdoor conditions are accompanied by increase in indoor temperatures. The plot for unoccupied rooms in figure 10 (ii) above shows a continuous approximately linear relationship. However the curvature in the pattern of points for occupied rooms in figure 10 (i) suggests that occupants accept the increase to a point when they intervene to limit indoor temperature rise. It also indicates the range of temperatures that are accepted in the various rooms varies across a daily range of as much as 8 $^{o}$C.

Figures 10 (iii) and 10 (iv) show the scatter of indoor daily mean temperatures in occupied and unoccupied rooms respectively plotted with daily minimum outdoor temperature as the independent variable. Regression analysis shows a strong binomial relationship with temperatures in occupied rooms ($R^2$ = 0.69). The relationship with temperatures in unoccupied rooms is linear and somewhat weaker ($R^2$ = 0.54). Weaker relationships with daily maximum temperatures are shown in figures 10 (v) and (vi), possibly because daily minimum temperatures in Sydney are less variable than maxima and the effect of variations in maxima is dampened by the thermal inertia of the building. This is convenient because the day minimum occurs before the daytime occupancy begins. The relationship might therefore be useful as a control algorithm. But it has limitations. If extrapolated below the observed range it is likely to indicate temperatures that will be unacceptably low. And if extended above the range it will suggest unnecessarily lower acceptable indoor conditions as outdoors temperatures continue to raise.

The indoor minima were therefore divided into two ranges of indoor temperatures in occupied rooms, up to 17 $^{o}$C and upward from 17 $^{o}$C. Linear regression was applied separately to each as indicated in figure 11 and it will be observed that the relationship is as strong for the lower range as it was under binomial regression whilst there is no significant relationship for the upper range. Also the slope of the regression line for the lower range is very similar to that for the unoccupied rooms. This suggests that mechanical intervention is not applied until necessary to limit indoor temperatures to a range between 22 $^{o}$C and 28 $^{o}$C. It also suggests that a control strategy that does not allow mechanical cooling until day minimum temperature reaches 16 $^{o}$C to 17 $^{o}$C might be acceptable to a majority of occupants. Although not defined in this work, it seems likely that a similar lower limit would be found to apply to outdoor and indoor temperatures below the range encountered in this study.




(i) Mean indoor temperature at 3 pm. Binomial regression with daily outdoor minimum temperature as independent variable.

(ii) Mean indoor temperature at 3 pm. Linear regressions with daily outdoor minimum temperature as independent variable.

Figure 11. Comparison of binomial and linear relationships between indoor and outdoor temperatures.

Considerable day to day variation in temperatures recorded in individual rooms is illustrated in records from five typical rooms as illustrated in figure 12 below. The reason(s) for these variations are not clear. They may be accounted for by passive adaptive actions by the room occupant or may be a result of higher tolerance of variation in the knowledge that action to change the temperature can be taken at any time.

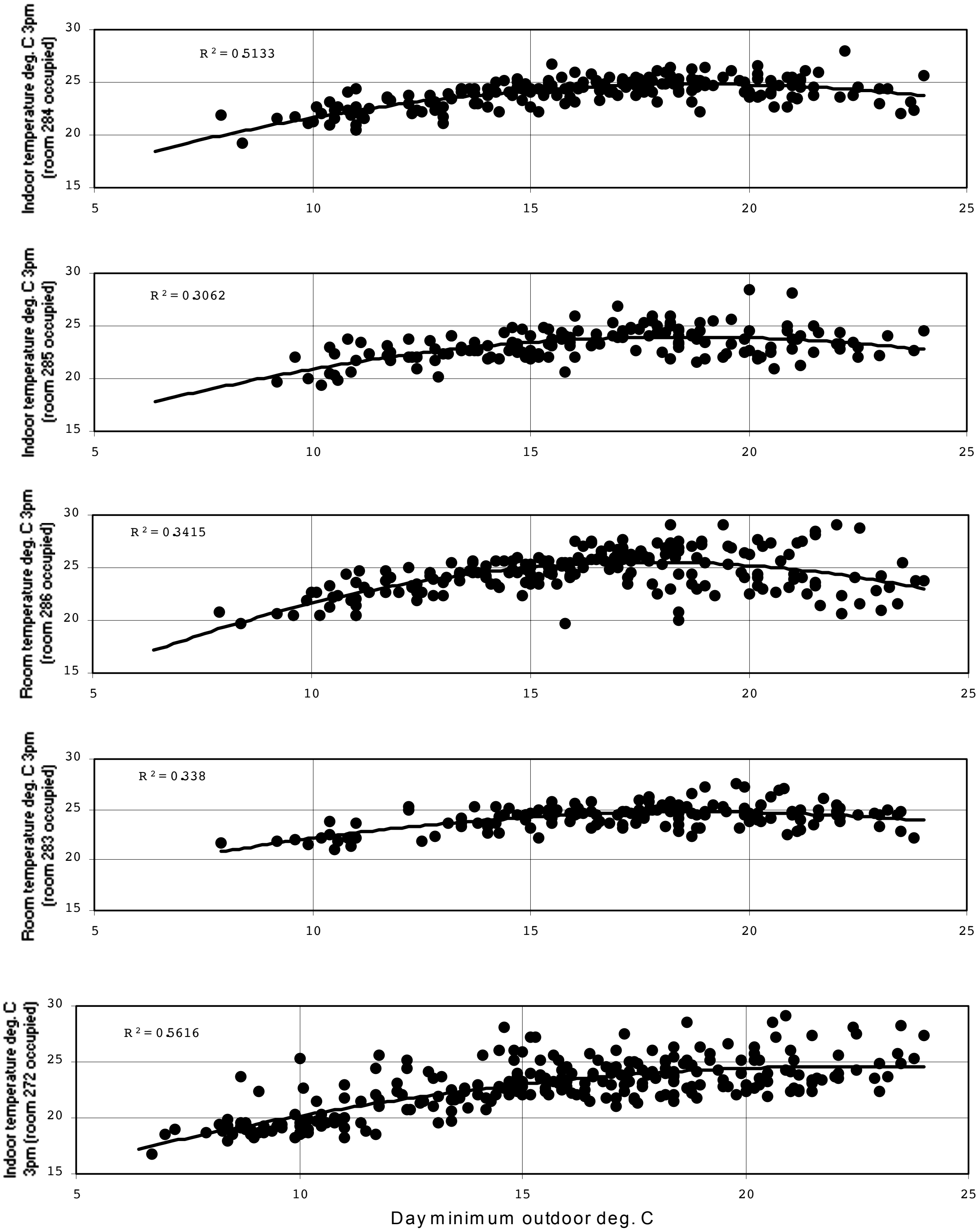
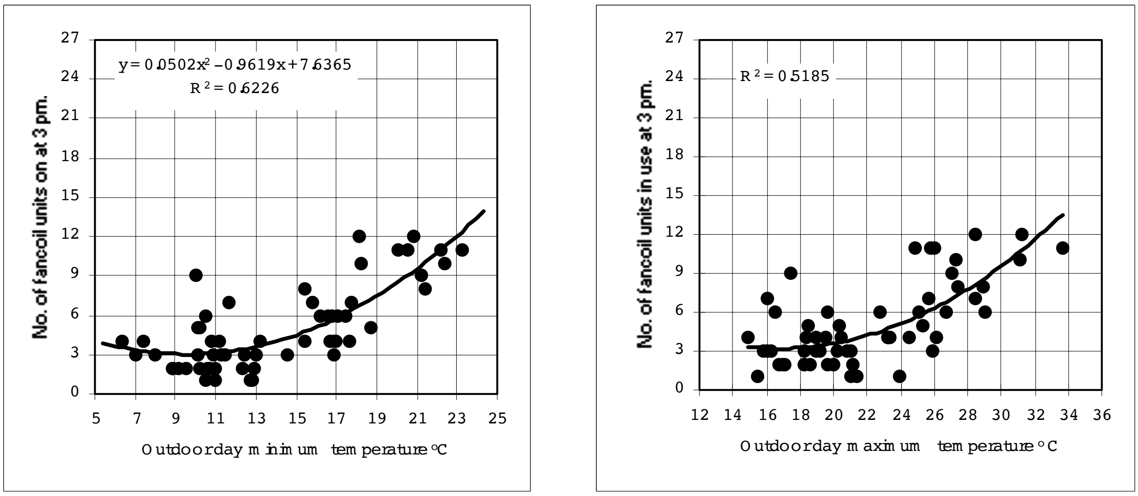



Figure 12. Day by day temperature variations in five typical rooms when occupied.

**Use of fancoil units**. As explained above intermittent records have been kept of numbers of fan coil units in use at 3 pm during the study period. Results of second order polynomial regression analysis of these data, illustrated in figure 13 below, show a strong relationship with outdoor day minimum temperatures (i). Again the relationship with outdoor day maximum temperature (ii) is weaker, suggesting that the less variable daily minimum is a more reliable independent variable. The strength of the relationship in this case would be affected by diversity of room occupancy from day to day. A more complete set of data would be required before confident predications could be based on this analysis. However it seems that a small proportion of users feel the need to operate the mechanical equipment to maintain acceptable indoor temperatures, even in the mildest weather, when outdoor minimum day temperatures are in the range from about 7 °C to 13 °C. It is also possible that more units would be used early in the morning in this mild weather but, unfortunately, no details of such use are available.




(i) (ii)

Figure 13. Number of fan coil units in use at 3 pm with outdoor temperature as independent variable.

**Carbon dioxide and particulate concentrations** as the averages of concentrations measured in ten rooms in the study area (setting 37) in July 2001 are reported in table 2. Because it was winter the windows in the study area were shut. The mean carbon dioxide concentration indicates a satisfactory average rate of ventilation by outdoor air of about 8 litres per second per person. This suggests that leakage infiltration is quite high. The high count of fine particulates is probably due to location of the building beside a busy highway.

These concentrations in the study setting 37 are considerably higher than those observed in the same year and season in two air-conditioned office settings, numbers 26 and 34. However ratings for occupant perceptions of thermal comfort, air quality, overall comfort and effect on performance of work in it are all higher and SBS symptom prevalence is lower as shown in figure 8**.** This suggests that the combination of operable windows and personal control of the thermal environment have a beneficial effect on occupant sensations of well-being.

Table 2. Concentrations of carbon dioxide and fine particles in three buildings.

| | Setting 26 | Setting 34 | Setting 37 |
|---|---|---|---|
| Carbon dioxide ppm | 660 | 770 | 930 |
| Particle >0.3μ count/$m^3$ | 2.49E+05 | 2.62E+05 | 1.10E+06 |

## 3.14 Lessons Learned

**Conclusions**

- Well designed naturally ventilated buildings with ventilation through occupant controlled windows and doors can provide thermal comfort and air quality as perceived by the occupants comparable with air conditioned premises in the moderate climate of Sydney and, by extrapolation, in similar climates in other parts of Australia and the world.
- Provision of supplementary on-demand mechanical cooling/heating equipment in the pilot study and in other buildings has raised occupant perceptions of comfort and well being significantly. In the light of self-reported high rating for effect of the space on performance of work, it could be expected that productivity would be above average.
- Prevalence of eight symptoms of minor ill-health similar to those commonly associated in the literature with “sick building syndrome” is lower in naturally ventilated and mixed mode settings than in many air conditioned premises.
- Hybrid systems, and indeed any ventilation systems, will be more acceptable to occupants if the control systems permit intervention by individuals to establish conditions that match their currently perceived requirements. These can frequently vary between individuals and can vary throughout the day for any particular person. Personal control may be more readily achieved in a setting such as the pilot study where accommodation is in the form of cellular offices, mostly with only one occupant.
- Occupants have demonstrated a tendency to use supplementary mechanical cooling/heating equipment sparingly in the pilot study. They appear to have a preference for use of windows and other adaptive behaviours to modify conditions in mild mid-season weather. Most do, however, appear to have an upper “tolerance” limit when active intervention will be applied if the opportunity is available. A similar lower tolerance limit will probably be found in colder climates. For many of those in this study an acceptable range of indoor temperatures across the seasons would seem to lie between 18 $^{o}$C and 27 $^{o}$C.
- It has been observed that the mechanical equipment provided in this pilot study tends to “default to off”. If one enters ones room and finds conditions satisfactory, one does nothing. If not, adjustment of windows or doors is frequently the first choice. The result of this behaviour is evident in the low energy consumption of the cooling/heating system.
- Mean indoor temperatures in occupied rooms display a strong adaptive relationship to daily outdoor minimum temperatures until the latter reach about 17 $^{o}$C. At this point the mean indoor temperature takes a constant value of about 25 $^{o}$C as indicated in figure 11 (i). The number of fan coil units in use also has a strong binomial relationship with day minimum outdoor temperature as shown in figure 12 (i).
- Monthly energy consumption is strongly related to mean monthly outdoor temperature as shown in figure 5.

**What did work?**

- Simplicity and transparency of the interface between users and the cooling/heating system. Very little instruction was needed and people understand the system and use it intelligently to achieve their objectives.
- The modular variable flow refrigeration system has a sophisticated proprietary control system, which enables it to operate with high part load efficiency over a wide range of loads. This system operates in the background to support the manual control actions of occupants of individual rooms. A good analogy is with the power steering system on a motor vehicle, which assists the driver without interfering with his/her intentions.
- The system has proven trouble free over four years of operation. Until recently the only maintenance carried out has been occasional washing of the panel filters in the fan coil units. A breakdown of the refrigeration plant in March 2002 was due to water penetrating the casing of an external isolating switch of third party manufacture. This was quickly rectified and the system continues in use.

- In this project the real (and best) sensors of temperature and air quality are the occupants who are able to implement decisions with rapid feedback to inform them of the effect.
- There can be little doubt that the high rating for air quality in this and similar situations is due to the combination of operable windows and occupant controlled cooling/heating equipment. The influence of thermal comfort on perceptions of air quality is illustrated in figure 7(i) above.

**What did not work?**

- Nothing really. However the supplementary system is charged with refrigerant 22 which will soon be phased out in Australia. When it was installed it was not available for use with completely non-ozone depleting refrigerants. Current versions have now been modified to suit these. At installation the piping system was carefully pressure tested with nitrogen gas and has given no sign of leaking in the four years of use to date.
- The already low energy consumption of the system could be further reduced by introduction of nighttime cooling with outdoor air. This could be accomplished easily by installing small window mounted fans in windows in the rooms and blowing cool air through them at night.

**Initial and running costs**

Initial cost of the supplementary system is no different from the cost of a conventional air conditioning system because it has to be sized for peak cooling and heating loads. Savings should be achievable in associated building works because there is no need for concealment space for ductwork. Running costs are obviously higher than for a ”free running” naturally ventilated building without the supplementary cooling/heating system but the penalty is reduced occupant satisfaction. Energy cost, year on year, is about a quarter of the cost that would be expected for a conventional air conditioning system for the same space. Maintenance costs are negligible.

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