Case Study of the Design and Post-Occupancy Evaluation of an Environmentally Sustainable Educational Facility

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ABSTRACT: A new innovative library and IT facility at Shellharbour 100km south of Sydney, Australia, was designed to incorporate a number of sustainable design features. These included fully automated mixed mode ventilation, displacement ventilation, passive solar heating, thermal labyrinth, rainwater collection and high levels of daylight. The building was designed to be a low energy facility that provided greater occupant comfort through the incorporation of these passive design features. During the design stage, state-of-the-art computational modelling was used extensively to evaluate and optimise the building and its systems. Following completion and hand-over of the building, a twelve month period of post-occupancy evaluation was undertaken.
The post-occupancy evaluation included extensive analysis of building data, collected through the building management system, including temperatures throughout the building, energy consumption and building performance. Feedback from staff and users as to the performance of the building was collected regularly and used to assess performance and fine tune the building operation. From a technical perspective, the building monitoring provided validation of the modelling used during the design process. Temperature distributions throughout the building were very similar to those predicted by the modelling.
The completion of the monitoring revealed a number of positive results with regard to overall building operation and performance. The process also highlighted some very important lessons in delivering low energy mixed mode buildings with respect to occupant satisfaction. Occupant control was found to be a fundamental issue with respect to achieving comfort despite achieving internal design temperatures.

Keywords: energy, comfort, sustainable design, post-occupancy, computer modelling

1. INTRODUCTION

1.1 General Description of the Building

The Library and Information Centre is located within the Shellharbour Technical and Further Education (TAFE) College 100 km south of Sydney, New South Wales, Australia. The purpose of the two storey facility is to provide lecture rooms and computer and information resources to the students and staff at the Shellharbour College of TAFE.

The building consists of the following rooms/spaces:

Ground Floor: 375 m^2.

- Information Technology/Commons Room
- Five Lecture/Seminar Rooms
- Toilets and Stores

First Floor: 710 m^2

- Open Plan Study Area
- Open Plan Computer Area
- Open Plan Resource Area
- Two Study Rooms
- Staff Workroom
- Office
- Toilets

The building has been designed with its longest facades orientated to the east and west. Glazing constitutes a large percentage of the eastern façade to provide passive heating during the cool mornings and to maximise the benefits of daylighting. Reduced window areas are located on the western façade to minimise solar heat gain during the hottest part of the day. The northern façade incorporates the entry foyer. The clerestory provides abundance of daylight. The rooms are generally large and spacious with interconnecting corridors on the ground floor between the lecture/seminar rooms to allow air movement and cross-flow ventilation. The building incorporates concrete floor slabs throughout to provide thermal mass to the structure. The roof is constructed of insulated sheet steel.

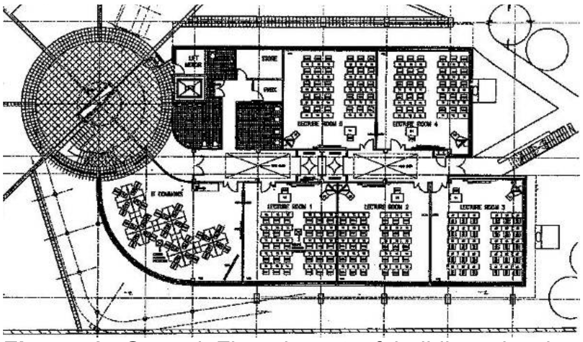

Figure 1: Ground Floor layout of building showing arrangement of lecture/seminar rooms and central corridor.

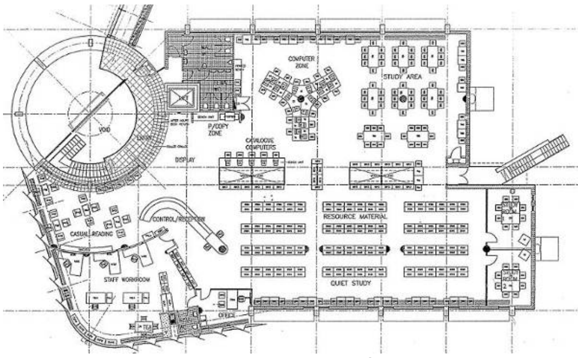

Figure 2: First Floor layout of building showing arrangement of open plan resource and computer area, study rooms and workroom.

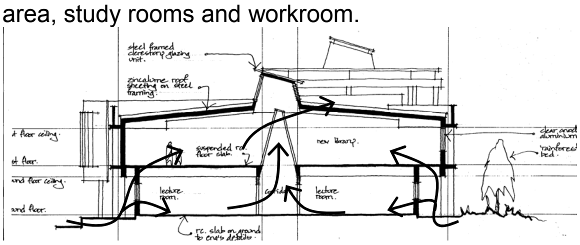

Figure 3: Sectional drawing of building showing conceptual natural ventilation air paths through the ground and first floor and out through the clerestory.

A two storey clerestory provides an abundance of natural light into the core of the building and acts as a thermal flue from the ground and first floors.

1.2 Building Shading

The shading devices around the building are positioned and sized such that the majority of the direct solar radiation throughout the year is blocked after 10 am.

During summer, penetration of direct solar radiation through the trees into the internal space is limited to:

- The east façade of the first floor in the early morning.
- The west façade of the ground floor in the late afternoon.

During the winter months, very little direct solar radiation penetrates the west façade. Significant early morning solar radiation penetrates the eastern façade during winter periods, assisting winter heating by passive means.

1.3 Natural Ventilation Openings

The ground floor and first floor are provided with inlet floor louvres that are sized such that their free area is 1% of the applicable floor areas.

a) **b)**

Figure 4: Photograph of; a) first floor air inlet louvres on the eastern side of the building. Note the early morning sun penetration, b) Clerestory above the library resource area. Note the ground floor flues are connected directly to outdoors to prevent short circuiting with the first floor.

The clerestory relief air louvres have a total free area of 26 m^2 and the floor louvres have a total free area of 7 m^2. This was optimised during the design process through modelling to provide a natural ventilation rate of six air changes per hour on a summer design day with no wind. The clerestory louvres are motorised to allow closing during winter or during adverse weather conditions.

The free area of the manually operable windows is 5% of the applicable floor areas in order to meet the Building Code of Australia requirements. This allows the building to be deemed fully naturally ventilated without the requirement of mechanical ventilation.

Passive night cooling is provided. All low level operable louvres on both the ground and first floors open at night to discharge the warm air from the rooms and replace it with the cooler ambient air. Despite being close to the sea, the concept of passively night cooling the building was shown to provide some effect through modelling.

1.4 Air Conditioning

The library area is served by a displacement ventilation system and is designed to operate when the natural ventilation cannot maintain internal comfort conditions. The system provides cooling only and operates through supplying air at a constant temperature of 18°C through low level floor mounted diffusers. The displacement ventilation system creates a cool pool of air at low level which is heated by internal loads. This heated air rises in plumes and is relieved to outdoors through the clerestory openings. The system supplies 100% outdoor air and was initially designed to operate when the external temperature exceeded 26°C. When the external conditions fall below this temperature, the displacement system stops and the building reverts to natural ventilation mode.

The displacement air conditioning system is sized to provide maximum air flow of 4.1 L/s/m^2.

a) b)

Figure 5: Photograph of first floor displacement air conditioning system outlets; a) incorporated into table in library resource area and, b) incorporated into the furniture in the computer and study area.

1.5 Thermal Labyrinth

The outdoor air is drawn into the air conditioning units through two 40 metre long, below ground concrete ducts before it reaches the air conditioning unit intakes. These below ground ducts provide passive pre-cooling of the outdoor air prior to it entering the air conditioning unit.

1.6 Heating

Heating is provided by a modular condensing boiler supplying 60ºC water to finned-tube hydronic convector radiators located in the occupied areas on the ground and first floor. Water is returned to the condensing boiler at 40ºC. It was demonstrated that this system resulted in a 39% reduction in CO_2 emissions when compared with a reverse-cycle displacement air conditioning system.

1.7 Other Environmental Initiatives

The building was designed to demonstrate environmental sustainability to the students and staff of the educational campus. Other passive low energy design and sustainability initiatives which were incorporated include:

- Rainwater harvesting and 30,000 L of water storage for landscaping
- Specification of low Volatile Organic Compound (VOC) materials throughout.

2. DESIGN PHASE MODELLING

2.1 Modelling Software

During the design process the building was extensively modelled to assist in the development of the design. This involved dynamic thermal and energy simulation modelling using the commercially available IES Virtual Environment software and Computational Fluid Dynamics (CFD) modelling using CFD ACE+.

The dynamic thermal modelling provided a vast range of results for the conceptual design stage including air and radiant temperatures, bulk air flows, heat loads and building energy consumption.

The primary purpose of the CFD investigation was to verify that the stack driven natural ventilation would perform as expected. The performance of the displacement air-conditioning system was also demonstrated.

2.1 Thermal Modelling

The methodology for the thermal modelling study involved carrying out a comparative analysis of different types of wall types, glazing materials and ventilation opening strategies to determine the most effective combination to reduce the internal comfort temperature of the naturally ventilated areas.

Table 1: Mean Temperatures Modelled for Natural Ventilation and Displacement Ventilation on a Peak Design Summer Day. Low level refers to the zone between the floor and 1.5 m above floor level. High level refers to the zone above 1.5 m above floor level to the ceiling level.

Space	Mean Temperature (°C)			
	Low Level		High Level	
	Air °C	Comfort °C	Air °C	Comfort °C
1st Floor Computer Area	25.4	26.5	26.3	27.5
1st Floor Resource Area	25.8	26.7	26.4	27.3
1st Floor Staff Workroom	25.8	26.6	27	27.5
Lecture Room 2	26	25.6	27.9	27.6
Lecture Room 5	25.6	25.2	27.8	27.2

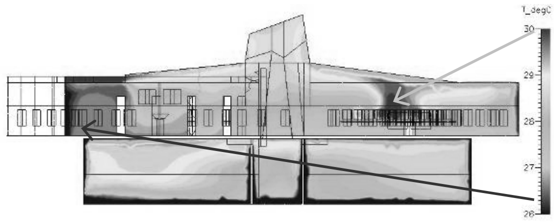

Figure 6: CFD model demonstrating the buoyancy induced ventilation during natural ventilation mode through the Library Resource area.

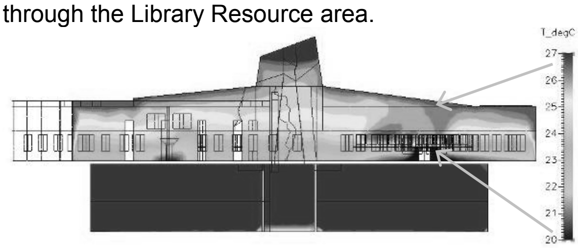

Figure 7: CFD model demonstrating the buoyancy induced ventilation during air conditioning mode through the Library Resource area.

The modelled summer cooling strategy uses natural ventilation when the outdoor ambient temperature was below 26°C. When the outdoor air temperature reached 26°C, the floor louvres on the first floor closed and the displacement air conditioning system operated. The resulting mean temperatures modelled for a summer design day are given in Table 1.

2.2 Energy /Emissions Modelling

The energy modelling study involved comparing the relative energy consumption of a standard reverse cycle overhead air conditioning system with a combined mixed mode natural ventilation/ displacement air conditioning system.

The energy modelling demonstrated that a 34% reduction in annual energy consumption could be realised with a mixed mode displacement system when compared to a conventional reverse cycle air conditioning system.

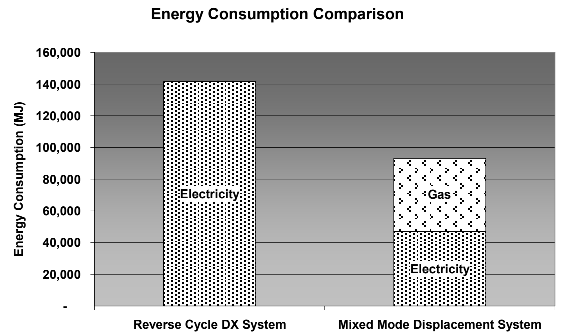

Figure 8: Modelled energy consumption for mixed mode displacement system and reverse cycle AC systems.

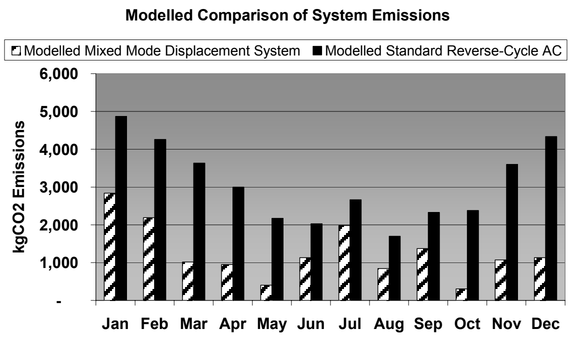

Figure 9: Modelled kg CO_2 emissions for mixed mode displacement system and reverse cycle AC systems.

The energy reduction translated into a 59% annual reduction in CO_2 emissions from the building air conditioning system.

2.3 Wind Modelling

The purpose of the wind modelling was to confirm the performance of the roof clerestory with winds headed directly onto the larger louvred opening. The purpose of the modelling was to ensure that air would always be drawn out of the clerestory relief louvres. The modelled 2-D representative CFD section is shown in the figure below.

The 2-D CFD modelling demonstrated that during a head on wind condition, the bow wave created by the building's parapet would create a low pressure area directly in front of the clerestory opening. The theory demonstrates that this would lead to air being drawn up through the building from both the leeward and windward sides.

3. POST CONSTRUCTION MONITORING

3.1 Monitoring Specification

The scope for post construction monitoring was developed during the early design stage. Post construction monitoring was deemed critical for a building with such an innovative environmental control system to ensure the various systems were commissioned correctly. The client was also keen to demonstrate the performance of the building after committing funds to develop such an environmentally sensitive development.

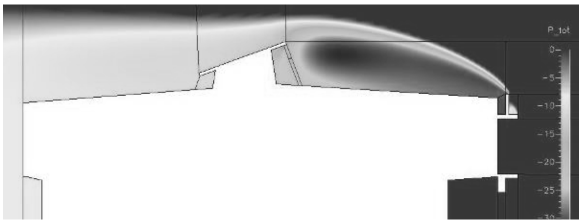

Figure 10: CFD model demonstrating the bow wave wind effect onto the building with parapet providing a low pressure regime outside the clerestory opening

The building management system was configured to log:

- Outdoor air temperature
- Wind speed
- Wind direction
- Rain detection
- Room temperatures
- Air conditioning plant entering and supply air temperature
- Gas and electrical energy consumption
- Ventilation louvre status (open/closed)

The data was downloaded from the site building management system into an Excel spreadsheet every three months. This data was then processed and a report was developed and issued to the client. During the monitoring year four reports were issued.

Occupants were also interviewed and encouraged to communicate with the monitoring engineer during the defects liability period. This interaction assisted in identifying how the building was operating during the odd occurrences such as winds from certain directions, extreme days or high occupancy periods. It also allowed the monitoring team to understand how the occupants were responding to the building operation.

3.2 Issues Associated with Monitoring

The commission to undertake the monitoring activity was for 12 months directly after the practical completion handover. It was found that during this time the monitoring activity mostly consisted of identifying faults with the system which required rectification by the installing contractor. Because the contractor was no longer on-site during this time, it often took many weeks for items to be fixed. The result was that the monitoring continued while the building was operating at less than optimum performance. Examples of some of these installation defects included:

- The ambient temperature sensor located in the weather station was found to be exposed to the reflected radiant heat from the light coloured roof. The result was that the building control system thought that the ambient temperature was hotter than it actually was, closed down the natural ventilation louvres and started the air conditioning system prematurely.

- Heating water piping serving the Librarians office and Workroom was incorrectly sized and installed resulting in unstable heating systems performance and room temperatures not reaching design levels in winter.
- A number of room temperature sensors failed which required replacing. When failed, these sensors would often send the building management system spurious temperature readings which would affect the system operating mode.
- A number of actuators failed during the defects liability period resulting in higher than acceptable infiltration levels.
- The boiler thermostatic relief valve had failed during the winter month of August as a result of the unstable heating system operation resulting in a continuous overflow of hot water into the drain. This resulted in a larger than expected gas consumption until it was identified 2 months later in October.

3.3 Results

3.3.1 Energy / Emissions

Despite the commissioning issues encountered during the monitoring period, Figure 11 demonstrates the consumption of energy and the emissions performance of the building were better than expected.

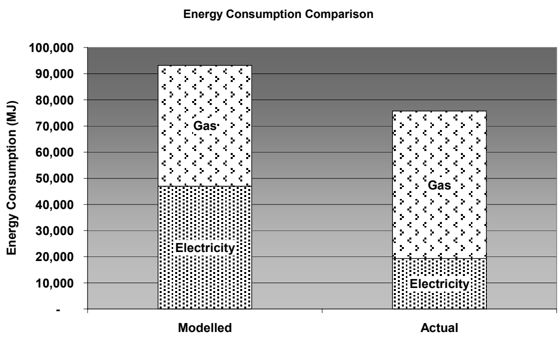

Figure 11: Chart demonstrating the comparison of energy consumption for the modelled mixed mode displacement system and the installed system.

Over the period of the year it was found that the actual energy consumption was in the order of 5% lower than that predicted by the simulation modelling. This is in itself is a remarkably close prediction, however, closer scrutiny of the figures demonstrate that the actual electricity consumption was 19% lower than that predicted and the actual gas consumption was 22% higher than that predicted.

Figure 12 provides a monthly comparison profile of CO_2 emissions for the year. The 19% lower electricity consumption has a more significant effect on the CO_2 emissions than the 22% higher gas consumption. This is mainly due to the CO_2 conversion factors in the Sydney region. Electricity is converted at 3.38 kgCO_2 per MJ and natural gas is converted at 0.828 kgCO_2 per MJ.

3.3.2 Space Temperature

The system was initially designed to achieve room temperature conditions as outlined in Table 1. During the monitoring stage, there were a number of days which reached design conditions which allowed correlation with the model. Figure 13 demonstrates the logged temperature in the Library space during a summer design day.

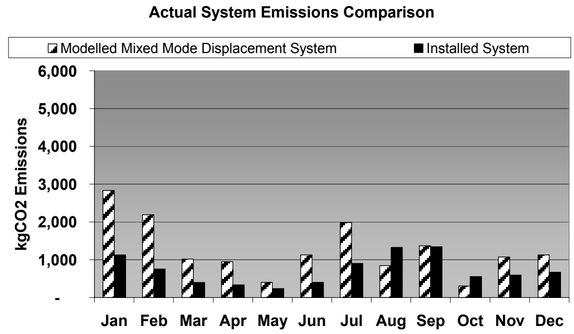

Figure 12: Monthly CO_2 emission comparison for modelled system and installed system

The maximum official Bureau of Meteorology (BOM) weather data for the area indicated that the maximum ambient temperature in the region reached 30.4°C. This was above the temperature recorded by the onsite weather station which measured only 28.0°C. The discrepancy in the ambient temperature measurements is thought to be possibly due to the closer proximity of the building to the ocean than the BOM station and the position of the outdoor temperature sensor in a shady location close to the thermally massive building.

The post occupancy monitoring evaluation demonstrated that the building was capable of maintaining a temperature of 25.6°C during a design day. This was consistent with the 25.8°C predicted during the modelling stage. The monitoring also demonstrated that the 40 m long concrete thermal labyrinth was capable of reducing the air temperature onto the air conditioning coil from the recorded outdoor ambient of 28.0°C to 25.5°C.

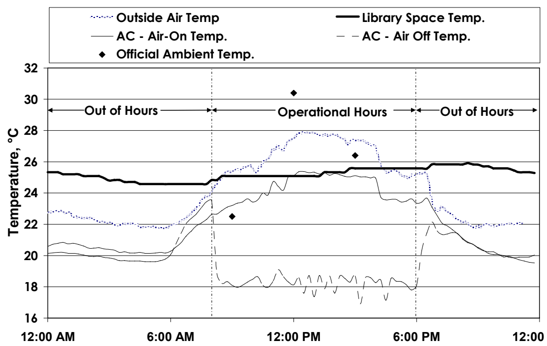

Figure 13: Peak summer day monitored temperature chart demonstrating the operation of the thermal labyrinth and air conditioning system to maintain internal design conditions.

4. POST OCCUPANCY EVALUATION

4.1 Post Occupancy Evaluation Scope

The post occupancy evaluation involved communication via email with the Library staff and a number of visits to the site for face to face interviews. Despite the client being very satisfied with the building design and performance, it became very obvious from the start of the post occupancy evaluation process that the staff who occupied the building had a preference for air conditioning.

4.2 Results

The staff recognised the design intent of the building and gave the impression early on that they felt it was a worthwhile goal to achieve a low energy building. However, despite an education process that involved on site presentations to the staff describing the building concept and functionality, the concept of extended temperature ranges and natural ventilation was never fully embraced. One piece of correspondence noted that it was “23.9°C and it is too hot and stuffy”.

A number of installation and commissioning issues that were resolved only after what seemed to be many weeks, also exasperated the problem. The remote location of the site resulted in contractors delaying site visits until a number of items could surface and be addressed at the same time.

When the building was operating well, there was a general perception that the building was a very pleasant environment to work in; however, when the system was not operating correctly the building was very unpleasant.

Despite being a fairly open building with large areas of natural ventilation louvres and a 100% outdoor air air-conditioning system, one of the main complaints was lack of air movement and stuffiness. This stuffiness generally appeared to occur when the room temperatures are over 25.0°C and when the internal humidity levels rise above 60%. The air conditioning system was designed to reduce the humidity levels in the occupied spaces, however, the higher than predicted internal humidity levels appear to be a result of higher than expected levels of infiltration through the façade. This is especially an issue as the entire façade is designed to open to promote natural ventilation during certain ambient conditions. It has been found that the quality of the operable louvres and their installation may not appear to provide satisfactory air tightness. This issue is currently being addressed by increasing the air conditioned supply air quantity and reducing the supply air temperature further.

During the monitoring period the other main complaint was draughts during natural ventilation mode. The weather station was designed to monitor the wind speed and direction and when the wind speed was over 20 km/h the building management system would close down the natural ventilation system and start the air conditioning system. During the early period of the defects liability period it was found that the setpoint of 20 km/h was too high. What complicated the control setting was that the building responded differently to different wind directions. So a compromise was needed and the lower wind setting of 10 km/hr was selected.

During low wind conditions, it was found that the library space was well ventilated by a cross flow of air from the floor grilles on one side of the building to the floor grilles on the other side of the building. This was in contrast to the CFD wind analysis which predicted that even under a direct head-on wind condition the floor grilles would always draw air up through the floor grilles from the outside. It is thought that the effect of neighbouring buildings has an adverse affect on the oncoming wind profile resulting in this effect.

5. CONCLUSION

Mixed mode buildings have the potential to reduce operational energy costs by up to 35% in the Sydney climate when compared to conventional air conditioned buildings. The design of a mixed mode building requires careful dynamic thermal and energy modelling to demonstrate system operation to prove system functionality. System modelling, however, only provides a theoretical performance and the selection of equipment and installation quality is critical to ensure the building operates as designed. Modelling has demonstrated its value in assisting in the design process, however, the true benefit of modelling is to allow a sensitivity analysis of the building performance to be undertaken to provide assistance for the installation and commissioning process.

Where buildings are designed to operate with automatic mixed mode control, a thorough commissioning process must be provided to continuously monitor and adjust the building to react correctly to the environment. This monitoring should continue for a minimum of 24 months so two full seasonal cycles can be accommodated.

The selection of operable louvres is critical to ensure air-tightness in mixed mode buildings when in air conditioning mode. The use of fully sealable windows is recommended in lieu of aluminium louvres or glass louvred shutters.

The end users of the building should be part of the design process to ensure their views are considered. Providing a fully automated mixed mode system is an ideal concept, however, the users can quickly become frustrated if they are unable to control their environment. Users should be provided with override controls to allow occupant switching between natural ventilation and air conditioning independent of the automatic control system. It is considered that this level of control provides occupants with a degree of psychological comfort in so much as they have some control over the system. Effectively they should only operate the system when they feel uncomfortable.

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