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THREE CASE STUDIES USING BUILDING SIMULATION TO PREDICT ENERGY PERFORMANCE OF AUSTRALIAN OFFICE BUILDINGS

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ABSTRACT

This paper compares the energy performance of three office buildings as predicted by building simulation (using only the information typically available at the design stage) with the measured energy consumption of the same buildings in operation for a twelve-month period. The buildings are located in Canberra, Australia. The study was limited to three buildings in a single climate, but it aimed to identify factors that caused discrepancies between the energy performance of an office building as typically predicted in the design stage and the energy performance of those buildings in operation. Once identified these factors will be used as the basis for more detailed investigations.

INTRODUCTION

There have been a number of studies, in European and North American climates, which identify likely sources of error in modelling buildings. These studies have identified sources of error in building simulation to be assumptions about equipment loads and heat generated by human activity (MacDonald, 2002). In addition, climate, lighting particularly in evaluation of daylight response, glazing and its interaction with factors such as urban pollution and shading, accuracy of monitoring devices and the effects of temperature, moisture and demand on the performance of system components were found to affect the accuracy of building simulation (Clarke, 2001). Incomplete or erroneous plant performance data, particularly information that does not allow for imperfections in control set point tracking is also considered to contribute to simulation inaccuracy (Jiang et al, 2007).

This study considers three office building in a single Australian city and uses one software package. There is no intention of drawing conclusions with a wide applicability. The aim of the study was identify factors that may be worthy of investigating in more detail.

In Australia, commercial buildings are typically fitted with two separate meters for each energy source:

- The base building meter - this measures the energy used by the heating and air conditioning, car park ventilation, hot water, exterior lights and lighting in non-tenanted parts of the building, such as plant rooms, circulation areas and amenities. The building owner pays for this energy.
- The tenant meter – this measures the energy used by lighting and equipment in the space occupied by the tenant. It also includes the use of tenant controlled supplementary air conditioning normally used in meeting rooms or computer rooms. The tenant pays for this energy.

This breakdown of metering is very helpful in analysing the differences between the modelled and measured energy consumption and is used in discussion of the results for each of the three building below.

DESCRIPTION OF THE BUILDINGS

The drawings of the buildings used for this study are shown in Figures 1 to 3. These drawings are produced in Google SketchUp Version 6. Rotating of rendered transparent objects such as windows in Google SketchUp causes some of these objects to appear opaque or disappear. Similar effects occur using AutoCAD. The bounding boxes of these objects are still apparent. All windows in these figures should be regarded as transparent and have been modelled as such.

Building One

Building One consists of a single storey above ground and has no basement. It has a total covered floor area of approximately 2,950m² and a net lettable area of approximately 2,600m². Figure 1 below shows the drawing of Building One generated by EnergyPlus.

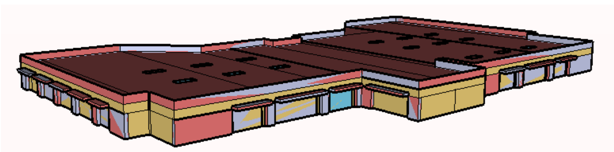

Figure 1 Building One

The air conditioning system in this building is comprised of several variable refrigerant flow (VRF) heat pump units, which provide both heating and cooling as required. A heat recovery system on the exhaust air preconditions the intake air. The building uses electricity only and has no connection to natural gas.

The windows of Building One are single glazed with Pilkington SolarE S4 Green glass. The external walls are metal clad with R1.75 insulation and the ceiling and roof have a total added insulation of R3.5.

For a building of this size in the Canberra climate to operate according to current market best practice (achieving 3½ stars as an Australian Building Greenhouse Rating (ABGR) with emissions of 198 $kgCO_2/m^2$), it would typically have an annual electricity consumption, including both tenant and base building consumption, of approximately 550 MWh.

Building Two

Building Two has a total covered floor area of approximately 21,400 m² and a net lettable area of approximately 16,500 m². It has 15 floors above ground and a single floor of underground car park. Figure 2 below shows Building Two.

The air conditioning in this building is a variable air volume (VAV) system with a separate constant volume gas heating system serving perimeter zones only. Natural gas also provides heating for amenity hot water used by the tenants.

The building is double-glazed with 6/12/6 Evergreen Solar Low-e glass. The external walls are metal clad with R1.5 insulation. The ceiling to the roof space has R4 insulation.

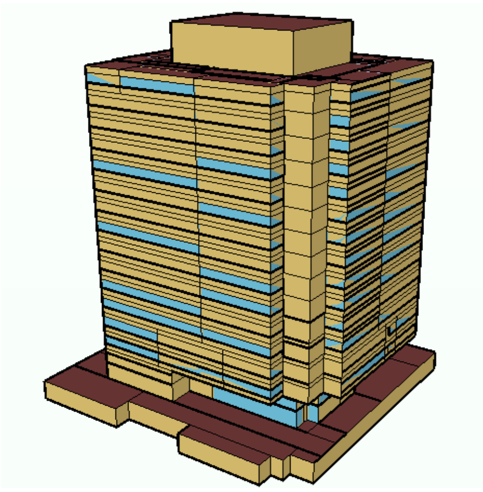

Figure 2 Building Two

For this building in the Canberra climate to achieve 3½ stars ABGR it would typically have whole building annual energy consumption of approximately 3900 MWh assuming a 1:4 sourcing from electricity and natural gas.

Building Three

Building Two has a total covered floor area of approximately 18,450 m² and a net lettable area of approximately 12,380 m². It has 6 floors above ground and an underground car park. Figure 3 below shows the model of Building Three.

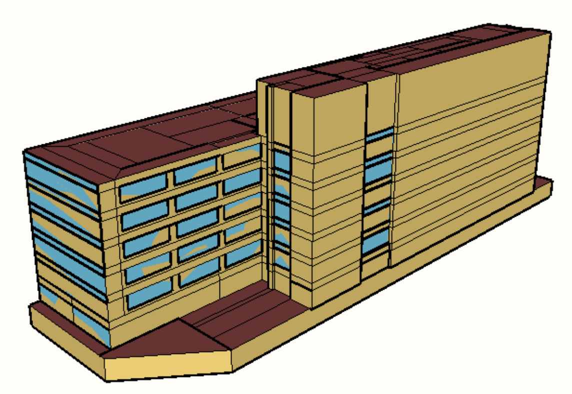

Figure 3 Building Three

The air conditioning in this building is a variable air volume (VAV) system with natural gas providing heating. Amenity hot water used by tenants is heated by natural gas.

The building windows are argon-filled double-glazed in a 6/13/6 configuration and a reflective outer pane. The external walls are metal clad with R2.5 insulation. The ceiling to the roof space has R6 insulation.

For this building in the Canberra climate to achieve 3½ stars ABGR it would typically have a whole annual energy consumption to approximately 3400 MWh assuming a 1:4 sourcing from electricity and natural gas.

MODELLING AND METERING

The three buildings were modelled using EnergyPlus Version 2.

As the purpose of the study was to compare the building performance as predicted in the design stage with measured usage, only information available at the design stage was used as inputs to the simulation. The models were developed from plans and information supplied by the building owners. Details of the tenant fitout and occupancy would not be known at the design stage, the values for levels and schedules of occupancy, lighting and equipment for the modelling were assigned the default values from the ABGR Validation Protocol for Computer Simulations.

These procedures for generating the models were the same as typically used prior to construction in Australia to generate models to assess the energy performance of a building design.

Nearly all the measured energy data shown below was provided by the utility supplying the energy. Time of use data at fifteen-minute intervals was available for electricity at all sites. Natural gas data was only available for monthly intervals from the utility though some data was available from each of the building management systems (BMS). This BMS data was intermittent and of poor quality.

RESULTS AND DISCUSSION

Building One

The modelled annual base building electricity consumption for Building One was 64 MWh compared with an measured annual electricity consumption of 151 MWh. Figure 4 below shows the modelled and measured electricity consumption on a monthly basis. Particularly in the winter months, the measured electricity used by the base building services was much higher than the amount predicted by the modelling.

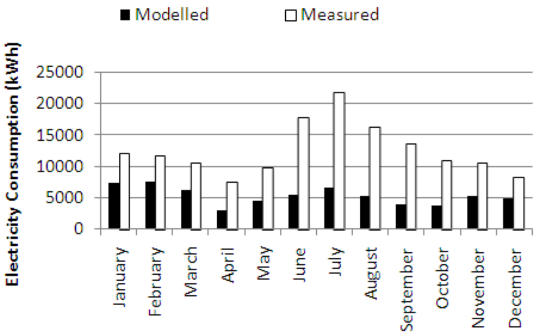

Figure 4 Building One – Base building electricity.

A major source of disparity is evident when comparing the pattern of measured and modelled base electricity use over a selected typical day as shown in Figure 5 below. (Note: The hour of the day shown on the horizontal axis in this figure, and all other figures in this paper showing hour of day, is the solar hour and does allow for daylight saving). The measured consumption for 6th June shows the greatest consumption of electricity occurred between 11:00pm and 8:00am. The building had been running its heating overnight without the tenant or owner's knowledge. This was due to an overreaction by the maintenance contractor to complaints from occupants arriving early in the morning arrivals who felt the building was cold.

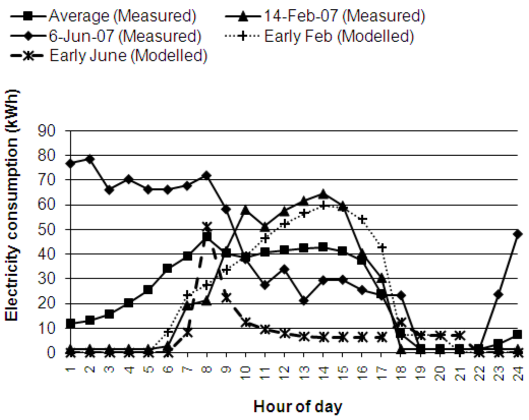

Figure 5 Building One – Daily pattern of base building electricity usage - Wednesdays

One problem encountered when modelling this building was that the EnergyPlus software had no specific modules to model a VRF system. An approximate equivalent system was devised using separate direct expansion systems for each zone with altered part-load efficiencies. The close match of the modelled early February data with measured data seems to indicate that this approximation has been accurate, and is unlikely to have contributed significantly to the differences.

The tenant meter in this building measures approximately 75% of all energy used in the building. This is higher than usual for an office building because the building contains a small computer server room. The computer equipment and the dedicated cooling units in this room consumed approximately 20% of the tenants' metered energy. The tenant data discussed below includes the server room consumption.

The modelled annual tenant energy consumption was 311 MWh which compared to a measured annual tenant energy consumption of 409 MWh. Figure 6 shows the monthly breakdown of this consumption. The higher measured consumption may indicate that the tenant equipment and lighting had been underestimated for the simulation. Alternatively the contribution of the server room equipment and cooling may have been underestimated. The difference between measured and modelled tenant consumption is at its lowest during the months November to January when occupants could be expected to be on holidays. This suggests that the cause of the discrepancy is the equipment over which the occupants have control, for example, personal computers, rather than the server room equipment. An inventory of the server room equipment was completed to verify the load assumptions used in the simulation. Although it is very difficult to determine what exact proportion of the server room equipment is operating at full rated power, the assumptions in the modelling appeared accurate.

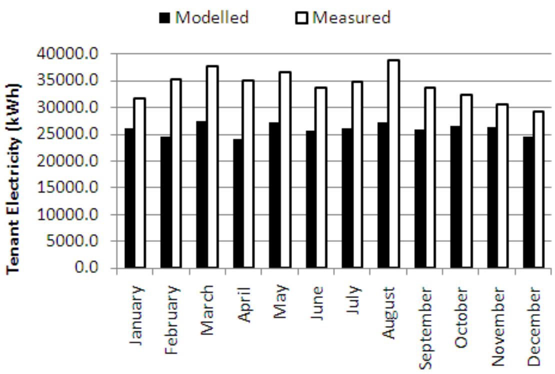

Figure 6 Building One – Tenant light and power electricity

The daily pattern of tenant energy use shown in Figure 7 below gives another indication of possible sources of discrepancies. In February, the measured tenant light and equipment loads rose earlier than assumed in the simulation. In both February and June, the loads remain higher until later in the day than the simulation assumed. Between 8:00pm and 6:00am when the building is unoccupied, the averaged load is approximately 60% above that assumed by the modelling; during the day however this difference is reduced to approximately 5%. This indicates that in this building much more of the office light and equipment is left on overnight than assumed for simulation in accordance with the ABGR protocol. This also indicates that the source of the discrepancy is not the server room as this load would be expected to be uniform throughout the course of the day.

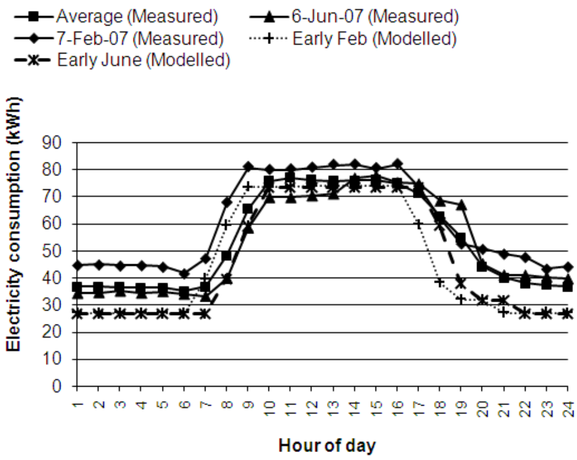

Figure 7 Building One – Daily pattern of tenant light and power electricity usage - Wednesdays

During a walk-through of the occupied office, it was observed that most workstations had two computer monitors and many had two computers. The tenant representative explained that this was because most employees were "scientists" and "scientists need extra monitors and computers". The underestimation of the tenant equipment load for simulation would in part explain the underestimation of the requirement for cooling energy in the summer months, as shown in Figure 4, as actual heat generated from this equipment is greater than assumed.

Building Two

The modelled annual base electricity consumption for Building Two was 717 MWh and the measured annual base building electricity consumption of 836 MWh. Figure 8 shows the monthly breakdown of this consumption. In all months, except February, March and November, the measured electricity used in providing the base building services was slightly more than predicted by the modelling.

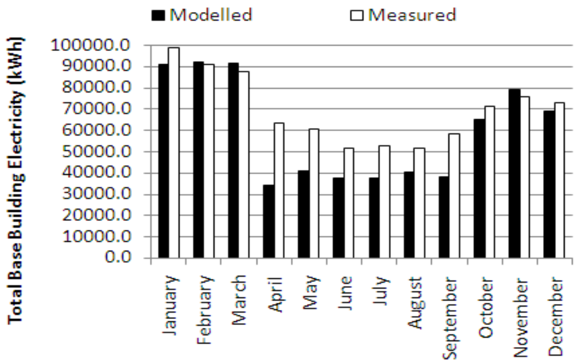

Figure 8 Building Two – Base building electricity

A substantial source of disparity is evident when comparing the pattern of measured and modelled base electricity use over a day as shown in Figure 9 below. At each end of the working day, the modelled base electricity consumption drops to approximately 8 kWh/hour whereas the measured consumption remains at approximately 50 kWh/hour. Figure 9 also indicates that after-hours use of lifts and base building lighting in this building is much higher than typically assumed for simulation.

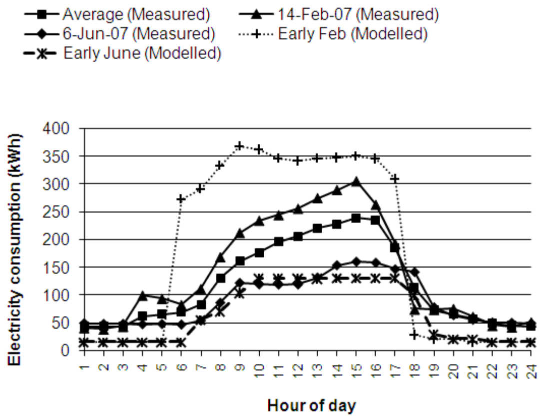

Figure 9 Building Two – Daily pattern of base building electricity – Wednesdays

Figure 10 shows the pattern of base building electricity usage for Building Two on Sundays. This clearly shows substantially more base building services are being used on Sundays and there is quite a range of energy use.

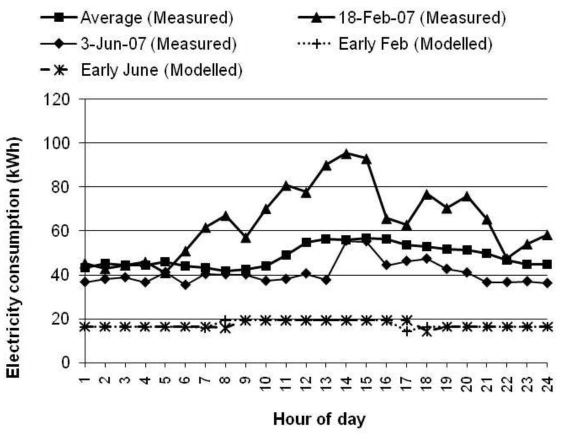

Figure 10 Building Two – Daily pattern of base building electricity - Sundays

The modelled annual gas consumption was 870 GJ and the measured annual gas consumption was 1566 GJ. The natural gas component of the base building energy consumption represents approximately 19% of the energy consumed in this building. It provides amenity hot water and heating in the zones near exterior windows. This energy usage appeared to be very poorly represented by modelling as shown by Figure 11 below.

One problem with attempting to match modelled consumption with measured consumption for this building was that the measured gas data included provision of hot water to a medium-sized café on the ground floor. It was difficult to quantify this usage.

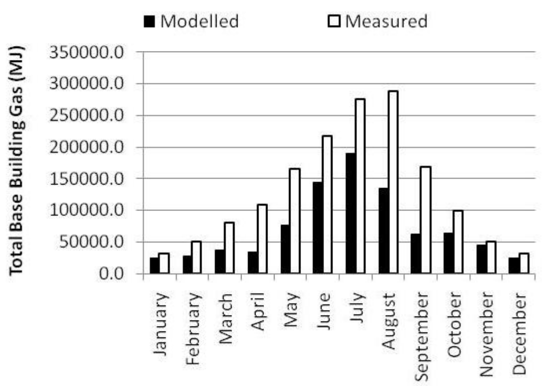

Figure 11 Building Two – Natural gas consumption

Data from the BMS allowed the comparison of the pattern of usage of natural gas on a winter day as shown in Figure 12 below. Two features of this daily pattern contribute to explaining the high gas usage. Firstly, the period of elevated gas usage, or heating, starts an hour earlier and continues an hour later than assumed in the modelling. Secondly, the peak gas usage is much higher between 8 and 10 am than the modelled usage. (Note: The BMS data is not well calibrated consequently the data shown in Figure 12 is an indication of the pattern of use over the day rather than an accurate representation of the actual quantities used.)

This building's heating system had a number of control algorithms, which only allowed heating when the temperatures in adjacent zones satisfied certain conditions. The heating system also had boiler lockouts based on outside temperatures. These controls and lockouts could not be represented in the modelling.

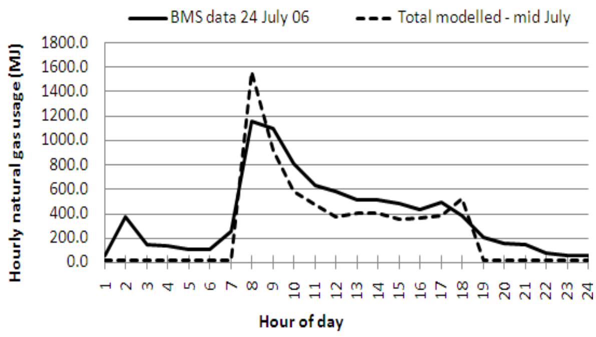

Figure 12 Building Two – Hourly gas data from BMS compared with modelled

The tenant light and power consumption shown in Figure 13 below may provide a partial explanation of the greater than predicted use of natural gas. The tenant light and power energy is approximately 55% of that used by this building. The annual modelled tenant electricity consumption was 1660 MWh while the annual measured tenant electricity consumption was 1390 MWh. Overall, the assumptions used in modelling over estimated this energy by approximately 20%. This overestimation flows through to an over calculation by the simulation program of the heat generated by lights and equipment used by the tenant, resulting in an under calculation of the heating required through the heating system.

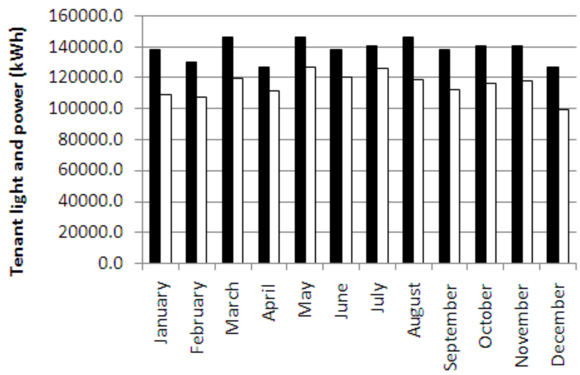

Figure 13 Building Two – Electricity used for tenant light and power

As Figure 14 shows this overestimation of tenant light and equipment is most apparent in working hours.

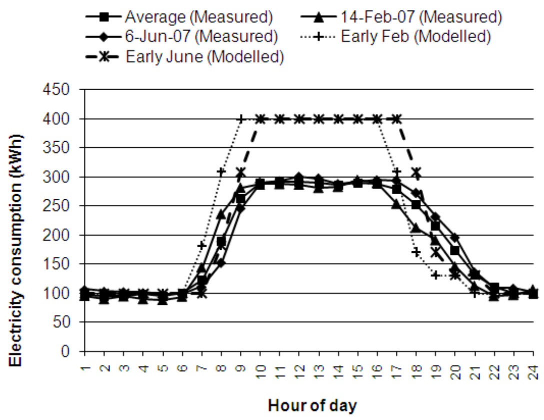

Figure 14 Building Two – Daily pattern of electricity used for tenant light and power – Wednesdays.

Building Three

For Building Three the annual base building electricity consumption was 508 MWh and the measured annual base building electricity consumption was 566 MWh. Figure 15 as shows the comparison of modelled and measured electricity use by month of the year. The measured electricity closely approximates the modelled electricity for most months of the year. In the summer months, particularly December and January, the measured electricity use was considerably higher than predicted by modelling.

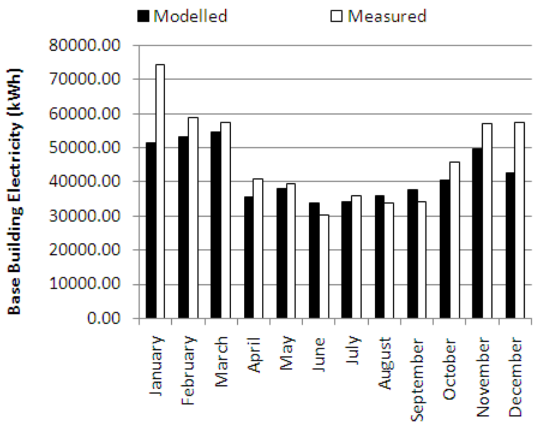

Figure 15 Building Three – Base building electricity

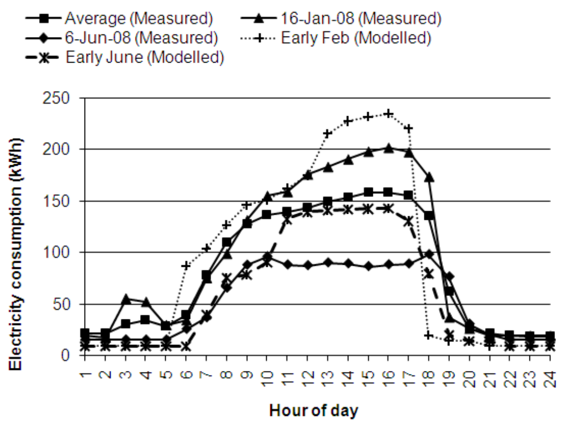

Figure 16 Building Three – Base building electricity daily pattern –Wednesdays

Figure 16 above shows the daily pattern of electricity usage for Wednesdays. Both the summer and winter measured daily patterns show less electricity used than predicted by the modelling.

The daily pattern of usage for public holidays for this building is shown in Figure 17 below (Note: Public holidays for this government building totalled 15 days including the close-down from Christmas Day to New Year. Most public holidays occurred in summer). The measured data shows that the electricity used in this building on public holidays was much higher than predicted by the modelling based on the assumption that the building would be vacant on public holidays.

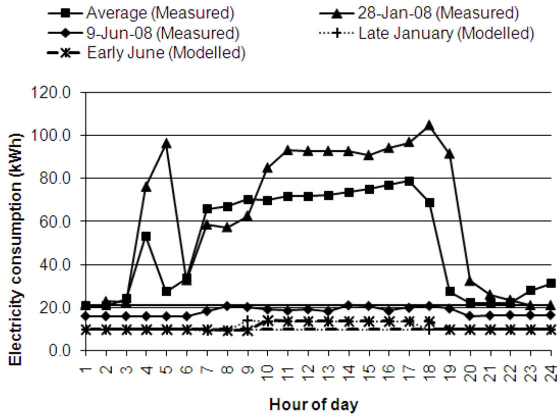

Figure 17 Building Three – Base building electricity daily pattern – public holidays

The other energy source used in this building is natural gas, which provides hot water for tearooms and washrooms as well as heating. The modelled annual natural gas consumption was 3407 GJ and the measured annual natural gas consumption was 1881 GJ. Figure 18 shows the monthly breakdown of this consumption. Particularly for the summer months, the modelling gives a poor approximation of actual heating.

On major contributor to this disparity is the inability of the simulation to model the control strategies used in this building. The boilers are locked out when the outside air temperature is above 20°C and remain locked out until the outside air temperature drops below 15°C. This control would typically lock out heating in the summer except for particularly cold mornings. This building is heavily shaded on the eastern side so modelling of early morning heating could be expected to more significant overstated than with Building Two which also had heating controls that could not be input into the simulation.

It is also likely that the inclusion of this summer heating in the simulation contributed to the increasing the modelled base building electricity usage as the modelled building would be assumed to require more cooling as the day progresses.

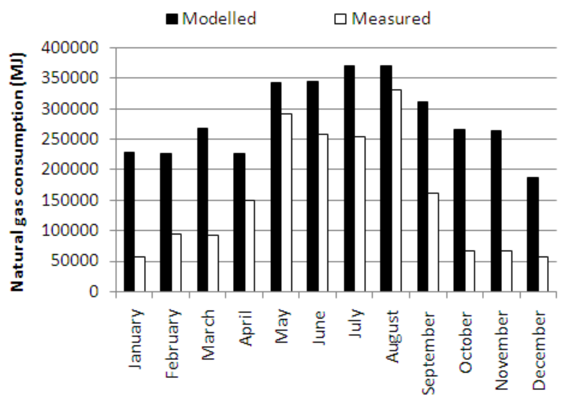

Figure 18 Building Three – Natural gas consumption

The annual modelled tenant power and lighting electricity was 1077 MWh and the measured annual tenant electricity was 670 MWh. The monthly breakdown of this electricity usage is shown in Figure 19. As discussed in the section below the building occupancy was well below that assumed according to the ABGR protocols. The disparity between the assumed and measured tenant electricity consumptions was greatest during occupied hours as shown in Figure 20.

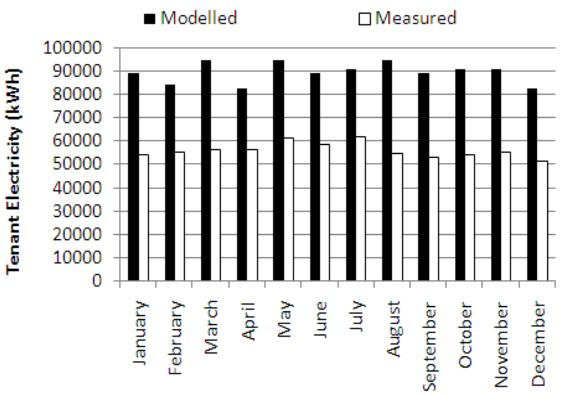

Figure 19 Building Three – Electricity used for tenant light and power

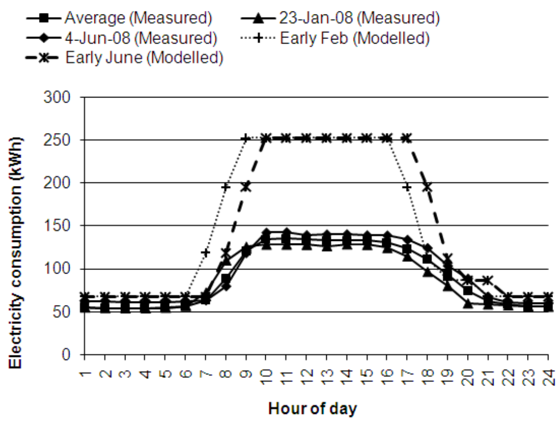

Figure 20 Building Three – Electricity used for tenant light and power - Wednesdays

Occupancy levels

Occupancy levels and schedules are one component of input data for building simulation assumed according to the ABGR Protocol for Building Simulation. This has flow on effects to tenant lighting and equipment levels.

As these building had either only one main entrance or a position where both entrances could be observed, it was possible to check arrivals and departures and so calculate the number of occupants in the building. Figure 21 below shows the outcomes of a single morning and a single evening check for all three buildings. These checks were done mid-week. Tenant representatives verified that the days of the checks were typical and there were no incidents that could cause unusual occupancy levels, for example, flu outbreaks.

The solid line shown in this graph shows how the level of assumed occupancy from the ABGR protocol for simulation purposes was much greater than the surveyed occupancy levels over the full day.

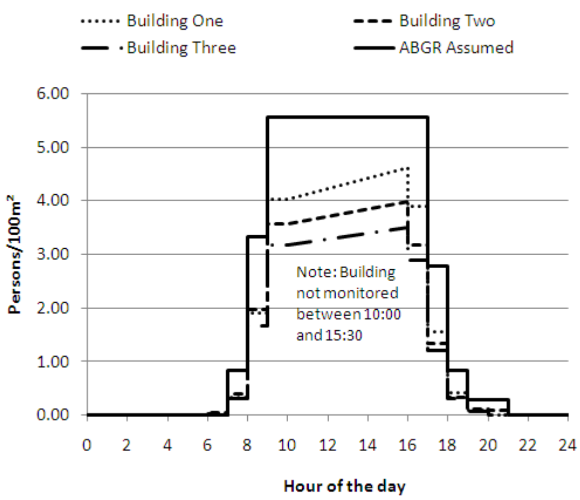

Figure 21 All buildings – Observed occupancy

CONCLUSIONS AND FURTHER WORK

Each of the buildings described in this study had a measured energy performance that differed significantly from that predicted by building simulation. However, the reasons for the disparity varied between buildings, with the much less than expected occupancy being the main common feature.

In Building One and Building Two, the lower than expected occupancy would be the most likely explanation of the less than assumed tenant light and power consumption over the occupied day. In Building One, where the occupancy was slightly higher than the other two buildings, the tenant load was much higher than assumed due to a workplace culture supporting the use of more than one monitor or PC per person.

The after-hours and non working day use of base building services and tenant light and equipment was generally higher than assumed by the modelling. On non-working days, particularly the Christmas to New Year closedown and Sundays, measured energy consumption varied widely.

One of the questions arising from these case studies is whether the variations from assumed occupancy and tenant lighting and equipment levels cause an energy efficient building design have a simulation outcome better or worse relative to an inefficient building design. If these inaccuracies alter the energy performance of all building designs equally this may not be a problem. I will be doing parametric studies of a larger number of office buildings to determine the effects of these variations.

The inability of the modelling to control strategies penalises good design as the effects of these controls cannot be quantified in the design. I will be developing schedules based on the TMY that will allow a mimicking of some of these controls based on outdoor air temperature. Eventually I hope to write some control modules for EnergyPlus.

ACKNOWLEDGMENTS

I am very grateful to the building owners, facility managers and utilities that are providing data for this project. They include the natural gas and electricity supplier ActewAGL, facilities managers Mirvac and Multiplex, energy consultants Exergy Australia, and building owners Indigenous Business Australia and Evri Group.

REFERENCES

Clarke J.A. 2001. Energy Simulation in Building Design. (2nd Edition) Butterworth-Heinemann. London, United Kingdom.

Macdonald, I.A. 2002. Quantifying the effects of uncertainty in building simulation. PhD thesis Department of Mechanical Engineering, University of Strathclyde, July 2002.

Jiang, W., Reddy, T.A. and Gurian, P. 2007. General Methodology combining engineering optimization of primary HVAC&R plants with decision analysis methods – Part II: Uncertainty and Decision Analysis. HVAC&R Research, Vol 13, No 1.