A preliminary evaluation of two strategies for raising indoor air temperature setpoints in office buildings

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ABSTRACT: The thermal comfort of office building occupants can be enhanced by adjusting the operation of heating, ventilation and air-conditioning (HVAC) systems to account for seasonal variations in ambient climatic conditions and the occupants' clothing insulation, behaviour patterns and expectations.

This paper presents findings from a study of the potential to reduce HVAC energy use and enhance thermal comfort by raising internal air temperature setpoints in Australian commercial office buildings. Setpoints at 33 large mechanically ventilated office buildings were adjusted throughout the period 1 November, 2009 to 31 March, 2010 using either:

- a *static* control strategy (i.e. raising temperatures 1°C higher than normal over summer), or
- a *dynamic* approach (i.e. adjusting temperatures in direct response to variations in ambient conditions).

It was found that occupant comfort, quantified by frequency of 'complaints' registered with a tenant helpdesk, was adversely affected in both trials. The 1°C static setpoint increase was associated with a 6% reduction in daily HVAC energy use, compared to a 1.4% reduction for the buildings where the dynamic approach was adopted.

These preliminary findings have significant implications for the implementation of adaptive comfort control strategies in large centrally air-conditioned commercial office buildings.

Keywords: temperature setpoints; adaptive comfort; energy savings; commercial buildings.

INTRODUCTION

In Australia, large centrally air-conditioned office buildings are operated to maintain an internal air temperature range of between 20°C and 24°C year-round. This requirement is usually formalised in the lease between building owner and tenant. Building managers (representing the owner) attempt to maintain conditions within the required band by programming Building Management and Control Systems (BMCS) to target 22.5°C ± 1.5 in summer and 21.5°C ± 1.5 in winter.

HVAC energy consumption varies most significantly with seasonal and daily weather conditions, and can be impacted by a variety of other factors such as occupancy rates and tenant equipment loads. Accordingly, temperature setpoint (thermostat) changes that reduce the differential between internal and external temperatures can produce HVAC energy savings and improve a building's capacity to maintain preferred internal temperatures under a greater range of external conditions. The air temperatures preferred by office building occupants engaged in sedentary or lightly active tasks also vary with seasonal and daily weather conditions because occupants adjust their clothing insulation. In summer, and on warm days, occupants wear fewer and lighter clothes; in cooler weather they wear more and heavier clothes. An opportunity exists, therefore, to achieve both greater occupant comfort and energy savings by adjusting air temperature setpoints to reflect occupants' clothing insulation choices.

We adopted two methods to ground this hypothesis in 'real world' operational data: temperature setpoints were adjusted uniformly in 33 buildings according to the season (static method); and, fine-tuned according to daily and hourly changes (dynamic method) at four of the buildings, reduced from an initial cohort of ten. The static method did not involve any intervention other than the initial setpoint change, whereas the dynamic approach employed a proprietary system that uses multi-agent systems science and machine learning techniques to automatically learn HVAC system behaviour and then deliver to occupants air temperature, air velocity and relative humidity that are considered appropriate according to the model in ANSI/ASHRAE Standard 55-2004 'Thermal Environmental Conditions for Human Occupancy' (Ward *et al.*, 2008; ASHRAE, 2004).

1. BACKGROUND

1.1. Coolbiz

In a simple strategy to meet its Kyoto Protocol 6% greenhouse emission reduction target, Japan's Ministry of Environment launched a national campaign in 2005 in which summer-time set-points were lifted from their usual setting at 25-26°C up to 28°C. To compensate for the increased temperatures Japanese office workers were encouraged to eschew the conventional office attire in favour of a casual and climatically more appropriate line of clothes labelled "Cool Biz." To date scant empirical evidence of the campaign's efficacy at reducing HVAC energy has been published in the international literature, but the fact that it has been repeated each summer since its inauguration in 2005, and that a winter-time campaign dubbed "Warm Biz" has also been implemented, both augur well.

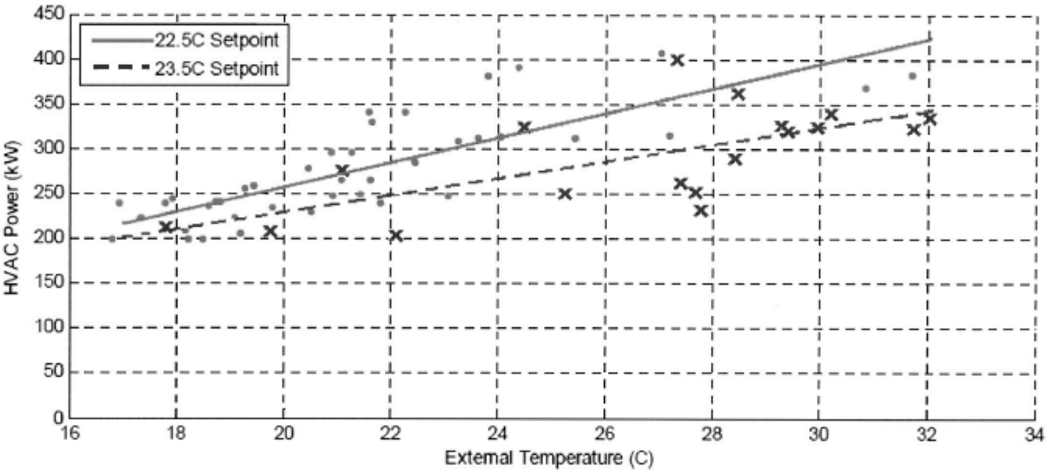
1.2. Smart thermostats

Over the summer of 2006/07 CSIRO conducted a "smart thermostat" trial at a 10,555m^2 office building in Melbourne owned and operated by Investa Property Group. The trial had two primary focuses:

- reducing annual energy consumption and greenhouse gas emissions by making a seasonal temperature setpoint (thermostat) adjustment; and
- reduce building electricity demand by temporarily raising temperature setpoints during times of summer peak demand (Ward & White, 2007).

The study used three approaches to evaluate energy savings potential from raising indoor air temperature setpoints, and all showed encouraging results. The first involved the selection of three days with very similar ambient conditions, including maximum temperature, temperature profile, relative humidity, cloud cover and wind speed & direction. Trials on those days (maximum ambient air temperature ranged between 26.1°C and 26.9°C) found a 15% reduction in total HVAC power demand per degree Celsius increase in indoor air temperature.

The second approach was to plot power demand data points as a function of external (ambient) temperature for periods of reasonably steady state conditions (Figure 1). That method identified a 10% to 20% change in total HVAC power demand for a 1°C change in indoor air temperature, which was consistent with the identical conditions experiments.



Source: (Ward & White, 2007)

Figure 1: Influence of external temperature and building setpoint temperature on HVAC power consumption

The third approach involved transient modelling of the full data set to characterise the building and draw more sophisticated conclusions based on the range of factors typically encountered in day-to-day operation. The model found ±12.1kW in total HVAC power demand per degree Celsius change in indoor air temperature, corresponding to a reduction in total HVAC power demand of 5% to 10% per degree Celsius increase in summer setpoint. Ward and White stated this slightly lower figure "is representative of the total (i.e. whole of season) savings available through thermostat setpoint changes – not just those achievable at the peak of hot days" (p.12).

The report acknowledged that "more buildings should be tested to determine the extent to which [these results] can be applied generically to other buildings" (p.20).

2. OBJECTIVE

2.1. Increase occupant comfort

The aim of the study was to test the energy saving potential of the two strategies in a 'real world' operating environment. Occupant comfort was expected to be enhanced as the common internal temperature band of 22.5°C ± 1.5 falls below the summertime comfort zone prescribed by the International Standardisation Organisation (ISO-7730,

2005) and the American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE-55, 2004) which recommend a range from 23 to 26°C for sedentary or lightly active occupants wearing typical summertime office attire of about 0.5 clo units.

2.2. Reduce greenhouse gas emissions

Given that HVAC energy consumption is responsible for approximately 55% of commercial building greenhouse gas emissions (DEWHA, 1999), a reduction in total HVAC power demand of 5% to 10% suggested by the "smart thermostat" trial corresponds to 2.8% to 5.5% savings at the building level. Furthermore, because long-range forecasts suggested higher than average temperatures for the 2009/10 summer, it was anticipated that the savings would be towards the top of that range using either of the two methods.

2.3. Increase operating income

Energy expenditure accounts for approximately 15% of the selected portfolio's operating budget and in the majority of cases these operating costs are borne by the owner. Therefore, a direct reduction in energy use of (say) 5% would equate to a 0.75% reduction in running costs, the majority of which would pass to the owner and contribute to an increase in net operating income.

A less direct, but potentially more important, benefit derives from the positive relationship between tenant satisfaction and retention. The owner identifies air-conditioning as an important factor in tenant stay/go decisions. As such, an improvement in occupant comfort may have a positive impact on tenant retention and portfolio income.

3. METHOD

3.1. Portfolio selected

In 2009 there were 22 million square metres of Net Lettable Area (NLA) in Australian commercial office buildings (PCA, 2009). This study focused on a single portfolio of large office buildings in the Melbourne, Sydney, North Sydney and Brisbane central business districts that accounted for approximately 3.5% (759,000m^2) of the national total. The portfolio operates under a common management platform and yet the performance of its buildings ranges widely on account of the diversity of building ages and 'attributes' (such as façade systems, building management and control systems, plant and technologies). The portfolio's owner supported the research and made resources available to assist throughout with the coordinated implementation and monitoring.

3.2. Static intervention

Indoor air temperature setpoints are adjusted on a seasonal basis, generally twice each year in May and November. During the cooler months the target range is typically 21.5°C ± 1.5 and this is raised to 22.5°C ± 1.5 for the warmer part of the year. On Monday 2 November, 2009 temperature setpoints were raised across 33 buildings to a level 1°C higher than they had been the previous year. In the majority of buildings this meant setpoints became 23.5°C, however, in some instances the setpoints were slightly higher or lower on account of individual building characteristics.

No other changes were made. A detailed record was kept of every action (many buildings have multiple zone setpoints), implementation challenges and tenant feedback. In some cases setpoints had to be readjusted to address specific occupant concerns (particularly for buildings where the previous year's setpoint was >22.5°C) and this was recorded. The analysis period ended on 31 March, 2010.

3.3. Dynamic intervention

The second strategy involved varying the internal conditions in response to external conditions. Supply air temperature and velocity were allowed to vary while maintaining the Predicted Percentage of Dissatisfied (PPD) occupants for a given set of conditions below 10% (PPD <10%). Load shifting strategies and optimised plant start/stop strategies were also utilised.

A commercialised version of a CSIRO-developed intelligent HVAC supervisory control system underpinned the dynamic approach (for a detailed description of the prototype refer to: Ward *et al.*, 2008). In each case the system was retrofitted to an existing BMCS through industry-standard control interfaces. According to a description of the prototype version, the intelligent HVAC controller "utilises multi-agent systems science and machine learning techniques to automatically form models of the surrounding built environment, using these models to evaluate different control strategies for determining optimal HVAC operating schedules" (Ward *et al.*, p. 2).

The intention was to install the control systems at ten large buildings which would form a subset of the 33 selected for the static intervention (accounting for 393,000m^2 or 52% of the study's total NLA) commencing in December 2009. Unfortunately the installation was delayed on account of a range of technical factors discussed in section 5.2 below.

4. EVALUATION MODEL

Occupant comfort, as expressed by 'too hot/too cold complaints' registered with a tenant helpdesk, was recorded for each building and analysed alongside energy savings. Maintaining or improving tenant comfort was deemed as important as achieving energy savings. Building occupants were not advised about the interventions. The following methods were used to calculate energy savings.

4.1. Static intervention

Data from the preceding summer of 2008/09 was used to baseline energy savings calculations. Wherever available, 15 minute base building total HVAC energy consumption data was collected from energy sub meters along with 15 minute external temperature and relative humidity readings from nearby Bureau of Meteorology (BOM) measuring stations. The data was consolidated into daily total HVAC energy consumption (calculated for periods between 7am and 7pm to capture plant run hours while attempting to exclude after hours consumption) and daily 'work-day' average temperature, as calculated between 8:30am and 5:30pm. Daily average temperature was found to be a more appropriate explanatory variable for load than daily maximum temperature, as determined by a higher coefficient of determination (R^2) when plotting HVAC load versus temperature.

Two scatter plots were produced to compare daily average temperature with daily total HVAC consumption: one for the 2008/09 summer period and one for the 2009/10 summer period. A line of best fit was drawn for each to enable a comparison of the variation in daily energy consumption to external temperatures. To quantify the reduction in energy demand attributable to the temperature setpoint increase at each building, the daily temperature data for the 2009/10 summer was used as the independent variable in the equation for the line of best fit from the 2008/09 period and the total energy consumption was then calculated. As such, following the load response profile of 2008/09, run using 2009/10 temperatures, we were able to create an appropriate baseline for analysis. While the internal temperature setpoint was raised at 33 buildings, only 22 buildings were analysed. Several buildings were excluded from the analysis because they did not have sub-metered data for the 2008/09 period or because their operations were impacted by refurbishment works.

4.2. Dynamic intervention

Since HVAC energy requirements vary with each day's prevailing weather conditions, it is inappropriate to simply compare one day's energy consumption with the same day from the previous year. As such, a climate adjusted performance model was developed for each building using historical energy and climate data to predict what the buildings' energy consumption may have been if the dynamic intervention was not in place. This modelling utilised the multiple regression tool in MS Excel to explain the relationship of one variable to several independent variables. While it is recognised that there are more advanced and robust statistical procedures available to undertake this analysis, such as time series analysis and neural networks, multiple regression has been chosen for its useability.

The output of the regression model is a formula which infers the relationship of HVAC consumption to the climate variables. A coefficient of determination (R^2) is calculated for each building, to give an indication of the strength of the fit between the model data and the actual data over the 'learning' period. An example of the actual daily energy consumption and the regression model's predicted daily energy consumption is shown for Building 1 below (Figure 2), with an R^2=0.93.

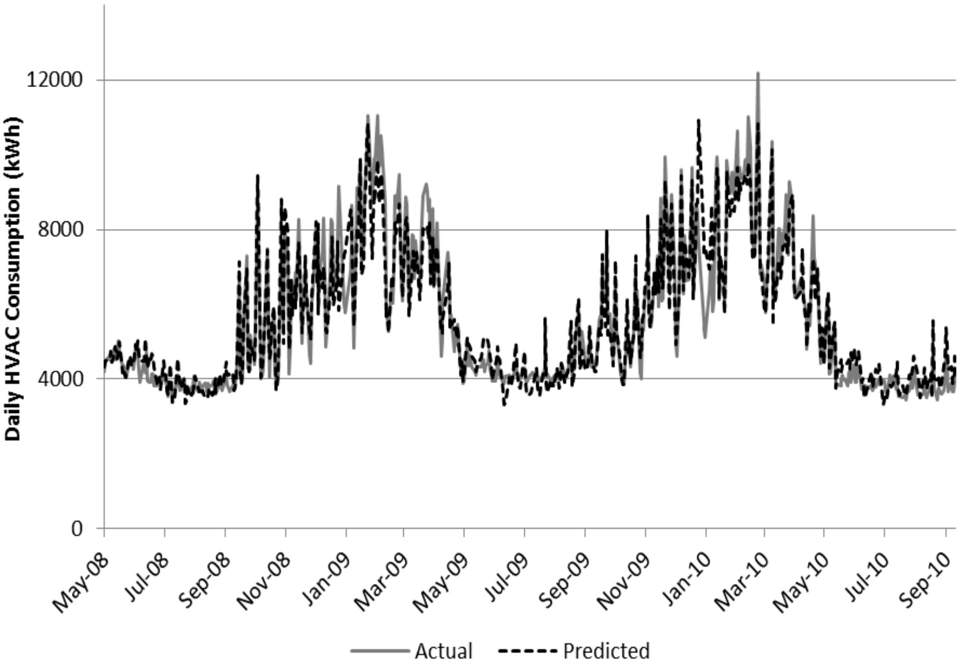


Figure 2: Actual and predicted electricity consumption for Building 1

BOM 15 minute interval temperature and humidity data was used to create the explanatory variables of daily 'workday' mean temperature, daily maximum temperature, daily 'workday' mean humidity, and overnight mean temperature and humidity. While previous studies (Ward & White, 2007; Ward *et al.*, 2008) have aimed to correlate daily energy consumption with daily temperature, few studies have incorporated the other variables into the analysis. High daily humidity often requires the dehumidification of outside air (inadvertently as air passes over cooling coils), which increases energy consumption. Overnight temperature can also influence a building's energy consumption, since warm nights maintain the stored heat load inside the building and limit the effectiveness of purge strategies. For one Sydney building, it was found that the HVAC electricity consumption on Mondays during summer was 6.4% higher than the average energy consumption for the remaining weekdays. This highlights the influence that stored heat loads may play on building energy consumption, and reinforces the need to incorporate overnight temperatures into the analysis.

Gas consumption was incorporated into the model to help explain the (generally weaker) correlation of electricity consumption to climate conditions during winter wherever 15 minute interval data was available. The day of the week was also incorporated into the regression, recognising its influence (particularly on Mondays) over daily energy consumption. Weekends and public holidays were removed from the analysis. For each building the regression 'learning' period was from the start of gathered data (generally 1.5 years of data) until the date that the dynamic adaptive comfort approach was first implemented.

5. RESULTS AND DISCUSSION

5.1. Static approach

The static setpoint increase was analysed for 22 buildings with a total NLA of 574,486m^2, including four buildings in Brisbane, five in Melbourne and thirteen in Sydney and North Sydney. Total electricity savings were calculated based on a sum of individual buildings' savings for the three cities separately and for all the buildings combined. It was found that the setpoint increase resulted in electricity savings of 2.2% in Melbourne, 7.4% in Sydney and 10.0% in Brisbane (Table 1). These findings conform with our expectation that the greater the differential between internal and external temperatures, the greater the potential for energy savings. Based on the results of the 22 buildings, we can reasonably conclude that a 1°C increase in internal air temperature setpoints between 2 November, 2009 and 31 March, 2010 led to a reduction in total HVAC electricity consumption of 6%.

Table 1: Results of static setpoint increase

	Electricity savings	Daily mean temperature	Increase in complaints
Melbourne	2.2%	24.1°C	
Sydney	7.4%	24.3°C	
Brisbane	10.0%	28.0°C	
Total	6.0%		24%

While the results show an average electricity savings of 6%, there was significant variability among buildings, ranging from a 29% reduction to a 17% increase. The factors contributing to this variability require further investigation and may include changes to occupancy, plant and equipment and management procedures. Figure 3 (below) shows the scatter plot analysis for a Sydney building that achieved a 4% saving.

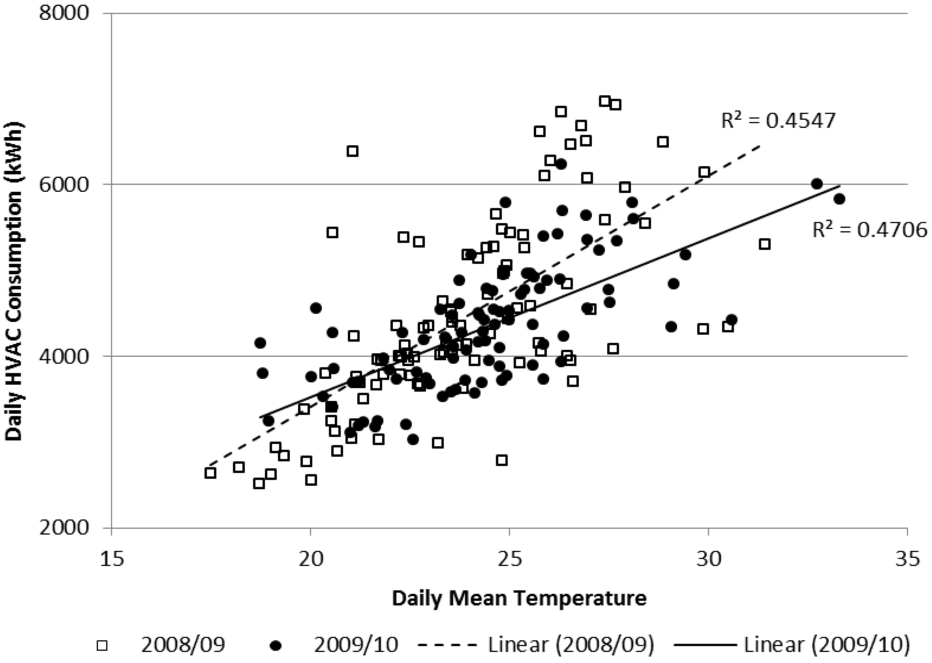


Figure 3: Static temperature setpoint increase, Sydney building

The two lines of best fit in Figure 3, which intersect at 22°C, illustrate that increasing temperature setpoints was an effective strategy for saving energy when daily mean temperatures exceeded 22°C. It was found that the strategy resulted in a small increase in HVAC electricity consumption at daily average temperatures below this point. From operational reports it was found that the zone electric reheats may have turned on during the cooler mornings when the temperature was well below the setpoint, contributing to increased consumption.

Daily total complaints have been found to be independent of external temperature when plotted against daily mean temperature. This may suggest that complaints are more closely associated with BMS control issues, rather than the setpoints *per se*. This also requires further detailed investigation. When calculating the change in complaints, as a proxy for occupant comfort, between the 2008/09 summer and the 2009/10 summer it was found that across the 22 properties analysed, complaints increased by 24%.

The tenant helpdesk recorded an increase in complaints about conditions being ‘too stuffy’. Stuffiness may be attributed to the Variable Air Volume (VAV) distribution systems operating at all of the buildings involved in the study. VAV control boxes located in supply air ductwork modulate airflow to maintain zone temperatures. Air volumes (and consequently velocities) decrease as space temperatures approach setpoint and increase again as they drift away. Anecdotal evidence and observations from this study suggest that VAV systems were limiting the opportunity for occupants to achieve comfort at the raised setpoints on mild days because of ‘stuffiness’ attributed to the limited airflow demand. This may have been less of a problem when thermal loads on the building envelopes were greater.

5.2. Dynamic approach

The complexity of the dynamic adaptive comfort approach in analysing and controlling the BMCS in real-time meant that there were significant implementation issues and delays. At the time of writing, only four buildings, three in Sydney and one in Melbourne, had fully implemented the approach. This limited the analysis. In some cases the implementation issues required that the software be taken offline at multiple times to address concerns, generally relating to temperature and duct pressure issues. With this being the case, the analysis only considered days when the approach was in operation throughout the building.

The rollout began in December 2009, however, commissioning for Building 1 only commenced in March 2010 and continued through until mid-May for building 4. Given our observation that the static method was most effective on days when the dynamic method was not operational (i.e. when daily mean temperatures exceeded 22°C), these delays have limited our ability to directly compare the two approaches.

There was a wide variation in results over the analysis period, ranging from daily HVAC savings of 15.6% at Building 2, to an increase in electricity consumption of 6.1% at Building 3. It was found that the dynamic approach has resulted in a 1.4% decrease in daily HVAC electricity consumption across the four buildings, as calculated by the difference of the actual and predicted electricity consumption (Table 2). It must be noted, however, that the strategy was only in place in late autumn and winter (when daily mean temperatures were well below 22°C).

The number of recorded occupant complaints was used to indicate the relative comfort of the occupants before and after the dynamic adaptive method was implemented. To establish a baseline, the average daily complaints was calculated for the period when the dynamic control method was not in place, and this was compared to the complaints during the time when the dynamic method was active. It was found that total complaints for the four buildings increased by 22%.

Table 2: Results of dynamic approach

	Year to date Electricity savings	Electricity savings since 1 July 2010	Daily mean temperature	Increase in complaints
Building 1	0.5%	8.1%	19.8°C	
Building 2	15.6%	6.9%	16.0°C	
Building 3	-6.1%	3.0%	16.5°C	
Building 4	2.2%	-1.3%	13.5°C	
Total	1.4%			22.1%

The dynamic approach was operational at Building 1 from the start of March, 2010, and continued for 50 days until it was removed to update the system with a new optimisation control code (to control duct pressure). It was reactivated at the end of June 2010, and from 1 July onwards (‘post-implementation’ period), savings of 8.1% have been seen. The total year to date impact, as measured against the dynamic baseline is a 0.5% decrease in electricity consumption, with a model R^2=0.93.

The approach was implemented at Building 2 in late May, 2010. It was taken offline in mid-June due to fan start problems and was then reactivated in mid-July. The net year-to-date result is a 15.6% reduction in electricity consumption, as estimated from the regression model with an R^2=0.89. An excerpt of Building 2’s actual and predicted electricity consumption profile is shown in Figure 4, with the relevant ‘online’ dates shaded in grey hatching.

In can be seen that during and proceeding the first implementation period in mid-May, the regression model significantly over predicted the daily electricity consumption. Between May 13, 2010 and June 7, 2010, the period of significant over prediction, daily mean temperatures averaged 16.7°C and daily mean humidity averaged 72.4%. It is believed that these unusual external ambient conditions are suitable for maintaining internal conditions without the requirement for air conditioning. Several other Sydney buildings experienced similar conditions, including Building 1 (where the dynamic approach was not in use at the time) where actual daily electricity consumption was 9% lower than predicted. As such, savings may have been achieved during this period with or without the dynamic adaptive strategy in place, and so attributing all the savings in this period to the dynamic approach may overestimate its benefit. Since 1 July 2010, savings of 6.9% have been observed.

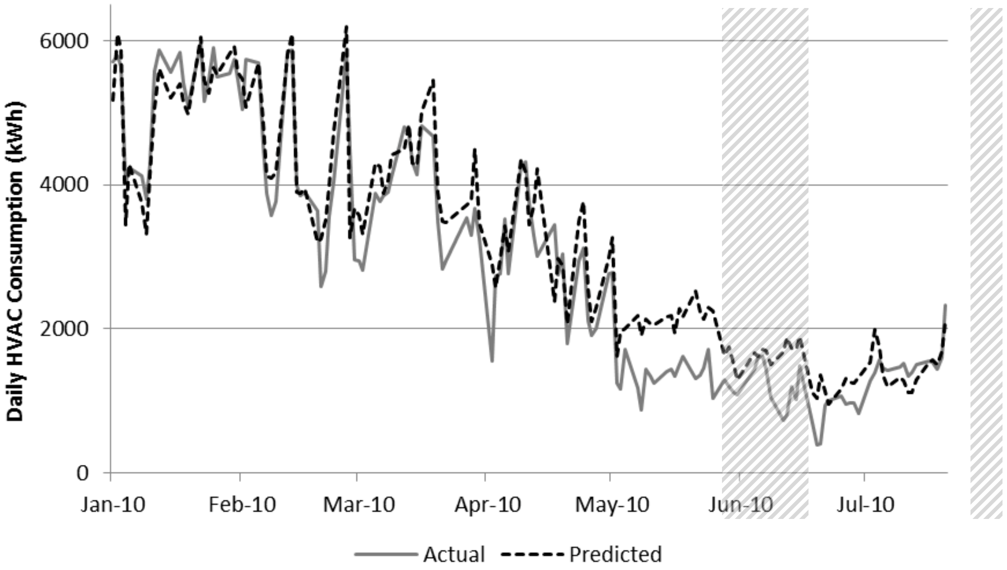


Figure 4: Actual and predicted electricity consumption for Building 2

The approach was not fully implemented at Building 3 until mid-May, 2010. Analysis suggests (with an R^2=0.83) that the building has consumed 6.1% more electricity as a result of the change, however, it must be recognised that the system was undergoing significant implementation issues and at the same time other BMCS upgrade works (potentially with their own issues) were being carried out. Recent ‘post-implementation’ savings are more promising, with 3% savings observed since 1 July 2010.

The approach was fully implemented at Building 4, the study’s only Melbourne building, in mid-May, 2010. It was disconnected in mid-June because of temperature and duct pressure concerns associated with an increase in occupant complaints. The model suggests daily HVAC energy use has reduced by 2.2% since its first implementation (R^2=0.70).

5.3. Further evaluation

The static setpoint increase was associated with moderate energy savings on the one hand and disappointing outcomes for occupant satisfaction, as expressed by the rise in tenant complaints, on the other. The dynamic approach appears to have been less successful in producing energy savings and only a little more successful than the static approach in terms of occupant satisfaction. In drawing conclusions, however, it is important to recognise that this study has not yet sufficiently tested the dynamic approach during warmer weather conditions or its post-implementation period.

Both strategies require further investigation using exploratory and explanatory methods. An expanded study is being planned for the 2010/11 summer period. The expanded study will draw on action research techniques to explain the 2009/10 results and to seek to replicate successes and eliminate factors that contributed to underperformance. The regression models developed to predict each building’s daily energy consumption will be used to provide timely and actionable feedback for the researchers and building operations staff.

Particular attention will be directed to exploring how Variable Air Volume (VAV) air distribution systems support or, indeed, undermine the effectiveness of increasing setpoints using a static method. Decreased airflow when internal temperatures were at setpoint, coupled with the rise in the setpoint, may have caused an increase in ‘too hot’ and ‘too stuffy’ complaints. Also, automatic electric ‘re-heat’ systems may have been inadvertently ‘turned on’ during cooler periods to ensure the zone temperature setpoints were maintained with a deadband of ±1.5°C. The next phase of the study will seek to identify whether this is a significant issue and suggest approaches for addressing it.

We anticipate an exploratory approach will yield additional factors that were not identified through this preliminary evaluation because a focus on atypical or extreme cases often reveals more information by activating more actors and more basic mechanisms (Flyvbjerg, 2001). Action research will then seek to establish causality.

CONCLUSION

We adopted two methods to achieve greater occupant comfort and energy savings in a portfolio of air conditioned commercial office buildings in Australia. Temperature setpoints were increased by one degree Celsius in 33 buildings and, at a subset of four buildings, an intelligent HVAC supervisory control system was introduced to constantly fine-tune the systems.

A theoretical analysis of the intelligent HVAC supervisory control system which underpinned the dynamic approach showed potential HVAC energy reductions of up to 30% without loss of thermal comfort (Ward *et al*., 2008). Predicted savings in total HVAC power demand from the static approach ranged from 5% to 10% per degree Celsius increase in summer setpoint (Ward & White, 2007). The static setpoint increase produced a 6% reduction in daily HVAC electricity consumption. The dynamic approach produced savings of 1.4%, however it was not operational until autumn 2010. This limited our ability to directly compare the two approaches. It was found that occupant comfort, quantified by frequency of 'complaints' registered with a tenant helpdesk, was adversely affected under both strategies.

These preliminary findings have significant implications for the implementation of adaptive comfort control strategies in large centrally air-conditioned commercial office buildings. Both strategies require further investigation.

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