OPTIMISATION OF SUPPLY AIR TEMPERATURE CONTROLS FOR VAV SYSTEMS IN TEMPERATE AUSTRALIA

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ABSTRACT

Previous work by the authors has identified that the selection of supply air temperature control reset schedule has the potential to influence total HVAC energy use in Australian office buildings by up to 10%. This previous work has also identified a general but not uniform trend for lower supply air temperatures, which go hand-in-hand with lower airflows, to produce generally improved efficiency relative to high temperature high flow scenarios. However these results also indicated clear evidence that such a generalisation would not always produce the best outcomes.

In this paper, the optimisation of supply air temperature control is considered in more detail using IES VE. Parameters investigated include the AHU configuration and zoning, reheat energy source, cooling energy source and the AHU load, across the temperate to subtropical climates represented by Melbourne, Sydney, Canberra and Brisbane. The results are used to generate more specific observations as to the optimisation of AHU supply air temperature controls with a view to providing better insight into the general programming of AHU controls in practice. The potential performance impacts of optimised alternatives are compared to the standard base case scenario to evaluate the potential of more comprehensive optimisation to generate additional efficiency relative to standard practice.

INTRODUCTION

Australian office buildings consume a large amount of energy in the provision of air-conditioning. The temperate Australian climate means that the associated controls play a significant role in the determination of air-conditioning efficiency. As a result, optimisation of HVAC controls is a common technique for efficiency improvement.

Previous work by the authors [Zhang and Bannister 2013] investigated the impact of a range of control parameters on Variable Air Volume (VAV) air-conditioning system efficiency for a range of Australian climates, and identified that relatively minor adjustments in control could cause significant impacts on energy use.

While most of the studies undertaken produced easily interpretable results, the results relating to supply air temperature controls indicated that further study into this area was merited. This was driven by the complexity of interactions governed by the supply air temperature control, which in effect balances fan energy, cooling energy and reheat energy against each other. It would be expected that the optimum control approach for supply air temperatures would be determined by a mix of plant efficiency, climate, fuel sources and the metric of evaluation (most particularly energy use versus greenhouse emissions). The purpose of this paper, therefore, is to examine the supply air temperature control in order to develop clearer insights into the optimisation of this important control parameter under a wider range of circumstances.

The existing literature on VAV system supply temperature control tends to fall into two categories, being either the control of supply air temperature based on outside air temperature (e.g. California Energy Commission 2003) or on a selected internal control zone temperature (e.g. Australian Institution of Refrigeration, Air-conditioning and Heating, 2011). Previous research [Ke, Y. and Mumma, S 1997; Fan, W 2008] has studied the optimisation of supply air temperature control based on outside air temperature and the impact of a few influencing factors like minimum air flow ratio, ratio of exterior zone area to total floor area, internal load and the electricity price etc.

However, in Australia and, it is suspected more generally in recent times, the use of some form of internal load proxy such as control zone temperature is used in practice. As a result, this paper uses this approach as a starting point.

As with the previous study, a base case model has been developed in IES <VE> and subjected to a range of variant scenarios across a range of climates. The modelling represents a variety of common VAV configurations. The simulation results of the base case and the scenarios have been analysed and compared to identify optimisation approaches.

BASE CASE MODEL

A typical Australian commercial office building with possible best practice HVAC system was modelled as the base case for this study. The simulation follows *NABERS Energy Guide to Building Estimation Version 2011-June* [NABERS 2011]. NABERS is The National Australian Built Environment Rating

System, which provides a benchmarking system for energy consumption of Australian commercial office buildings.

Basic characteristic

The base model has these characteristics:

- 8 storey building with underground car-park
- 50% WWR, double glaze with tint
- Uninsulated walls, R2.5 roof
- 25m by 25m floorplate, 4 perimeter and 1 centre zone per floor, the total area is 5,000m²
- HVAC: VAV system with electric terminal heating
- Floor to ceiling height 2.7m
- Plenum height 0.9m

Diagrams of such a building as shown in Figure 1 and Figure 2:

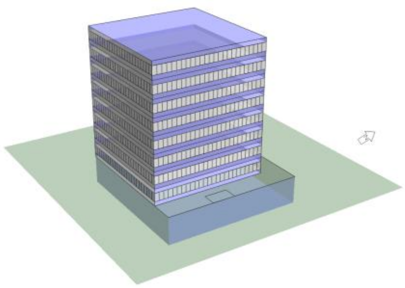

Figure 1: View of simulation model

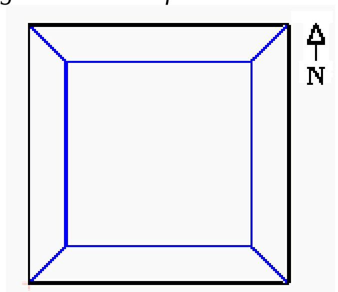

Figure 2: Floor plate showing zones

The total area is 5,000 m².

Building Construction

The following constructions were used:

- Glazing

Double glazing with the characteristics shown in Table 1 was used in the simulation.

- Opaque construction

The opaque constructions used in the simulation were as listed in Table 2:

Table 1: Glazing characteristics for the base model

Type	Construction (From outside to inside)	U value (W/m^2.K)	Shading coefficient	% Light transmittance
External glazing	6mm Pilkington Optifloat Green	2.8	0.53	76
	Air cavity			
	6mm Clear float			

Table 2: Opaque construction details for the base model

Construction description	**Material (From outside to inside)**	**Thickness (mm)**	**Total R-Value (m²·K/W)**
External wall	Concrete	150	0.53
	Air cavity	25	
	Plasterboard	12	
Floor	Carpet	6	0.41
	Concrete	150	
Underground carpark floor	U-value correction layer	50	3.39
	Ground contact correction layer	3,069	
	Concrete	200	
Ceiling	Acoustic tile	17	0.488
Roof	Metal sheeting	5	2.72
	Glass fibre	100	

Note that the total R-Values above include the surface resistances and represent typical figures in the existing building stock. The R-Value of the ground floor has been adjusted using EN-ISO 13370 method.

Building Loads

The building loads are as follows:

- Occupancy. 10 m² per occupant. Sensible load of 75 W/person and 55 W/person latent load.
- Equipment. 15W/m²
- Lighting power density. The lighting power density of 10 W/m² distributed equally between plenum and zone.

Ventilation and infiltration

The ventilation rate during occupied hours was set at 7.5 l/s/person.

The infiltration through the windows was simulated by the MacroFlo module of IES. The wind pressure coefficients were determined by the ratio of the height of the window location to the building height. A median crack flow coefficient of 0.23 $l/(s \cdot m \cdot P_a^{0.6})$ was selected to represent the average leakage through the windows. The crack length is equal to the window perimeter.

Weather file

The TRY weather file appropriate to the region was used. Building was modelled in Sydney, Melbourne, Brisbane and Canberra, which covers the cool temperate to subtropical climate zones. Temperature distributions for these centres are shown in Figure 3.

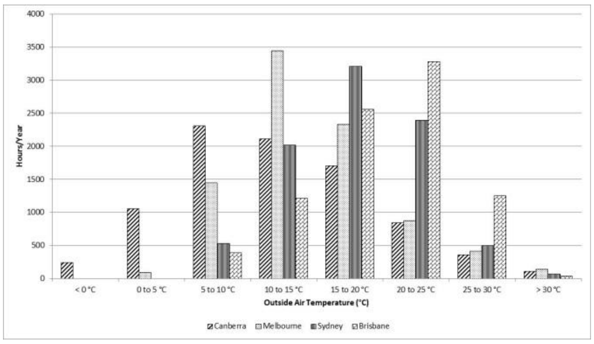

Figure 3. Outside air temperature distribution for the climates used in this study.

Modelling software

Modelling was executed in IES<VE> which was developed by Integrated Environmental Solutions Limited and has passed BESTEST accreditation. The program has been widely used in Australia and has widespread international acceptance.

Schedules of operation

The Australian NABERS schedules were used as shown in Appendix 1:

HVAC

- Zone temperature control

The zone temperature control was to 22.5 ºC with a dead band from 21.5 ºC to 23.5 ºC and 0.5 ºC proportional bands either side of this. The VAV box minimum turndown was set to 30% for perimeter zones and 50% for centre zones.

- AHU configuration

Separate AHUs were provided for each facade and for the centre zone. All AHUs were configured with an temperature economy cycle with a dewpoint lockout at 14°C and a dry-bulb lockout at 24°C. Minimum supply air temperature was set to 12°C. Supply air temperature reset from minimum to 24°C when the high select zone temperature drops from 23.5°C to 21.5°C. AHU fans were modelled as having an efficiency of 70%, motor efficiency of 90% and an $x^{2.7}$ turndown (representing variable pressure control). A total fan pressure of 800 Pa was used.

- Heating

The heating was assumed to be direct electric so that the heating required from the model was used to establish the annual energy required.

- Cooling

The chillers used in the model were a York low load water-cooled scroll chiller (YCWL0260HE50) of thermal capacity 246.2 kWr and two York centrifugal chillers (YMC2-S0800AA) of thermal capacity 798 kWr. The chilled water temperature was fixed at 6°C. Part load performance data at a range of condenser water temperatures were used to look up the Coefficient of Performance (COP) over a range of operating conditions. Three cooling towers with 7W/kW of heat rejection were modelled.

SCENARIOS

In order to examine the impact of a range of supply air temperature control regimes, a base case control and 4 bracketing scenarios were developed based on the control curves shown in Figure 4.

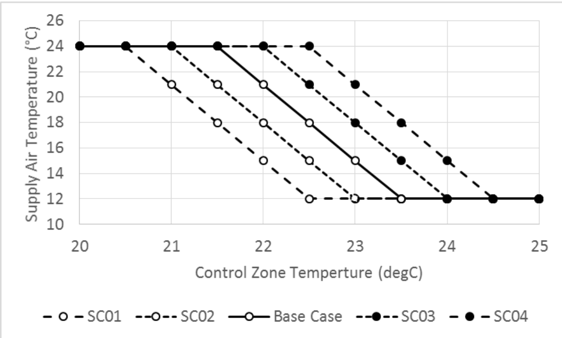

Figure 4. Supply air temperature control scenarios

These scenarios represent a range of supply air temperature control from a strong low temperature bias through to a high temperature bias. These scenarios are used as common references through multiple variations in system configuration and location presented in this paper.

The basic impact of the change in SAT control regime can be seen for the reference building in Sydney in Figure 5.

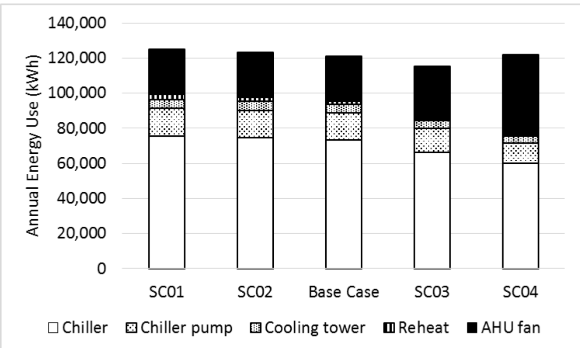

Figure 5. Impact of supply air temperature scenario on HVAC energy end use breakdown for the reference building in Sydney.

It can be seen that as the control regime moves from cooling dominated (Sc01) to heating dominated (Sc04), the fan energy increases while the chiller and reheat energy reduces, as would be logically expected.

INDIVIDUAL AHU OPTIMISATION

It is common practice to apply a single SAT control regime across all AHUs in a building. This assumes that this optimisation is correct for AHUs; in practice it is possible that different AHUs have different optimum SAT control regimes. To examine this question, the equivalent energy use for each AHU in the standard AHU configuration was calculating using AHU-specific fan and reheat energy, and a proportionate share of chiller energy based on chilled water load. The results are shown in Figure 6, which is based on reference building in Sydney.

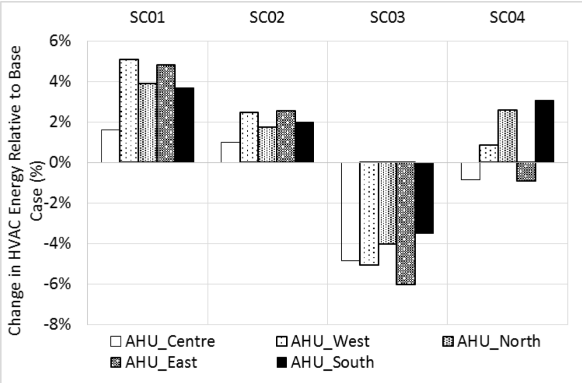

Figure 6. Effect of AHU orientation on SAT schedule optimisation.

It is clear from the figure that the AHU orientation has no impact on the optimum scenario, which is Scenario 3 in all cases for this plant configuration. This suggests that the use of a common SAT control regime for all AHUs is valid as a first order approach for further optimisation.

EFFECT OF CLIMATE ZONE

As the climate zone is varied from cool temperate (Canberra) to subtropical (Brisbane) it is reasonable to expect that there may be differences in optimum SAT control regime.

In order to review this, the reference building was simulated using representative Canberra, Melbourne, Sydney and Brisbane weather files. The results are shown in Figure 7.

The figure again shows that the overall optimisation is reasonably insensitive to climate zone for this plant configuration. However, it can be seen that there that there are significant differences in the degree of response with some evidence that the cooler climates are more biased towards the warmer scenarios. In order to test the extrapolation of this to colder climates, the scenarios were repeated for Auckland and Wellington in New Zealand. For these locations SC04 was found to be optimum, a trend which appears plausible based on the data in Figure 7.

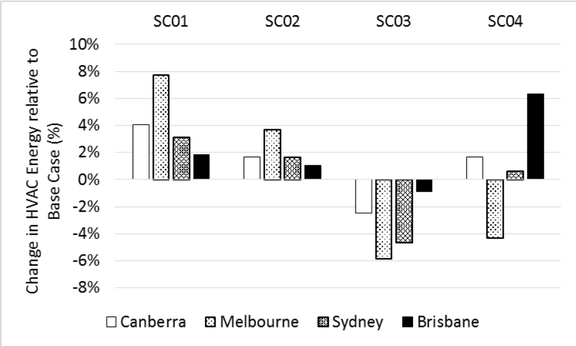

Figure 7. Effect of climate on SAT schedule optimisation.

EFFECT OF CENTRAL PLANT CONFIGURATION

Given that the optimisation is a balance of the energy use across multiple plant categories, it follows that the relative efficiency of each plant category, or the environmental impact of the associated fuel, will have a potential impact on the optimum SAT control regime.

In order to test this, the following central plant configurations were tested:

- Reference Case: Water cooled chiller, electric reheat
- Configuration 1: Water cooled chiller, gas fired hot water reheat
- Configuration 2: Air cooled chiller, electric reheat
- Configuration 3: Air cooled chiller, gas fired hot water reheat

In order to enable comparisons of multiple fuels, the energy sources being weighted by the greenhouse gas emissions coefficient (Scope 1+2+3). In Australia, these vary from state to state, as per the table below.

Table 3: Greenhouse gas emission coefficient

City/State	Electricity GHG Coeff (kg/kWh)	Gas GHG Coeff (kg/kWh)
Canberra (ACT)	1.07	0.24
Melbourne (VIC)	1.37	0.20
Sydney (NSW)	1.07	0.24
Brisbane (QLD)	1.02	0.22

The significantly higher emissions for electricity in Victoria arise from the proportion of brown coal used in generation in that state.

The effect of central plant configuration on SAT optimisation in Sydney is shown in Figure 8. It can be seen that the changes in central plant configuration affect the magnitude of changes but do not fundamentally change the optimum SAT control. This result was found to be repeated for the other cities.

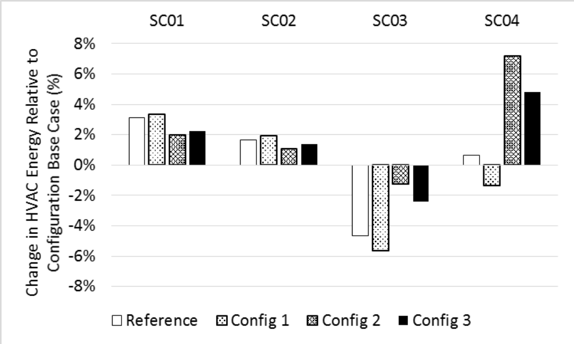

Figure 8. Effect of plant configuration on SAT schedule optimisation.

AHU CONFIGURATION

A further factor that has the potential to affect supply air temperature control optimisation is the configuration of the AHU. This is because AHU configurations where the AHUs serve multiple zones will tend to have a greater amount of reheat which in principle could result in a different sensitivity to supply air temperatures.

In order to test this, three AHU configurations were modelled, being:

- Reference Case : 5 AHUs, 1 per façade and 1 centre zone
- Zoning 1: 3 AHUs, 1 for North and West facades, 1 for South and East façade, and 1 for the centre zone.
- Zoning 2: 1 AHU serving all zones.

Each of these configurations is reasonably common for buildings in Australia.

The impact of AHU configuration is shown for the reference building in Sydney in Figure 9.

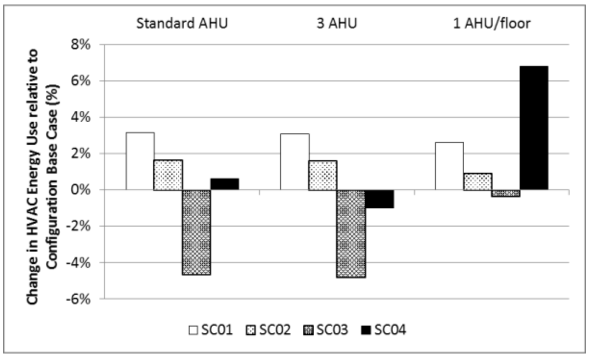

Figure 9. Effect of AHU configuration of SAT optimisation for the reference building in Sydney.

Once more it can be seen that the optimum SAT regime does not change significantly, although benefit of SC03 relative to the base case drops significantly in the single AHU case. This finding was repeated across other central plant configurations and cities, with SC03 either approaching or marginally exceeding the base case energy use.

IMPACT OF ECONOMY CYCLE

The reference building assumes the presence of a functioning economy cycle. Given the importance of the chiller energy in determining the optimum supply air temperature schedule, it follows that the operation of the economy cycle may be important as well. To test this, the reference building was simulated for each city with the economy cycle disabled. The results are shown in Figure 10.

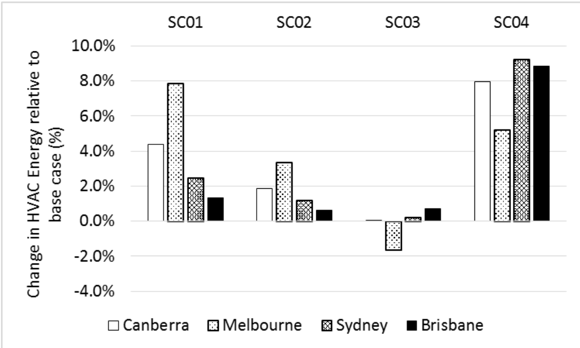

Figure 10. Effect of climate on SAT optimisation for the reference building with economy cycle disabled. For this figure, changes in HVAC energy are measured relative to the reference building base case with no economy cycle.

It is notable in Figure 10 that the optimum SAT scenario has become the base case in all centres other than Melbourne, where Scenario 3 is marginally favoured; however it should also be noted that the difference between the performance of the base case and that of Scenario 3 is at best marginal.

IMPACT OF PROPORTIONAL BAND

All the analyses presented to this point have changed the supply air temperature from maximum to minimum across a 2°C proportional band, which is common industry practice. However, it is worthwhile to test the validity of this approach. In Figure 11, the reference building is simulated using narrower proportional bands. The narrower proportional band produces a better overall performance than the wider bands, to a limit of a proportional band of around 0.5°C, albeit with best results at a 23.5°C midpoint rather than rather than a 23°C midpoint as occurred with a 2°C proportional band.

It is relatively easy to conceptualise why this might be the case: in essence, the function of a wide proportional band is to balance the needs of multiple diverse zones. In the reference building simulation, the AHUs each serve zones that are highly thermally similar, and thus there is little diversity in the heating and cooling needs of the zones. By contrast, an AHU servicing multiple diverse zones would be expected to have a higher optimal proportional band.

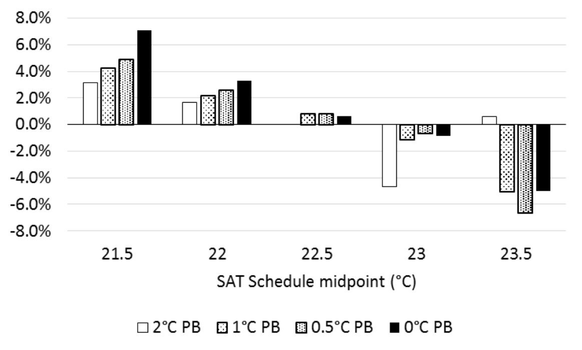

Figure 11. Effect of SAT schedule proportional band on SAT schedule optimisation in Sydney. Note that the reference building base case is equivalent to a 22.5°C midpoint with a 2°C proportional band; changes in HVAC energy are measured relative to this scenario.

WEATHER/SEASONAL IMPACTS

The previous analyses are all based on the assertion – and common industry practice – that a single reset can be used to optimise performance for a whole year. To investigate this is necessary to review the optimisation of the reset against the obvious variables of season and external temperature.

In order to undertake this somewhat more complex optimisation, it is helpful to simplify the analysis process by focussing on a single HVAC configuration, plant configuration and climate rather than working with multiple options and variations. This approach is, at least partly, vindicated by the apparent insensitivity of the optimum schedule to these variables demonstrated in the previous analyses.

As a result, the next series of analyses focus on the optimisation of the reference building in Sydney.

The simplest analysis of impacts is to review which supply air temperature reset scenario is optimal in each month of the year. This is shown in Figure 12.

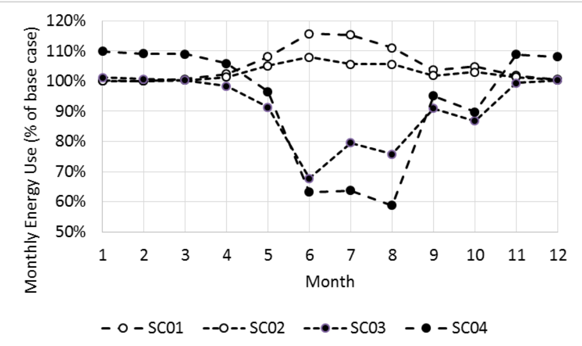

Figure 12. Performance of scenarios as a % of base case energy performance for the base case building in Sydney

It is apparent from Figure 12 that the apparent annual optimum schedule (Scenario 3) is actually a compromise across nearly every single month. This makes a strong argument that a single fixed schedule is a sub-optimal approach. However, the benefit is marginal, with annual performance based on selection of the optimum schedule for each month only achieving a savings of 1.7% relative to Schedule 3 (6.4% improvement relative to base case).

A further insight into this can be obtained by identifying the optimum schedule against outdoor temperature. This is presented in Figure 13 for the South AHU.

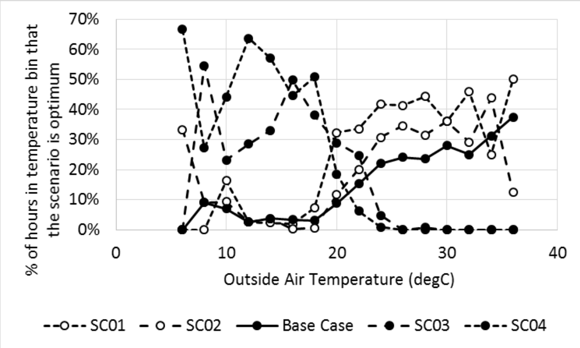

Figure 13. Optimum temperature schedule as a function of outdoor air temperature for the south AHU. X-axis values are based on 2°C temperature bins ending at the value shown on the axis. Results for each AHU are different.

For Figure 13, the optimum schedule in each hour has been selected and categorised for each temperature bin for the south AHU only. It is immediately apparent that the true optimum schedule is not a mid-range schedule such as represented by Scenario 3, but rather a dynamic schedule with a strong influence from outside air temperature. As these results for each AHU are different, this would imply different schedules for each AHU, which represents a level of customisation that would be difficult to replicate in practice. As a result, a simplified approach has been taken utilising one outdoor air temperature reset schedule for the centre zone AHU and one for the four perimeter AHUs. These are shown in Figure 14.

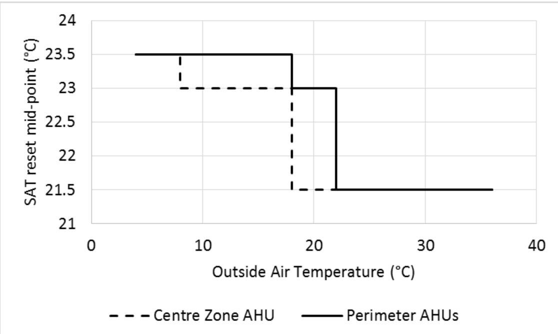

Figure 14. Optimised adjustments to the SAT reset schedule based on the reference building in Sydney. The adjustment are applied by changing the midpoint of the SAT reset schedule; for instance, if the midpoint is 23.5°C then the in effect schedule 4 is used.

Applying the outside air temperature adjustments in Figure 14, one obtains a reduction in energy use of 7%

relative to the base case, or 2.3% better than the simple fixed schedule optimum (schedule 3), a result that would appear worth the additional complexity of the outside air temperature adjustment.

However, for this type of adjustment to be truly useful, it would need to be able to be applied universally. To test this, the OAT schedules shown in Figure 14 were used on the reference case building in the other climate centres. Results are shown in Figure 15.

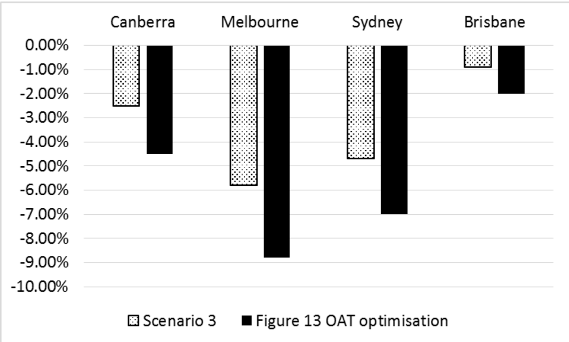

Figure 15. Impact of the application of the outside air temperature optimised schedule for all four climate centres, relative to previous optimum (Scenario 3). All figures measured relative to the base case.

It can be seen that the adjustments made in Figure 14 do indeed produce further optimisation of the performance in each climate centre. This indicates that the approach has potential for use as a universal improvement relative to the best available alternative.

However, the response to outside air temperature adjustment of the supply air temperature reset was found to be complex; several credible alternatives to the Figure 14 adjustments were also evaluated but did not produce as good results. In particular, it seems clear that the abrupt change in optimum schedule at or around a notional balance point temperature is a critical feature of an optimised approach. In practice, this creates risks as the balance point temperature will in practice vary with internal as well as external loads.

CONCLUSION

This paper has reviewed the impact of a wide range of factors on the selection of an optimum algorithm for supply air temperature control. For the mild temperate climates of Australia, the temperature schedule represented by Scenario 3 in this study proved robustly optimal in almost all situations, implying that this optimisation is relatively trivial.

However, closer investigations shows that this Scenario is a compromise between warmer and cooler supply air schedules during cooler and warmer external conditions (respectively). A simple monthly reset and a simplified outside air temperature adjustment were tested and it was found that both could be used to achieve moderate improvements over the previously optimum Scenario 3. Application of the simplified outside air temperature adjustment demonstrated that the improvement in performance associated with this approach was robust to climate. This indicates that combination of a supply air temperature reset schedule with an outside air temperature adjustment has the potential to produce robust improvements in performance without necessarily requiring custom modelling and evaluation on a case-by-case basis.

However, this result was tempered by the finding that the achieved improvement in performance was relatively sensitive to the detail of the application of the outside air temperature adjustment. In particular, the relatively abrupt change reset schedule midpoint around the notional balance point of the zone was found to be a sensitive parameter in the optimisation. Similarly, it was also found that a narrow proportional band for the supply air temperature reset was also beneficial, again indicating the operation of a notional balance point. As in practice the balance point of a zone is dependent on internal load, forward prediction of this sensitive parameter will be difficult in practice. The various levels of proportional band for both the zone temperature to supply air temperature relationship and the outside air temperature to supply air temperature relationship tested in this study reflect the real-world compromise by which this variability is handled. However, the use of proportional bands will reduce the efficiency of the system relative to ideal.

Future work, therefore, needs to focus on means of capturing the findings of this project into an algorithm that is more self-adaptive to the needs of an actual building. This is likely to involve adjusting the supply air temperature schedule based on zone demand or temperature deviation as well as – or instead of - outside air temperature.

REFERENCES

NSW Office of Environment and Heritage. 2011. NABERS Energy Guide to Building Energy Estimation.

Integrated Environmental Solutions Limited. 2012. IES<VE> User Guide.

Zhang, H. and Bannister, P. HVAC Control Simulation Study for Australian Office Buildings. Building Simulation 2013, Chamberey, France 25-28 August 2013.

Fan, W. Optimization of Supply Air Temperature Reset Schedule for Single Duct VAV Systems. Master Thesis of Texas A&M University, Texas, US. December 2008.

Ke, Y. and Mumma, S. Optimized supply-air temperature (SAT) in variable-air-volume (VAV) systems. Volume 22, Issue 6, Energy. June 1997.

California Energy Commission, Advanced Variable Volume Air-Conditioning Design Guide, October 2003

Australian Institute of Refrigeration, Air-conditioning and Heating, Design Application Guide DA28 Building Management and Control Systems, 2011. Available at www.airah.org.au

APPENDICES

Appendix 1 - Australian NABERS schedule

Table 4: Australian NABERS schedule for Weekdays

Time Period	Occupancy	Lighting (limited control)	Equipment	HVAC Operation
0000-0100	0%	15%	50%	off
0100-0200	0%	15%	50%	off
0200-0300	0%	15%	50%	off
0300-0400	0%	15%	50%	off
0400-0500	0%	15%	50%	off
0500-0600	0%	15%	50%	off
0600-0700	0%	15%	50%	off
0700-0800	15%	40%	65%	on
0800-0900	60%	90%	80%	on
0900-1000	100%	100%	100%	on
1000-1100	100%	100%	100%	on
1100-1200	100%	100%	100%	on
1200-1300	100%	100%	100%	on
1300-1400	100%	100%	100%	on
1400-1500	100%	100%	100%	on
1500-1600	100%	100%	100%	on
1600-1700	100%	100%	100%	on
1700-1800	50%	80%	80%	on
1800-1900	15%	60%	65%	off
1900-2000	5%	60%	55%	off
2000-2100	5%	50%	55%	off
2100-2200	0%	15%	50%	off
2200-2300	0%	15%	50%	off
2300-2400	0%	15%	50%	off

Table 5: Australian NABERS schedule for weekends and holidays

Time Period	Occupancy	Lighting (limited control)	Equipment	HVAC Operation
0000-0100	0%	15%	50%	off
0100-0200	0%	15%	50%	off
0200-0300	0%	15%	50%	off
0300-0400	0%	15%	50%	off
0400-0500	0%	15%	50%	off
0500-0600	0%	15%	50%	off
0600-0700	0%	15%	50%	off
0700-0800	0%	15%	50%	off
0800-0900	5%	25%	55%	off
0900-1000	5%	25%	55%	off
1000-1100	5%	25%	55%	off
1100-1200	5%	25%	55%	off
1200-1300	5%	25%	55%	off
1300-1400	5%	25%	55%	off
1400-1500	5%	25%	55%	off
1500-1600	5%	25%	55%	off
1600-1700	5%	25%	55%	off
1700-1800	0%	15%	50%	off
1800-1900	0%	15%	50%	off
1900-2000	0%	15%	50%	off
2000-2100	0%	15%	50%	off
2100-2200	0%	15%	50%	off
2200-2300	0%	15%	50%	off
2300-2400	0%	15%	50%	off

The schedules above are effectively for a building operating with comfort conditions from 08:00 to 18:00 hours with an hour's warm up of the HVAC system. This is 50 hours per week