An Adaptive Comfort Approach to Air-Conditioning

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Abstract- Do we need air-conditioning in Brisbane? If so, how much? The surprisingly complex answers to these simple questions are explored through quantitative modelling and then validated via three years of data-logged operation.
The conservative nature of heat load inputs has led to arguably widespread oversizing and associated energy and comfort problems.
Calculation of peak load from an industry standpoint is examined. The inputs to the tools – such as setpoints, outside air and thermal mass – are varied to determine those with greatest impacts.
An argument for dynamic, non-traditional setpoints is made, using thermal comfort and adaptive comfort-based models.
An integrated approach to design – with the control of radiant heat, enthalpy recovery ventilation, phase change materials, air velocity control, airtightness and humidity control – was used to halve air-conditioning sizing (i.e. peak heat load).
A case study residence was constructed and logged for three years. The first two years had no air-conditioning. The results are presented to demonstrate the usefulness (or not) of the initiatives and how the residence performed compared to the thermal comfort bands. The residence was found to not achieve adequate thermal comfort for several days during Summer.
One year's data with air-conditioning is then presented to demonstrate the suitability of the peak load reduction methods. Electrical energy data was simultaneously collected. Together this showed whether the "aggressively small" sizing methodology was suitable.

Index Terms- Air-conditioning, sustainable design, HVAC

INTRODUCTION

Give a set of plans to five mechanical designers and you'll get five peak loads ($kW_{thermal}/m^2$) and energy consumptions ($kWh_{thermal}/m^2.ann$).

If you were to go to that building and interrogate the BMS to determine the peak load, it is likely the actual peak load will be well below the estimated peak load. This is a known problem in the industry (Thomas & Moller, 2006), and has often been personally observed.

In a perfect world, with perfect equipment, it would not matter – the units would just turn down to the required load. In practice, oversizing typically increases energy consumption due to the following:

- If the controls are not quite right, which is common, the building will use more energy. For example, consider a zone with an open window and a large unit, compared to a moderately sized one.
- The potential for fighting (e.g. with duct heaters) is increased.
- Thermal comfort suffers as the large units fail to trim cooling effectively.
- Occupants become habituated to over-cooling and descend into a cold-spiral led by one vocal person who wants it 20°C in Summer.

Also, higher theoretical loads need larger ducts, ceiling spaces and the like. These costs are often hidden to decision makers.

In practice, an oversized design has the possibility to be worse than an appropriately sized system in terms of energy, comfort, and cost. We should not over-size plant, but we do. Our five designers had to account for lots of unknowns, so assumed worst-case inputs, then added on a bit "just in case".

In short, there is significant risk in appropriately sizing systems, and little risk in oversizing. There are few incentives for our designers to reduce oversizing heat loads.

Here, we will systemically address the inputs that determine the heat load, by suggesting a thermal-comfort approach. After all, we air-condition to provide thermal comfort, not for its own sake.

The case study house provides a simple, easy-to-control and flexible case study. It likely provides a "best-case" scenario in terms of occupant satisfaction, compared to public or commercial buildings.

AIMS

Specifically, we aim to answer the following questions:

- How can we quantify enough air-conditioning for "adequate comfort"?
- Theoretically, does a well-designed house in Brisbane require any air-conditioning for "adequate comfort"?
- In practice, how (un)comfortable is a well-designed, un-air-conditioned house in Brisbane?
- Theoretically, how can we reduce peak load and energy consumption in our designs?
- Is it practical to implement these strategies (i.e. are they "build-able")?
- In practice, do these reductions work?

METHOD

Identifying elements to reduce peak thermal load

Various methods, from simple watts-per-square-metre to complex computer modelling, exist to estimate the peak load. Different approaches and software will give different results. We will stick with CAMEL, a relatively simple and widely used piece of software, to estimate peak thermal load in the building. The following options were considered to reduce peak load:

- Minimising and/or heat exchanging outside air
- Using good passive design principles (shading, orientation, etc.)
- Good insulation and glazing
- Differing amounts of thermal mass
- Setpoint modification to reflect thermal comfort requirements.

In this study, we look particularly at the impact of designing for thermal comfort, instead of a "standard" setpoint.
A single storey, 100m² new-build house in Brisbane was used as the case study. Results of the CAMEL runs are shown in Figure 1. We start with an estimate of 125W/m² (including outside air supply) and work through the options.

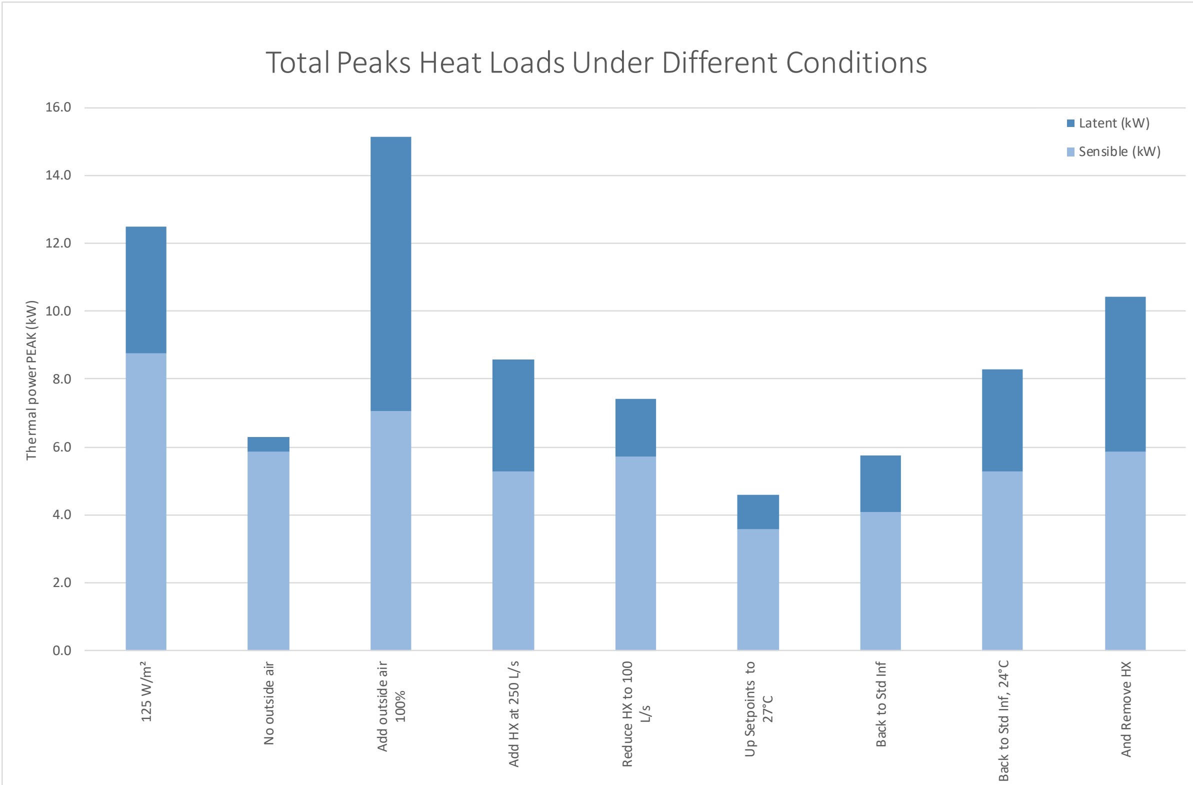

Figure 1 - Peak Heat Loads - Change to Adaptive Comfort (27°C) Selected

Some care is required in interpreting results, as they are dependent on house geometry and the like. However, some conclusions can be drawn:

- The last option, at about 11kW is close to the initial 125W/m² estimate. It represents normal setpoints, normal leakage and normal outside air rates. Although the design had good passive performance, the small area means this 100W/m² "feels" about right.
- The selected option is about 5kW, or less than half the "typical" heat load.
- Changing the thermal mass on the selected option had almost no effect on the peak load. (Not shown on figure.)

We break down the selected option (i.e. 5kW peak load) into its constituent parts, to see where the heat is coming from. These are shown in Figure 2.

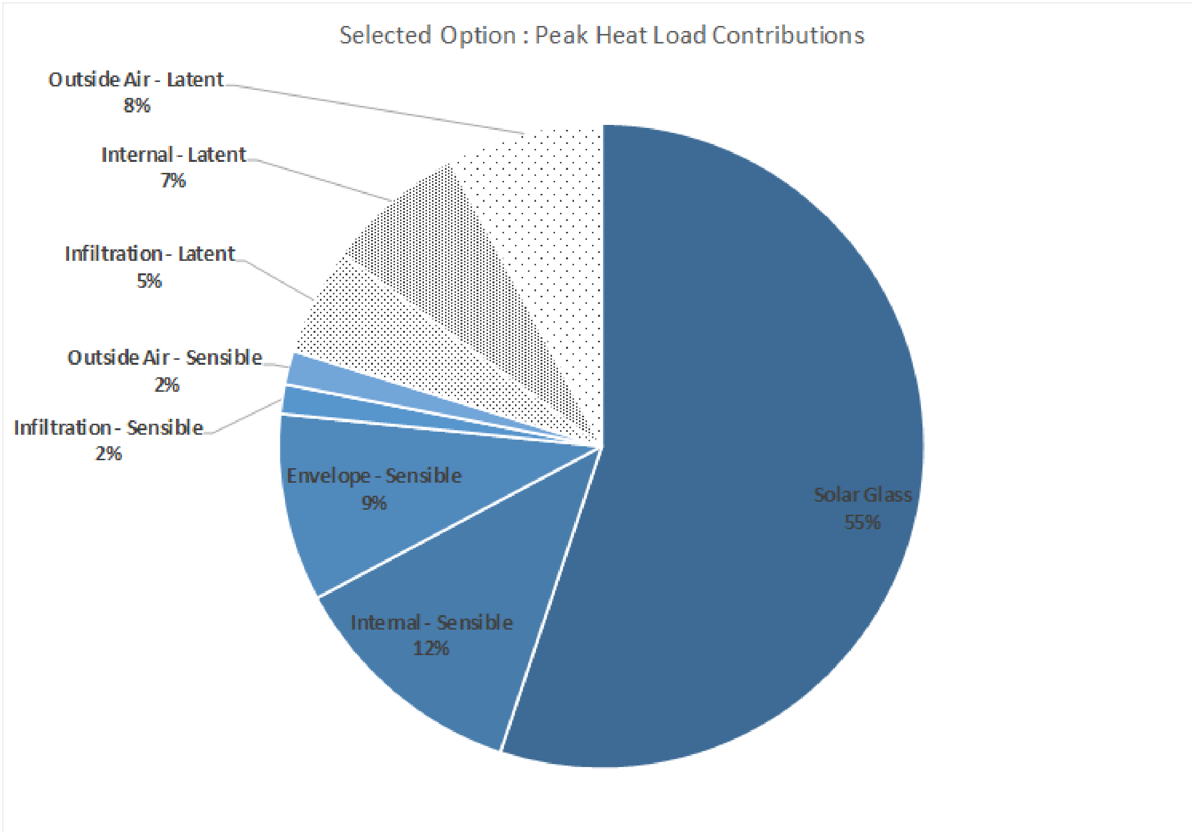

Figure 2 - Selected 5kW Option – Breakdown

These results suggest that to reduce thermal peak load we can (most important first):

- Manage glazing – a reasonable wall has insulation of R3.0. A standard window has an insulation value of R0.2. Even the best windows (double or triple glazed) are only R1.0. On top of this, the solar gain (i.e. radiation) in direct sun is around 1000W/m². Both these figures are included in “Solar Glass”.
- Manage Outside Air – indoor environment quality requires fresh air. A heat exchanger is a simple option to reduce both sensible and latent load from outside air. Removing the heat exchanger adds 26% to the heat load.
- Infiltration – often overlooked, changing infiltration from “low” to “normal” added 24% to the heat load.
- Setpoints – changed from 27°C to 24°C adds 44% to the heat load.

Addressing Identified Elements to Reduce Peak Thermal Load

We address the significant elements, which were identified via the options study.

Adaptive Comfort, Air Movement and Setpoints

Traditional setpoints are around 21 to 24°C with a deadband of 1K. The use of traditional setpoints affects occupants' behaviour (e.g. clothing choice) and expectations. This in turn feeds back to facility managers via their expectations. It is a reinforcing loop. Hence "traditional" here does not necessarily mean "right", but rather the "status quo" – there does need to be grounds for modification.

These setpoints are based on traditional, male office attire with no adaption to local climate allowed for. Others (De Dear & Brager, 2002) have tried to raise setpoints to save energy. A dynamic setpoint was found to be similar in performance to a static one (Roussac et al., 2011). Instead of "just one degree more", can we find a basis to select the setpoints?

The standard thermal comfort metric is Predicted Mean Vote (PMV). Adaptive Comfort – described in ASHRAE Standard 55 (De Dear et al., 1998) – allows for climatic adaption. (*Further details can be found in the references.*) Adaptive comfort requires the occupants have exposure to the outside conditions. This is generally the case in houses and mixed-mode buildings, but not the case in fully air-conditioned offices and public buildings.

We calculate the adaptive comfort metrics for Brisbane in Table 1. These provide the theoretical limits of comfort and were used to quantify "good" thermal comfort.

Table 1 PMV and Adaptive Comfort

Air Temp. °C	Radiant Temp. °C	Air Speed m/s	PMV	PMV	Adaptive Comfort
19.2	19.2	0.1	-0.5	Cool	80% Comfort Level in Brisbane Winter
20.2	20.2	0.1	-0.4	Cool	90% Comfort Level in Brisbane Winter
28.3	28.3	0.1	1.2	Hot	80% Comfort Level in Brisbane Summer
29.3	29.3	0.1	1.5	Quite Hot	90% Comfort Level in Brisbane Summer

According to these metrics, a mostly naturally ventilated house in Brisbane should be reasonably comfort up to a seemingly high 28°C. A slightly more conservative 27°C is used in this test.

Infiltration

For commercial buildings, infiltration figures used are typically 0.25 – 0.50ACH. For this case study we used 0.25ACH, which is roughly equivalent to a permeability of 4.0m³/hr/m². Note the units of Air Permeability and ACH are not strictly comparable directly (AIRAH Building Physics Special Technical Group, 2017). This is a reasonably "tight" building, but far from the benchmark Passivhaus standard.

Door blower tests were conducted post-construction. The results are in bold in Table 2. The actual infiltration was 0.19ACH, so slightly less infiltration could have been modelled.

To examine the effect of infiltration on the heat load, an infiltration of 1.0ACH (about 23m³/hr/m²) was used. This sits between an "Old Queenslander" and a "Decent Queenslander". Think of a typical house without gaping holes, but many small cracks.

Table 2 Infiltration Rates for Various Buildings

Name	**Air Permeability m³/hr/m²**	**ACH50**	**ACH "Natural" (approx.)**
Old Queenslander	**23**	**26**	**1.3**
AIRAH houses in Canberra test	23	18	0.9
Old Queenslander with easy fixes	10	11	0.6
UK Building Code	10	-	-
USA typical house	7.8	6.0	0.3
Case Study Road House	**3.7**	**3.9**	**0.2**
Australia proposed best practice	3.0	-	-
Passivhaus	*0.8*	0.6	0.03

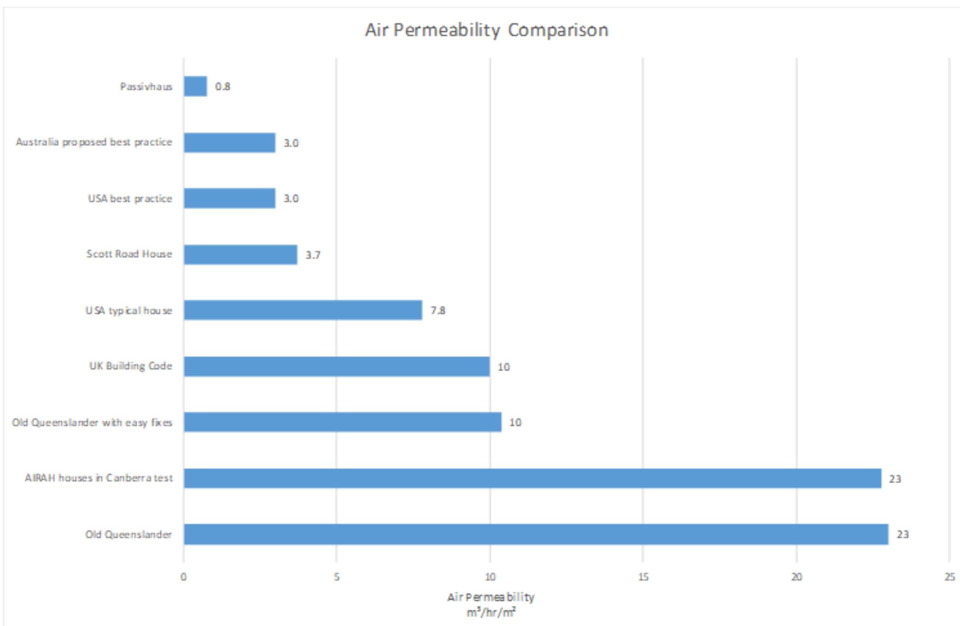

Figure 3 Infiltration Rates for Various Buildings

By using the reduced infiltration of 0.25ACH, we avoid a 24% increase in peak load. This level of building sealing is not difficult to achieve, even with "standard" windows and doors.

Outside Air

If infiltration is reduced, mechanical ventilation is required to provide fresh air when the building is closed. A 100L/s enthalpy plate heat exchanger was used. It is simple and cheap.

Glazing

Standard single glazing with reasonably well-sealing windows was used. Double-glazed, more air-tight windows are available, at extra cost. A low-E coat on the inner surface and a light tint provided an SHGC of 0.63, and good shading was used. Casement aluminium windows were selected for better air-sealing (compared to sliding) and open-ability (compared to awnings).

Air-Conditioning

A reverse-cycle ducted unit (5.2kW cooling) was selected. It serves the whole house (100m²) via ducting. Due to good passive design and shading, heat load ratios do not vary much between zones. This allows for a simple system without active dampers for zone control. Similarly, temperature sensors in a return air and control panel in the centre of the house are sufficient for control.

Design methods to reduce thermal energy requirements

Energy efficient design usually focuses on just that – energy. We cross-check our peak thermal load reduction strategies against energy-reduction strategies. We will typically see reduced energy use with a design that reduces peak thermal load. However, in some cases only one (peak power or year-round energy) will be affected.

For houses, NatHERS (with the Chenath thermal simulator) is the standard, so we use that to determine thermal energy required to condition a house, although it is not as sophisticated or flexible as other programs.

The design process starts with clear glazing and no shading. Figure 4 shows the results of various improvements. As expected, good "passive design" – insulation, glazing and shading – provide the easiest improvements. The addition of ceiling fans is a significant benefit – the thermal engine allows for the cooling effect of air ('Nationwide House Energy Rating Scheme (NatHERS) Administrative and Governance Arrangements,' 2015). This relates back to our original peak-load reduction strategy of setpoint increases. Adaptive comfort does not account for air speed, but the related metric of PMV can estimate its effects (see #1 and #2 in Table 3).

The marginal benefits of additional measures (shading, thermal mass) initially make them unappealing. Instead of overlooking them, we can cross-check against the peak-load results and per-zone benefits. For example, movable shading is of marginal benefit energy-wise. However, it reduces peak load by 20W/m² in some zones, and greatly improves thermal comfort in these (see #3 and #4 in Table 3, which model sitting near a warm window surface).

Table 3 - Thermal Comfort Equivalences (RH: 50%, Met:1.2)

#	DB °C	Radiant °C	Air Speed m/s	PMV	Note
1	24	24	0.1	**0.0**	2K ambient increase...
2	26	26	0.6	**0.0**	... is offset by 0.6m/s air speed
3	24	27	0.1	**0.4**	A 3K increase in radiant temperature ...
4	27	24	0.1	**0.4**	... is roughly equivalent to the same increase in air temperature

The same argument – that peak block load, peak zone load and total energy should be considered – can be made for thermal mass, improved air-sealing and detailed shading.

Name	Walls R_con	Roof R_con	Floor R_con	Windows	Heat MJ/m²	Cool MJ/m²	Cost (1)
2 Bad windows - DTS without Shading	2.8	4.1	0.0	U7 SHGC 0.77	31	183	$ 297
3 Add shading - DTS	2.8	4.1	0.0	U7 SHGC 0.77	31	148	$ 240
4 Add deck shading	2.8	4.1	0.0	U7 SHGC 0.77	39	96	$ 156
5 Add better windows	2.8	4.1	0.0	U5 SHGC 0.50	39	73	$ 118
6 Add more insulation	4.5	6.0	2.0	U5 SHGC 0.50	11	70	$ 113
7 Add ceiling fans	4.5	6.0	2.0	U5 SHGC 0.50	12	43	$ 70
9 Add movable shading lourves	4.5	6.0	2.0	U5 SHGC 0.50	5	46	$ 75
10 Add detailed east/west window shading	4.5	6.0	2.0	U5 SHGC 0.50	4	43	$ 70
11 Add lighted coloured roof and walls	4.5	6.0	2.0	U5 SHGC 0.50	4	41	$ 66
14 Add medium weight walls and floor	*4.5*	*6.0*	*2.0*	*U5 SHGC 0.50*	*5*	*39*	*$ 63*
12 Test only: Super windows	4.5	6.0	2.0	U2.7 SHGC0.64	1	48	$ 78

Figure 1 - Thermal Energy Consumption According to NatHERS (COP: 3.0, 25c/kWh)

Based on these analyses, the following additional elements were incorporated in the design:

- Good thermal insulation – R6.0, R4.0, R2.0 to the roof, walls and floor
- A medium amount of thermal mass.

PRACTICALITIES OF IMPLEMENTING THE MEASURES

It is one thing to specify the performance requirements, but another to implement them cost-effectively. The perceived risk and uncertainty implementing energy efficiency measurements limits their uptake. In this case I acted as designer, client, and builder, as I was able to implement the nominated measurements. The following summarises the procurement and construction process:

Infiltration – implemented through a vapour permeable, taped membrane and square-set plasterboard. A re-usable foam gun, quality tape and attention-to-detail were all helpful. Material costs were negligible since standard windows and doors were used. (Tests show the bulk of the leakage was via these doors and windows.)

Shading – larger eaves (1200mm) were not difficult to design or build, but some research was required as they are non-standard in Brisbane.

Thermal Mass – a concrete slab was not practical for this site. Instead, 19mm cement sheeting was used as the subfloor (instead of particle-board) and a phase-change material was used behind the ceiling plasterboard. According to the manufacturer, this has the latent equivalent energy of 100mm of concrete's sensible energy storage.

Adaptive Comfort with Local Control – in addition to the air-conditioner, ceiling fans were installed throughout.

RESULTS

The house was monitored for energy consumption on each circuit and temperatures in key locations.

To test the “free-running” (i.e. without air-conditioning) performance, no air-conditioner was installed during construction, but ducting and an isolator were provided. The house was occupied for 18 months, and data logged, then air-conditioning was installed. The house was occupied for the next summer period with air-conditioning available.

Free Running Results

A close-to-design day was selected to access performance. The temperatures (“LivingWithPCM”) in the main space is shown in Figure 5. Notice the peak internal temperature is delayed by the thermal mass to 18:00, and the peak internal temperature was 28°C. The adaptive comfort metric predicts this will (just) be comfortable. Do we even need air-conditioning?

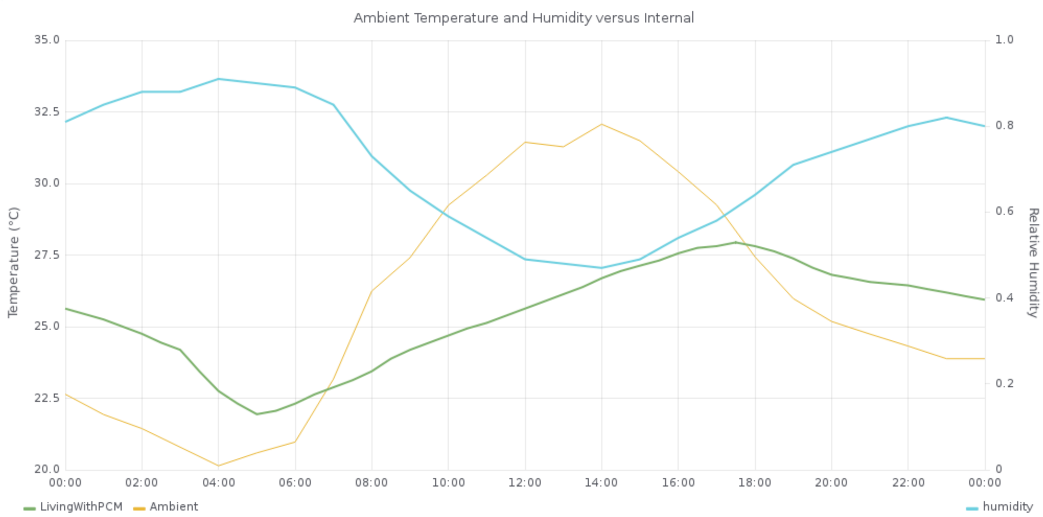

Figure 5 - 23 January 2018 - Design-day-like (32DB/24WB) - Free Running

On the worst-case day, the outside temperature ranged from 23°C to 36°C. This provides no opportunity to cool the PCM (melting point: 23°C). The internal temperature rose to 31°C with (external) humidity at 70%. This is theoretically uncomfortable (PMV 1.9 even with Summer clothing and air movement) and was indeed reported as uncomfortable by the occupants.

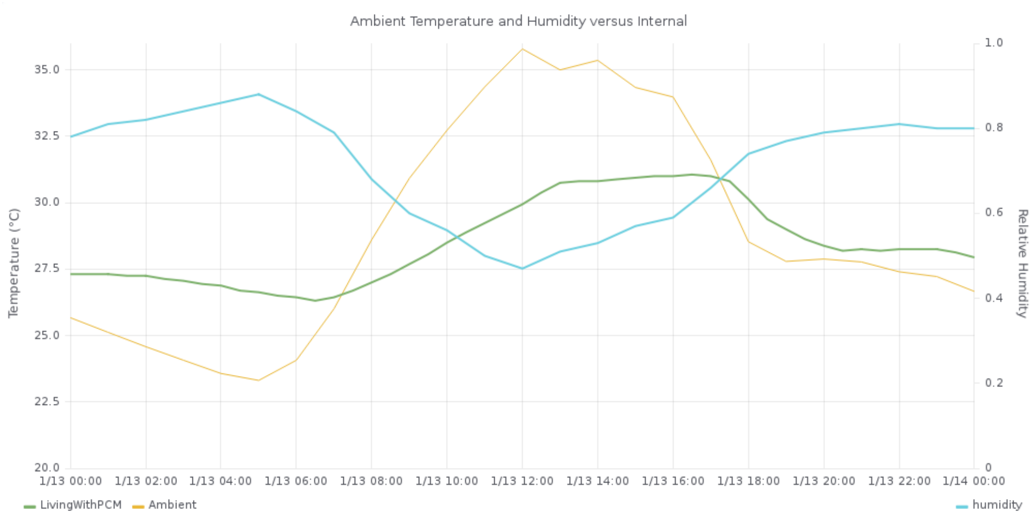

Figure 6 - 23 January 2018 – Worst-case Day (36°+)

If we look at all the temperatures throughout the year (Figure 7), we see 4.5% of hours above adaptive comfort 80% temperature of 28.3°C.

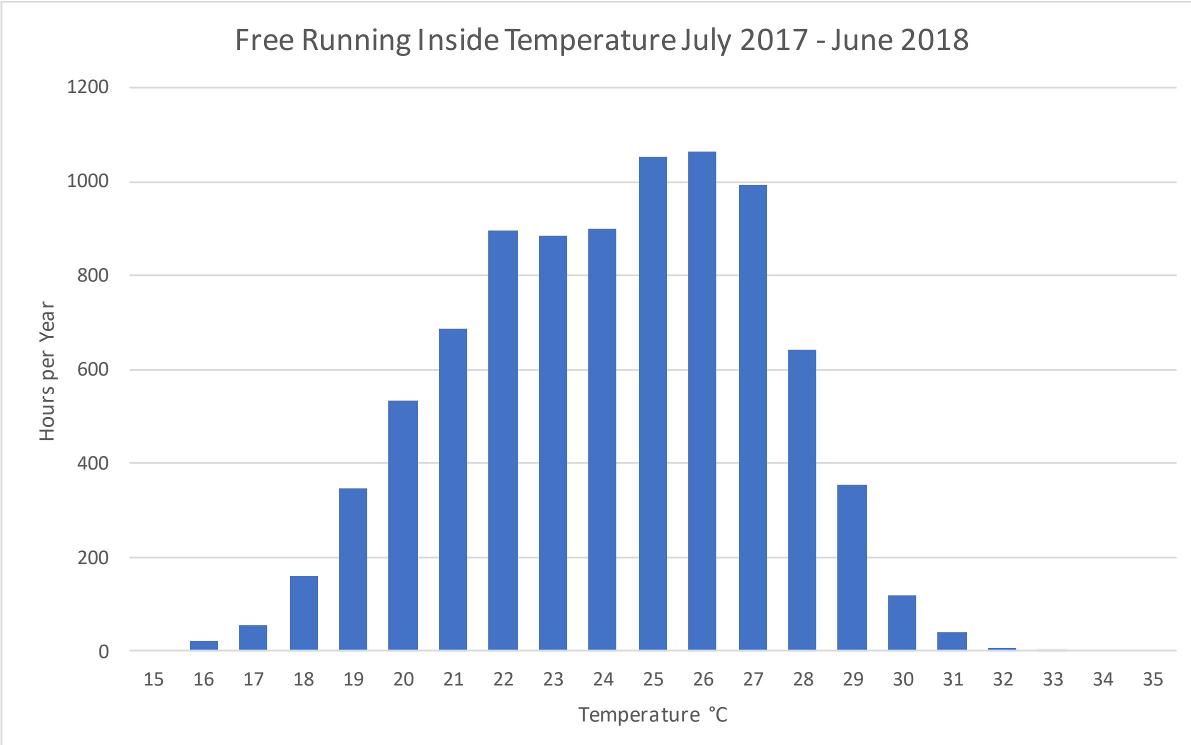

Figure 7 - Frequency of Internal Temperature in a Free Running House

This answers our original question – "do we really need to air-condition for comfort?" We do – but not for very long. Refer to the Conclusions for discussion.

Peak Load Results

We do not expect our peak load calculation to cover every hour, but we do expect it to "meet setpoint" on a design day. A real day with design-day-like conditions is show in Figure 8.

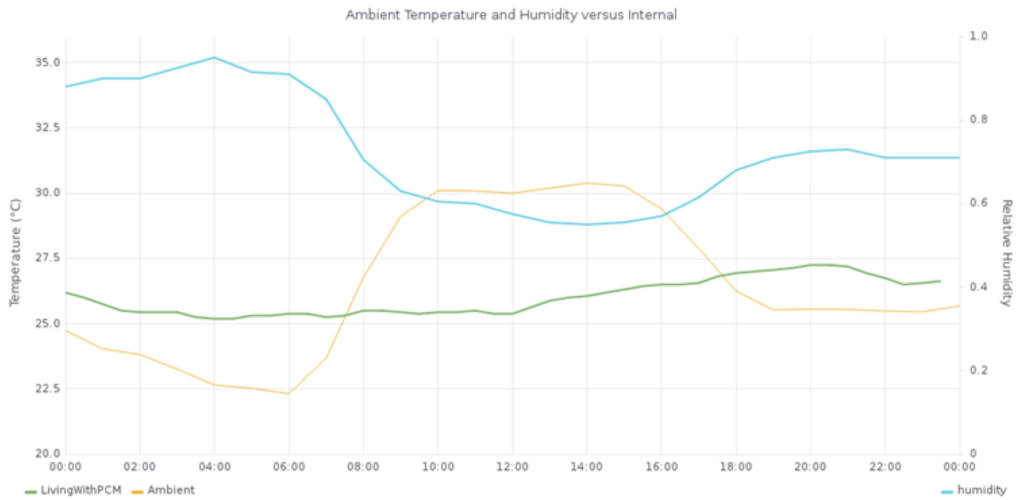

Figure 8 – 10 February 2019 - Design-day-like (31DB/23WB) - Conditioned – Temperatures

On this design day, the internal temperature reaches just over 27°C – the unit is just meeting the load. We have just enough capacity – that means the (low, 5kW) heat load was a good estimate.

If we include all conditioned hours over Summer, we see that for 5% of the time we're 28°C or above. These conditions are still comfortable with the lowered internal humidity and lightly running ceiling fans. Like most design, we do not expect it to meet 100% of hours, as it uses Comfort Conditions.

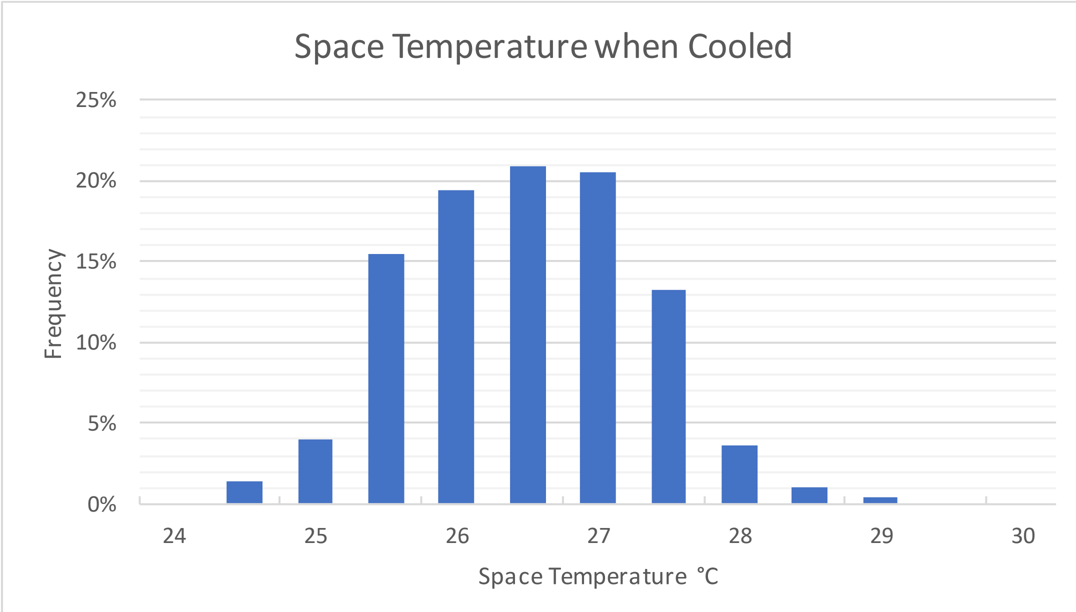

Figure 2 – Summer 2018-2019 – When Conditioned – Temperatures

The design-day-like results are summarised in Table 4.

Table 4 - Peak Temperatures on a Day like the Design-Day

		Outside			Inside				
Type	**Date**	**Dry Bulb °C**	**Wet Bulb °C**	**Humidity**	**Dry Bulb °C**	**Humidity**	**PMV**	**PMV With Fan**	**Adaptive Comfort 90%**
Free Run	23/01/2018	31.8	23.9	51%	29.0	60%	1.3	0.8	No
Cooling On	10/02/2019	30.6	24.5	60%	27.0	*50%*	0.5	0.1	Yes
Figures in italics are estimates									

CONCLUSIONS

We tested, in a limited fashion, whether "air-conditioning is required for thermal comfort for Brisbane." A best-case case study was used; instead of an office, a house was evaluated. In houses, clothing can be adapted, occupants have greater contact with the outside and greater tolerance for setpoint changes. An adaptive comfort model was used to quantify what "thermal comfort" means.

Quantitatively, thermal comfort could not be achieved throughout Summer. Although not frequent (4.5% of Summer hours), there were uncomfortably hot periods without air-conditioning. This was despite a good passive solar design. Humidity was a key factor in discomfort.

Qualitatively, the occupants of the house found it "occasionally too hot". Interestingly, these periods were most frequently between 6pm to 8pm, when outside relative humidity was high but the dry-bulb was moderate. This was not captured by the comfort metrics used (PMV, adaptive comfort), suggesting they do not evaluate high-humidity conditions well.

We tested various methods to reduce peak thermal load. The analysis showed peak load could be halved through controlling outside air (heat exchanger), infiltration (building sealing) and delta-T (adaptive comfort setpoints).

Implementing these methods was found to be straightforward, but required the builder to research some new methods. Quantitively the "real-world" suitability of the lower peak load was tested by installing a small (5kW) ducted system and running it over Summer. The energy and temperature data showed the setpoint (27°C) was rarely exceeded (5% of run hours) and then only by 1K. The reduced humidity in the space was not logged, but reported as the key to comfort, compared to outside.

Qualitatively the occupants considered the system "very comfortable" and that it did not lack cooling capacity. The ceiling fans were often used to supplement air-conditioning. An interesting extension would be better tracking of humidity, and the verification of existing comfort metrics' treatment of humidity.

ACKNOWLEDGEMENTS

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