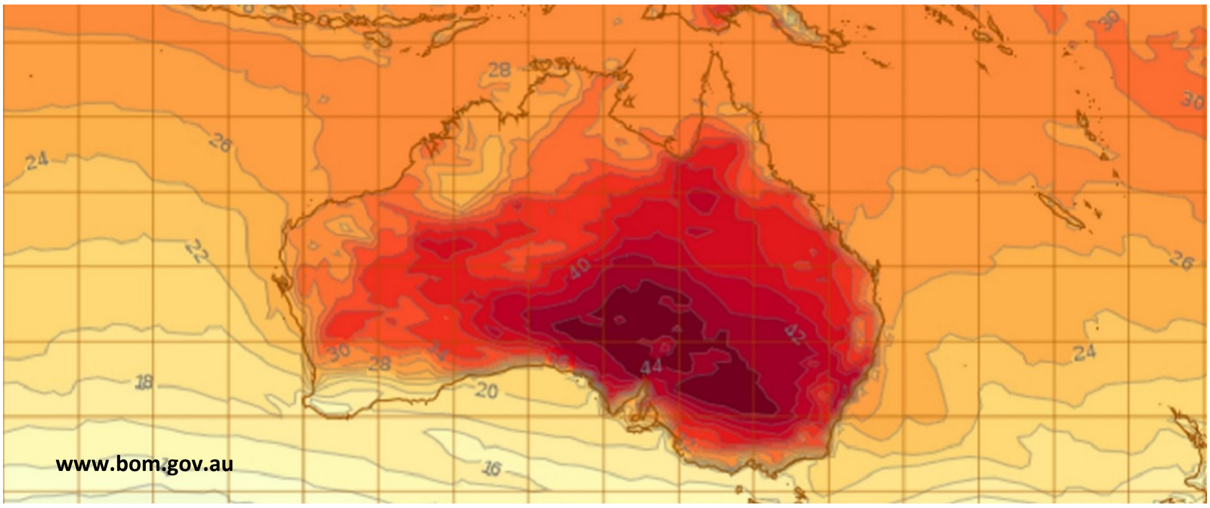

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Living Well

Apartments, Comfort and Resilience in Climate Change

Green Cities Innovation Fund

March 2017

www.thrive-research.com.au

Executive Summary

This report has been produced by the University of Melbourne for the Australian Communities Foundation Green Cities Innovation Fund to document an international review on high-rise apartment building thermal performance and comfort in heat wave conditions. This identified four international standards that represent best practice in protecting the health of apartment residents in heatwave conditions. Using computer energy modelling, six apartment designs typical to Melbourne were performance tested against the international standards, the main research question being: 'how will they perform in free running mode – that is if there is no ability to turn on mechanical cooling systems?'

The computer model was developed for the six buildings using as constructed construction elements, and standard occupancy parameters. A weather data set based on a severe heat wave as experience in Melbourne in 2009 was used. The result of the six buildings that were tested against the international standards showed that none of the apartments would comply with the standards under these heat wave conditions.

To investigate what could be done about this the worst performing apartment design was retrofitted in the model to determine the type of upgrades that would be required for this apartment to comply. This showed that even the worst performing building could be retrofitted using standard retrofit strategies to comply with two of the four international standards and protect their residents.

Key recommendations of this report are that the retrofits tested here be considered for all existing apartments, that new apartment regulations consider best practice international standards for summer comfort and finally that until retrofits are able to be implemented the residents of apartments have an action plan if heat wave conditions occur.

Contents

1 Introduction

Everyone has the right to live well, living in a place that is safe and comfortable. As we move into the uncertainty of climate change the increase in weather extremes, especially heat in Melbourne, is expected to have significant negative impacts on comfort for existing apartments. For these homes to be able to stay comfortable, without significant cooling energy, will be a challenge. This means that people in homes that do not have cooling systems are facing potentially higher health risks. Further, if there are infrastructure failures and there is absence of energy for cooling even more people will be at risk. This was the situation in 2003 when France had their deadly heatwave; their authorities responded by regulating that all homes need to be comfortable for 5 days in "free running mode" (without heating or cooling).

This project analyses six apartment buildings (including low and high-rise, old and new, minimum standards and best practice) and models their performance based on the extremes of the 2009 Victorian heatwave that began on the 27 January with daytime temperatures topping 43°C across 3 days, with night-time minimums of above 25°C (BoM 2009). The project specifically seeks to determine how the Melbourne apartment samples perform in the context of the international standards, and finally, looking at retrofit options to future proof apartments and make them more liveable.

2 Literature Review

2.1 Overheating Definition

Despite the absence of an exact definition of overheating, the international thermal comfort standards such as ISO 7730, ASHRAE Standard 55, and the EN 15251 European Standard have commonly defined overheating as when the level of indoor temperature exceeds a maximum comfort temperature, and this, over a defined length of time. By contrast, Heat Stress is a term used to define the physiological state in which a human body is no longer able to cool itself satisfactorily. This maximum comfort temperature varies according countries, function of buildings, rooms in buildings, time of the day, and if buildings are conditioned or not. For examples the British CIBSE Environmental Design, Guide A recommends a maximum temperature of 28°C for living room and 26°C in bedrooms for less 1% of running time, while also allowing this maximum temperature to rise up to 31°C when using adaptive comfort approach (variable comfort temperature dependent on occupant behaviour and clothing) for buildings in free running mode (Dengel & Swainson, 2012).

2.2 International Standards Review

According to the last State of Climate report (State of the Climate, 2016), the duration, frequency and intensity of extreme heat events have increased across large parts of Australia, and globally. During the 2003 European heat wave, France claimed over 14800 excess deaths (Fouillet et al., 2006) due to heat stress. Following this extreme heat event, France, which shares the same temperate oceanic climate (Cfb) with the Australian southern east coast, based on the of the Köppen-Geiger climate classification (Peel et al.,2007), has decided to integrate a new requirement into their building code called "summer comfort". It is now a requirement of the French Building Code to design buildings able to maintain a "comfortable" indoor temperature during a heat event without help of active systems such as air conditioners. Similar standards are now in place in other countries globally. Despite the global movement, there is no common standard or calculation methods to define summer thermal comfort parameters, which consider multiple variables such as air temperature, mean radiant temperature, humidity, air velocity, metabolic rate and clothing insulation. It should also be noted that each standard has individual specific criteria used to determine compliance. For example, the French RT2012 standard requires modelling to begin with internal mass at 26 degrees Celsius.

In 2017, Building Research and Information published a special issue on overheating in buildings, and noted that of the 12 published articles, 8 were from the UK (Building Research and Information 2017) and the remainder predominantly concerned with temperate climate regions, where retaining of winter heat is the dominant design requirement, with specific reference to the Passivhaus standard. In order to provide a summary of the research contained in this special issue, the findings generally supported the view that:

- Overheating was a significant problem in both existing stock and new buildings, including low energy buildings and generally exceed the performance requirements in the relevant standards
- Occupant awareness and operation of ventilation was poor and contributed to the overheating experienced, and in some cases were more important than climatic and location factors
- It can be difficult to determine overheating performance using energy modelling due to the number of uncertainties (occupant, behaviour, weather events)

Despite being a continent of extreme heat waves, there is currently no comprehensive requirement for building summer comfort in Australia. The 2016 NCC which incorporates the Building Code of Australia (BCA) allows for energy efficiency measures in all classes of buildings (Australian Building Codes Board, 2016). Volume 1, covers class 2-9 (apartments are class 2) which encompasses the commercial classes considers the building envelope and the services with regards to energy efficiency. There is no consideration of thermal comfort or overheating. In order to follow the international example of considering overheating in the building code, additional modelling for thermal comfort would be required in addition to current requirements.

In December 2016, the Victorian Department of Environment Land Water and Planning (DEWLP) released new design standards for apartments, the Better Apartment Design Standards (Better Apartments, 2017). Although not particularly comprehensive, these will take effect in March this year when they are incorporated in Victorian Planning Schemes. The Standards include a maximum cooling load (variable by location) as calculated using the required NatHERS software for Building Permit compliance.

2.3 Comparison of International Summer Comfort Conditions

Four international standards that address overheating have been utilised for this study, and a summary of each is provided below.

2.3.1 United Kingdom – Chartered Institution of Building Services Engineers (CIBSE)

Regulation - No more than 1% of annual occupied hours over an operative temperature of 28˚C in living rooms, or 26˚C in bedrooms. (1% of occupied hours across one year equals 87.6 hours) (Environmental design: CIBSE guide A., 2015). For purposes of consistency, temperatures of the living room will be used.

2.3.2 France – Norme Française Haute Qualité Environmentale (NF HQE)

Regulation - Operative temperature for all rooms should not exceed 28˚C for more than 3% of the annual operation time. 3% of occupied hours across one year equals 260.1 hours. For purposes of consistency, temperatures of the living room will be used. Operative temperature under this standard is defined as the average between the radiant and dry-bulb temperatures. 3% is specific to the H3 climate zone (Mediterranean), which is closest to Melbourne climate (Hetzel, 2013).

2.3.3 Germany – Passivhaus

Please note the Passivhaus Standard is not a required certification standard

Regulation - Temperatures during annual occupied hours should not exceed 25˚C for more than 10% of the time. 10% of the occupied hours across one year equals 876 hours (PHI Building Criteria PHPP9, 2015).

2.3.4 USA – American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE)

Regulation – The ASHRAE standard utlilises the predicted mean vote (PMV) measurement which is a standard measurement methodology for thermal comfort. The hours where the Predicted Mean Vote (PMV) is greater than +0.5 is considered heat stress (PMV ranges from +3.0 to -3.0). The comfort parameters are set to the following:

Metabolic activity: 1.1 met
Clothing insulation: 0.5 clo
Air velocity: 1.6ms^{-1}
Humidity ratio: 0.010

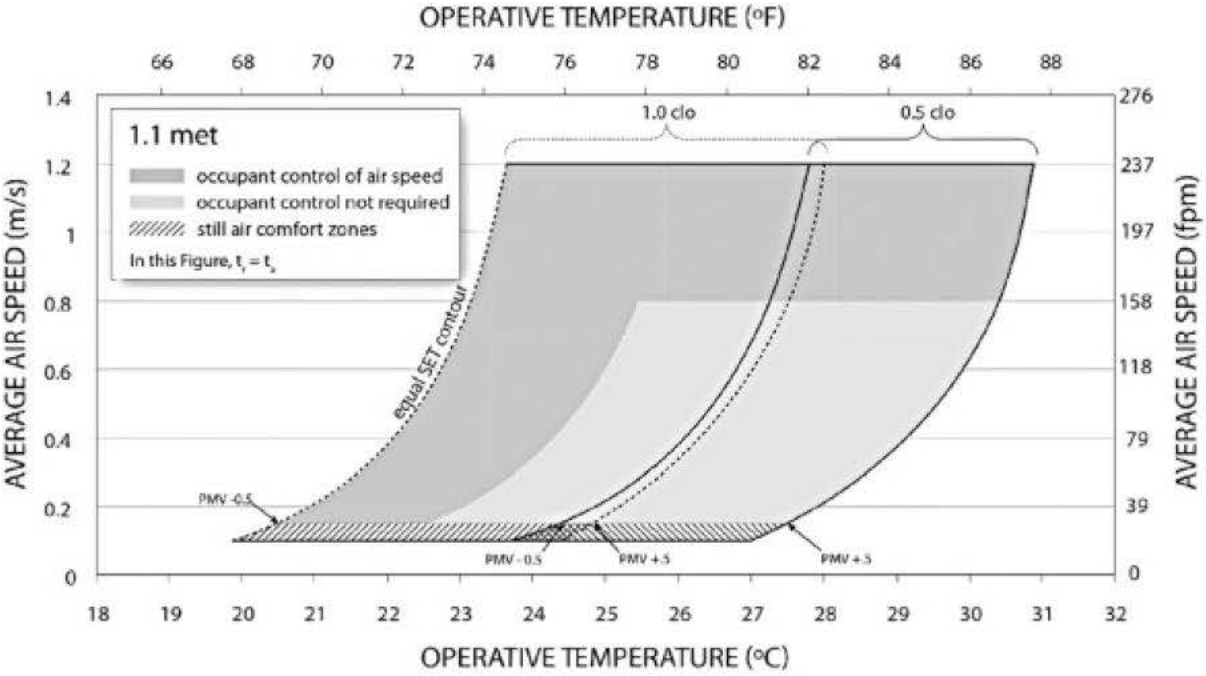


Figure 1: ASHRAE parameters to determine occupant comfort (ASHRAE, 2016)

2.4 Retrofit opportunities

At the same time that France introduced summer comfort to its National code, they also started to review their Social Housing Stock (SHS) and implemented innovative solutions using prefabricated glazed facade modules. This strategy preserves and extends the life of buildings, and also improves their thermal performance and ensures resilience against heat events (Affordable Housing Hub, 2016). By avoiding the destruction of elderly SHS, extending their initial layouts and making them energy efficient, this retrofitting solution has proven to be cost effective and well received by the community (Rahola et al., 2014). With the target to renovate 800,000 of the most energy inefficient SHS by 2028, the French government offers financial support ranging from tax deduction to zero interest loans (Fawcett et al., 2013). France is not the only nation to invest in retrofitting its SHS, this is a global trend around the world. In Germany for example, the renovation of 13000 apartments of the vast housing complex Märkisches Viertel in Berlin is about to be completed with an estimated cost of 480 million euros (690 millions AUD) (Nordregio., 2011). A 2012 Deutsche Bank study revealed that every $1million invested in energy efficient retrofits of affordable housing, $1.3 million was generated and $3.9million energy savings were achieved in energy savings and increased GDP (Deutsche Bank, 2012). Social Housing is indeed a great investment however in Australia considering the big demand and the small existing stock (AIHW,2015), most of investments are concentrated on new construction (Cranston, 2016).

3 Methodology

3.1 Case Study Buildings

Energy models of six buildings were produced in order to test their performance in a heatwave scenarios. The six buildings represent a collection of different building configuration and a combination of different construction systems. The models were modelled according to the specifications of the buildings and respected strict materials and constructions to ensure accurate results. All models were run in free mode (no active heating and cooling) with a focus on the second fortnight of January, and the first fortnight of February (19th of January – 15th of February). For all the models, the worst orientation for heat waves was tested (largest glazed area facing west).

Building 1

Building 1 is a best practice lightweight four-storey apartment building. It has a reinforced concrete structure and lightweight cladding (cement sheet and timber cladding). Some of the internal partitions are made of concrete panels but are otherwise mostly lightweight.

The apartment tested occupies the north west corner of the building and has two bedrooms, one bathroom and an open plan kitchen/living area. The apartment shares 39% of its boundary walls with adjacent tenancies.

The external walls have an insulation of R2.8, R2 in the internal walls, R2 in the ceiling and R3.2 in the roof. All windows are double glazed (U 2.63, SHGC 0.42). All windows are relatively narrow, with larger glazed sliding doors horizontally shaded by external balconies.

Natural ventilation is a major thermal strategy used in Building 1, and the window operation profiles have been set in a way to maximise passive conditioning through natural ventilation.

Building 2

Building 2 is a high rise heavy weight apartment building. The structure is entirely made from concrete, with concrete floors, external walls and internal partitions.

The apartment tested has shared walls with adjacent tenancies and has two bedrooms, one bathroom, a separate water closet, a storage area and an open plan kitchen/living area. The apartment shares 42% of its boundary walls with adjacent tenancies.

The external walls, internal partitions, floors and ceilings are not insulated. The windows are clear single glazed in standard non-thermally-broken aluminium frames. Weather stripping is quite old and only provides moderate level of draughts sealing. Some of the windows are operable, but the fenestration has not specifically been designed to take advantage of natural ventilation.

Building 3

Building 3 is a high rise heavy weight apartment building. The structure is entirely made from concrete, with concrete floors, external walls and internal partitions. Building 2 and Building 3 are the same building, but the apartments under study are of a different size and configuration.

The apartment tested occupies the north west corner of the building and has three bedrooms, one bathroom, a separate water closet, a storage area, a hallway/entrance area and an open plan kitchen/living area. The apartment shares 11% of its boundary walls with an adjacent tenancy and 9% of same with a fire stairwell.

The external walls, internal partitions, floors and ceilings are not insulated. The windows are clear single glazed in standard non-thermally-broken aluminium frames. Weather stripping is quite old and only provides moderate level of draughts sealing. Some of the windows are operable, but the fenestration has not specifically been designed to take advantage of natural ventilation.

Building 4

Building 4 is a heavy weight two-storey apartment building representing student accomodation. The structure, floor and external walls are concrete, with the internal partitions having a combination of concrete blocks and autoclaved aerated concrete.

The studio tested is sandwiched between 2 adjacent tenancies and consists of an open plan sleeping/study/kitchenette area and a separate bathroom. The studio shares 68% of its boundary walls with adjacent tenancies, and 17% of same with a shared corridor.

The roof has an insulation of R3.2, the external walls R1.8 and floors R1.5 where exposed below. Internal partitions have an insulation of R2. Studio only has one window, which is clear single glazed (U 5.8, SHGC 0.8)

Building 5

Building 5 is a 1st floor apartment in a retrofitted heritage building. The external walls are triple brick, floors are concrete and internal partitions are a combination of double brick, concrete or lightweight construction.

The apartment tested occupies the north west corner of the building and consists of one bedroom, one open plan living/kitchen area and one bathroom. The apartment shares 44% of its boundary walls with adjacent tenancies and 6% of its boundary walls with a shared corridor.

The external walls, internal partitions, floors and ceilings are not insulated. The windows are clear single glazed in timber frames.

Building 6

Building 6 is a two-storey brick building. The external walls have a brick veneer construction and the internal partitions are lightweight. The floor is made out of concrete and is carpeted in the living and sleeping areas, and covered with vinyl in the wet areas and the kitchen. The roof is tiled. There is some level of insulation in the roof and walls, but it was reported that the insulation is ineffective. The windows are clear single glazed in double hung aluminium frames.

The apartment tested occupies the west end of the building and consists of 2 bedrooms, one lounge area, one kitchen and one bathroom/laundry room. The apartment occupies an area of about 62m^2 and shares 25% of its boundary walls with a communal hall/stairwell.

Occupancy Settings

All occupancy settings were adopted from the NatHERS Standards, which governs the energy modelling strategy in the Building Code of Australia (http://nathers.gov.au/). Of specific importance to overheating is the ventilation strategy, which varies greatly between occupants. As found in the literature review, occupant understanding of ventilation through window opening is poor. The strategy for the building ventilation is as follows:

Building 1 – best practice, encouraging natural ventilation for adaptive comfort – windows open to 50% when inside conditions are above 23 degrees and are greater than the outside temperature

All other buildings – windows are kept closed during heat wave conditions.

3.2 Computer Modelling

Performance modelling is an exploratory and or optimisation process typically employed to improve both thermal comfort and reduce energy use through heating, cooling and ventilation. Using the latest dynamic modelling software (IES VE-Pro), a detailed 3D model is constructed to represent the proposed building in a virtual environment. The interaction of the construction elements, glazing, climate, solar access, occupants and HVAC systems predicts real life performance and consequently allows analysis of all of the factors that dictate the final performance - of individual rooms or the dwelling as a whole. Hourly temperature data as well as solar exposure are standard outputs from this process, amongst many others. Such computer modelling is powerful in absolute terms (i.e. predicting performance with high accuracy), but is equally useful for comparative analysis. The main opportunity for this project was to look at the performance of case study dwellings compared to the international standards; and model alternate scenarios, such as for example, adding insulation and additional ventilation

3.3 International Summer Comfort Criteria (simplified) as used in the analysis

The following table identifies the summer comfort criteria that were used in the analysis in this study. In some cases the standards have been simplified for this application. For example the CIBSE standard has only been applied to the living spaces. In reality it applies different requirements to living and bedrooms. As such bedrooms have not been tested.

Country	**UK**	**France**	**Germany**	**USA**
Regulation	**CIBSE**	**NF HQE**	**Passivhaus**	**ASHRAE Std 55-2013**
Indoor Temperature for Summer Thermal Comfort	28°C in Living areas. Not exceeded >1% of annual operation time	28°C not exceeded for > 3% of annual operation time	25°C to be met in all living areas, no more than 10% of hours in a year over	Predicted Mean Vote (PMV) under 0.5
Additional criteria	recommended for free running mode	free running mode, according climatic zone, orientation and altitude.	without cooling system but requiring energy for heat recovery system.	considering 1.1 met, 0.5 clo, 1.6m/s air velocity and 0.010 humidity ratio.

Table 1. Comparison of Maximum Temperature for summer comfort per nation and standard.

3.4 Retrofit Opportunities

A Retrofit test was conducted to determine what strategies might be useful in upgrading the existing buildings used in the study. The strategies that have been tested to improve thermal performance are:

- Thermal mass
- Insulation
- Light coloured walls
- Natural ventilation

Building 2 was the worst performer overall due to the lack of insulation, high levels of thermal mass and minimal opportunities for ventilation, so was used for testing the retrofit options. A brief description of the strategies are outlined below:

Insulation

100mm of expanded polystyrene (R2.5) applied externally to the walls, to keep the thermal mass in contact with the inside air.

Light coloured walls

Absorptance of external wall set to 0.2, and emissivity of same set to 0.9. This would mimic painting the external wall white.

Natural Ventilation

All windows set to be 50% openable and remain open as long as the external temperature is lower than the internal temperature. This improves all buildings to match the performance of building 1, which incorporates natural ventilation into its adaptive comfort strategy.

Thermal mass

Building 2 includes a substantial amount of thermal mass and therefore the addition of more mass was not a suitable strategy. However, lightweight buildings receive a great benefit from additional thermal mass (it is assumed an apartment building already has concrete slabs representing some mass). The use of additional mass elements as partition walls or external walls should be considered, based on thermal modelling for each case.

Shading

Shading of windows is a critical strategy to reduce heat gain, and has been included as designed for each apartment. Additional shading would benefit some of the apartments, dependent on current shading, orientation, size of window, ability to operate, and location (external vs internal)

4 Results – International Standards Comparison

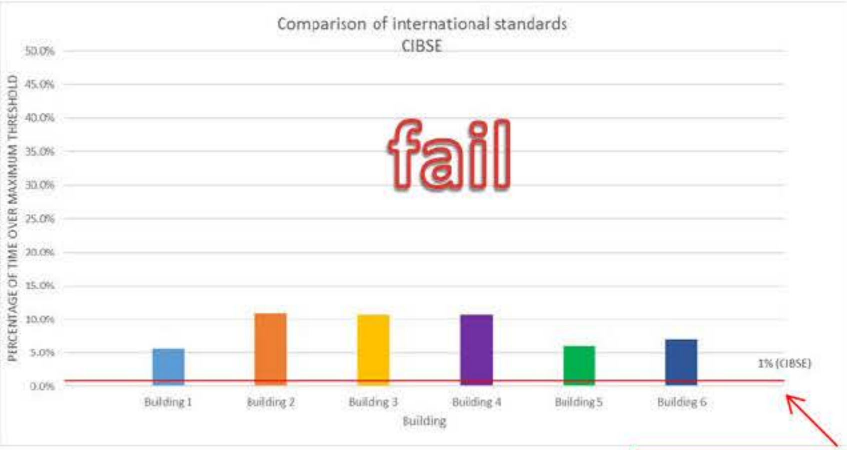
4.1 Country by Country Analysis

Building	CIBSE	NF-HQE	Passivehaus	ASHRAE
	Hours above 28	Hours above 28	Hours above 25	Predicted Mean Vote (PMV)
	Max 1% of occupied hours	Max 3% of occupied hours	Max 10% of occupied hours	PMVx>0.5
Building 1	5.70%	5.70%	15.20%	22.60%
	499	499	1331	1980
Building 2	11.00%	11.00%	23.10%	31.10%
	964	964	2024	2724
Building 3	10.80%	10.80%	29.50%	41.00%
	946	946	2584	3592
Building 4	10.80%	10.80%	33.60%	46.20%
	946	946	2943	4047
Building 5	6.10%	6.10%	17.30%	24.30%
	534	534	1515	2129
Building 6	7.10%	7.10%	17.70%	24.50%
	622	622	1551	2146

The table and chart above show that none of the Melbourne apartments under study comply with any of the international standards.

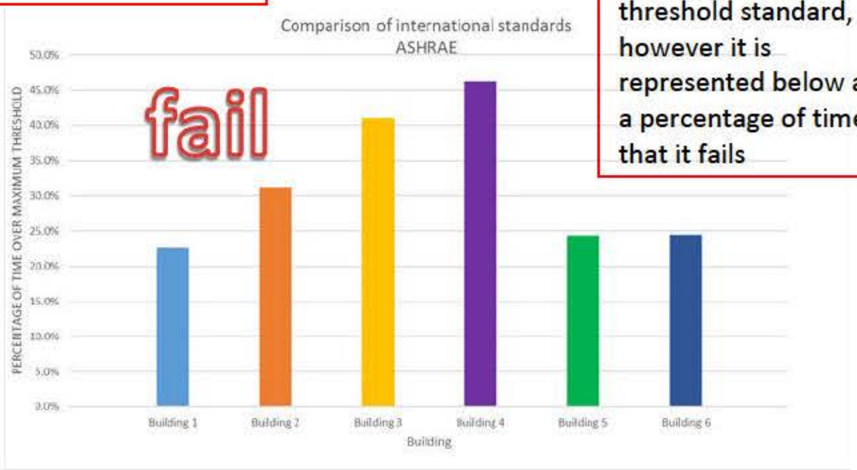
4.2 Building Performance under International Standards

The percentage shows the amount of time over the regulated threshold



Red line indicates % of hours allowed over threshold temperature

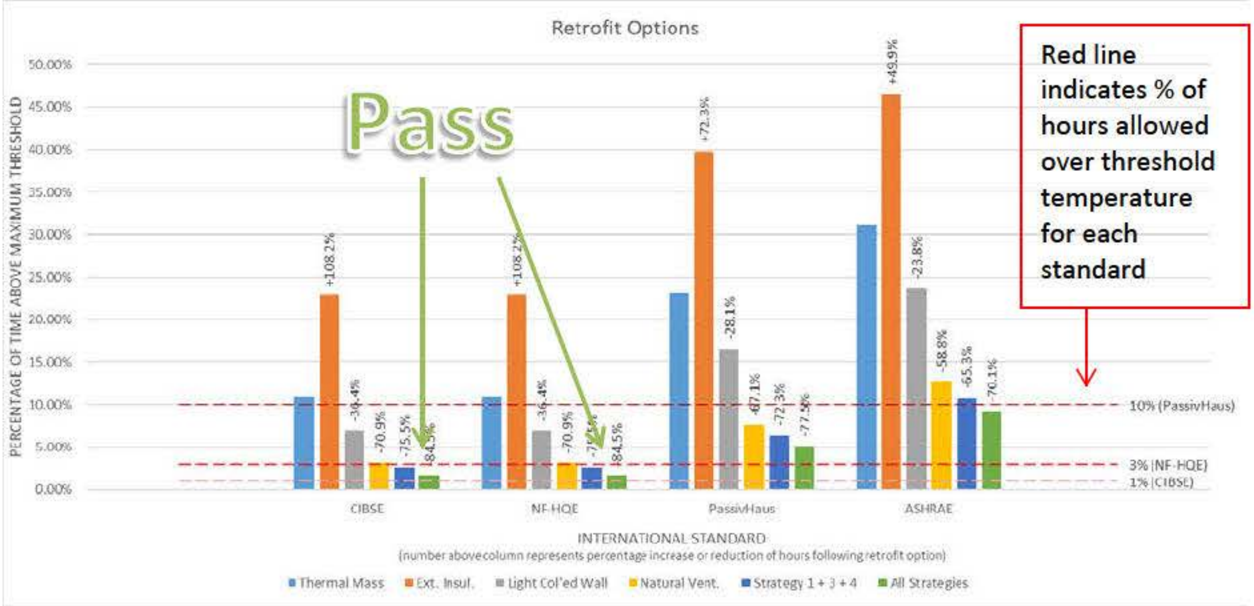
ASHRAE does not use a temperature and % threshold standard, however it is represented below as a percentage of time that it fails



The degree of non-compliance varies according to the different standards. For example, the UK (CIBSE) and French (NF-HQE) standards have the same temperature threshold (28˚C) but have different time allowance threshold. While climate is an important element to consider while assessing the accuracy of comparison between Melbourne apartments and international standards, the absolute measure of heat stress (how long a person can sustain a certain level of heat) should not vary significantly around the world. The fact that all the Melbourne apartment types that have been modelled cannot maintain safe internal environmental conditions raises concerns about the standard of construction in Melbourne.

4.3 Building Performance with Retrofit Strategies

The chart below graphically shows the impact of each strategy and compares them again to the 4 international standards.



All the strategies tested resulted in a reduction in the number of hours above the maximum threshold were then applied conjointly and resulted in an overall reduction of 65 to 76% of hours across the 4 international standards.

The only strategy that has resulted in an increase in the hours above the maximum threshold temperature was external insulation, suggesting this is not a good strategy alone for retrofit for heat wave scenarios. However, the reason why Strategy 2 has a negative impact is that the insulation prevents the heat from escaping through the envelope. However, paired with appropriate heat rejection mechanisms (such as ventilation), external insulation could theoretically have a positive impact on the temperature. With all strategies applied, and the addition of insulation to thermal mass, wall colour and ventilation resulted in further reduction of hours inside the heat stress zone by up to 85%.

The single strategy that has the most impact is natural ventilation, with a reduction of up to 71% in the number hours above the maximum temperature threshold.

Even with all strategies applied, the model shows that Building 2 still cannot comply with CIBSE standard (the most stringent), despite significant improvements in indoor conditions. However, due to the variations in the different standards, the model also shows that if applied properly, some of the strategies can improve the indoor environment sufficiently that Building 2 can comply to the French (NF-HQE) and German (PassivHaus) standards (as far as heat stress is concerned).

5 Conclusions

After having modelled and analysed the peak temperatures of the different apartments during several days of heat wave, and the number of hours these apartments stay in specific temperature bands over a four-week period, the following conclusions can be made:

- Thermal mass is very effective at moderating temperature extremes, thus **reducing peak internal temperatures**
- Thermal mass will retain heat for longer periods of time after the external temperature has dropped, and radiate the heat back inside the buildings, **Prolonging elevated temperatures**
- Internally insulated thermal mass is not effective at moderating internal temperatures as the air is not in contact with the thermal mass.
- Internal temperatures of spaces with uninsulated lightweight structure will react very quickly to changing thermal condition, **affecting the rate of temperature change**
- Insulated lightweight constructions will moderate temperature extremes, but in the case studies analysed, the level of insulation in the insulated lightweight apartment was not as effective as thermal mass at curbing temperature peaks.
- Lightweight structures will cool down quickly as the external temperature drops, **and therefore performed better at creating more comfortable temperatures at night and after cool changes.**
- Internal temperatures of spaces with uninsulated lightweight structure will quickly drop as the external temperature drops.
- Internal temperatures of spaces with insulated lightweight structure may remain moderately high as the external temperature drops if no heat rejection strategy (e.g. ventilation) is set in place.
- Natural ventilation is an effective way of rejecting excessive heat that accumulates inside a building, **and is free and easily retrofitted to most apartments**
- Strategically used natural ventilation can be effective for both heavy and lightweight buildings as a passive cooling/heat rejection strategy.
- Shading of windows is critical to prevent overheating. Operable external insulation is the best option to maximise energy efficiency, but **any shading is better than none to reduce overheating**

6 Recommendations

6.1 Upgrade of Australian Standards

A new requirement that measures overheating of apartments at the design stage is required in the Building Code of Australia in order to bring it up to the same standard as is found internationally. This occurs at a time that the climate is warming and heat waves events are shown to be increasing. Although modern apartments have mechanical cooling systems, many older apartment do not have this feature and this puts occupants at risk. In addition, in the event of a power shortage or outage, modern apartments are also at the risk of overheating resulting in heat stress and possibly fatalities as a result, as has been observed in other countries.

Our recommendation is that the Australian Building Codes Board (ABCB) who administer the BCA should review opportunities to design to reduce overheating as a standard requirement, specifically for apartments. This might include a requirement to assess the design in free-running modeto determine comfort levels across a period of time.

6.2 Retrofit opportunities

Existing apartments are at the greatest risk of causing heat stress, due to the lack of or inadequacy of mechanical cooling, and often poorer building fabric thermal performance. However, this study shows that it is possible to retrofit existing poorly performing buildings to comply with two of the four international standards reviewed in this study. The retrofit improvements differ for different building, but in order of likely cheapest to most expensive, the following retrofit opportunities are effective:

- Light coloured walls
- Natural ventilation
- Insulation
- Thermal mass
- Shading

Our recommendation is that existing buildings seek review of strategies to pursue building thermal performance and mechanical cooling to protect occupants as a priority. This may include façade retrofit or building services upgrades.

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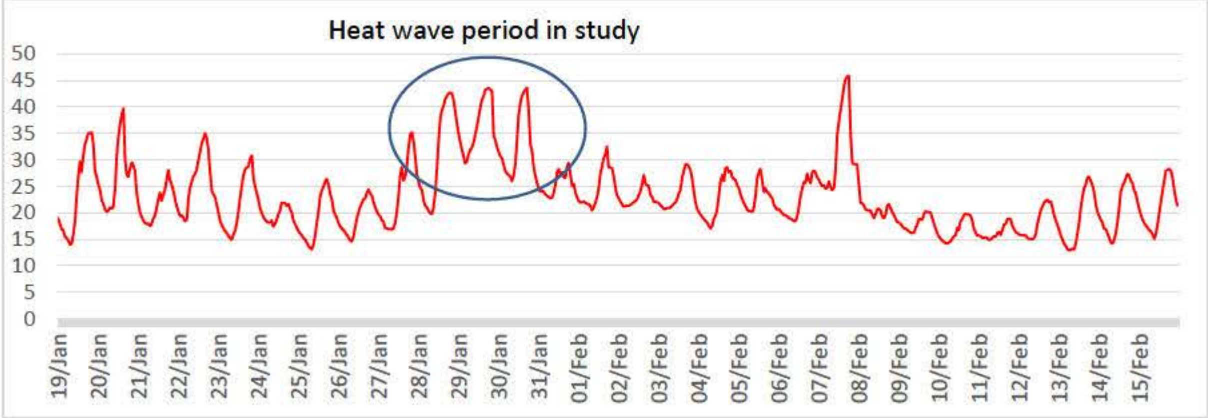
Appendix 1 – Building Energy Modelling Data

Weather file details

A special weather file based on actual data was created to simulate the heatwave of January-February 2009.



The graph above shows the temperature fluctuations across the 28 day heat wave period. This period includes 3 consecutive days where the temperature exceeded 40 °C (29th to 31st of January) as well as Black Saturday on the 7th of February. The data were collected from the Melbourne Regional Office and was supplied by the Bureau of Meteorology.

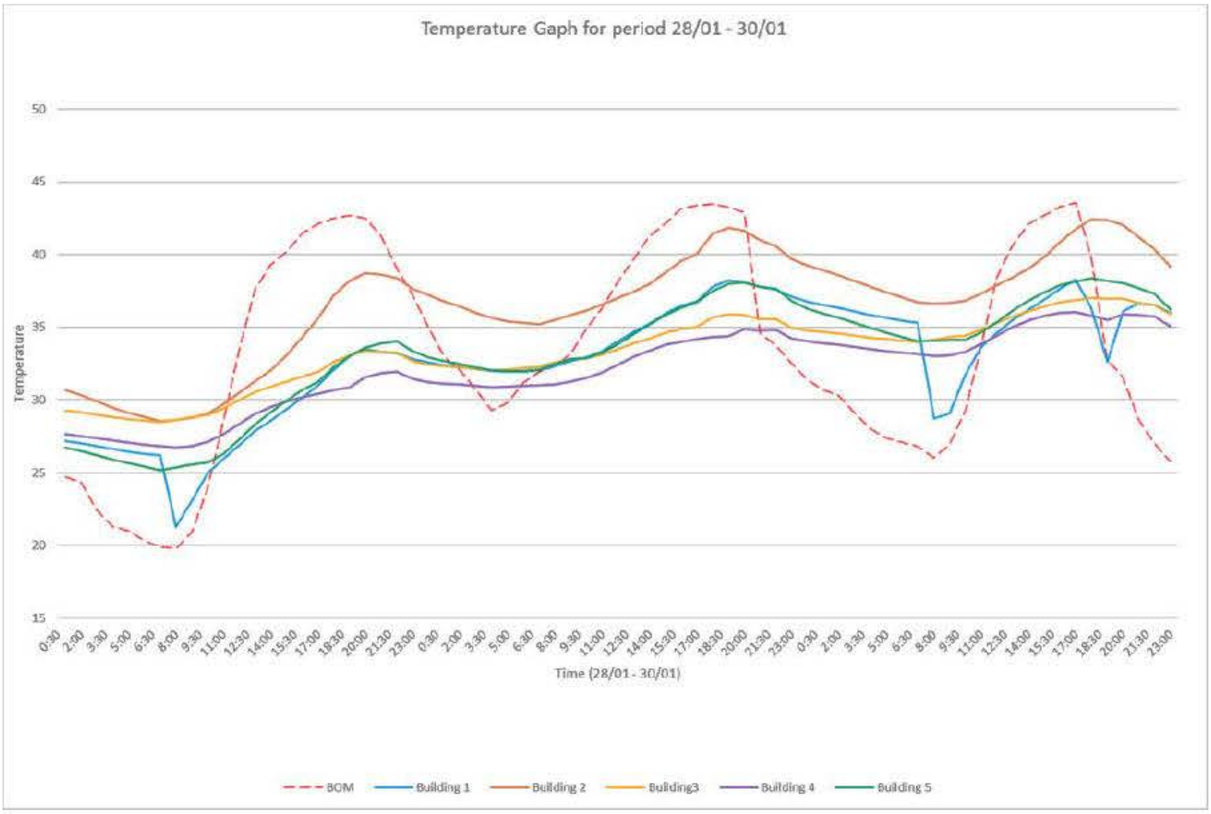
Modelled Variables

While various results can be output from the energy modelling, two sets of data were thoroughly analysed so assess the performance of each building under heat stress:

Temperature profile during Heat Wave

The indoor temperature of every room in each of the apartments/studio have been monitored individually and averaged. The results were then plotted across the 4 weeks and compared with one another and against the BOM data.

The data for each model have been plotted against one another and plotted individually for clarity.

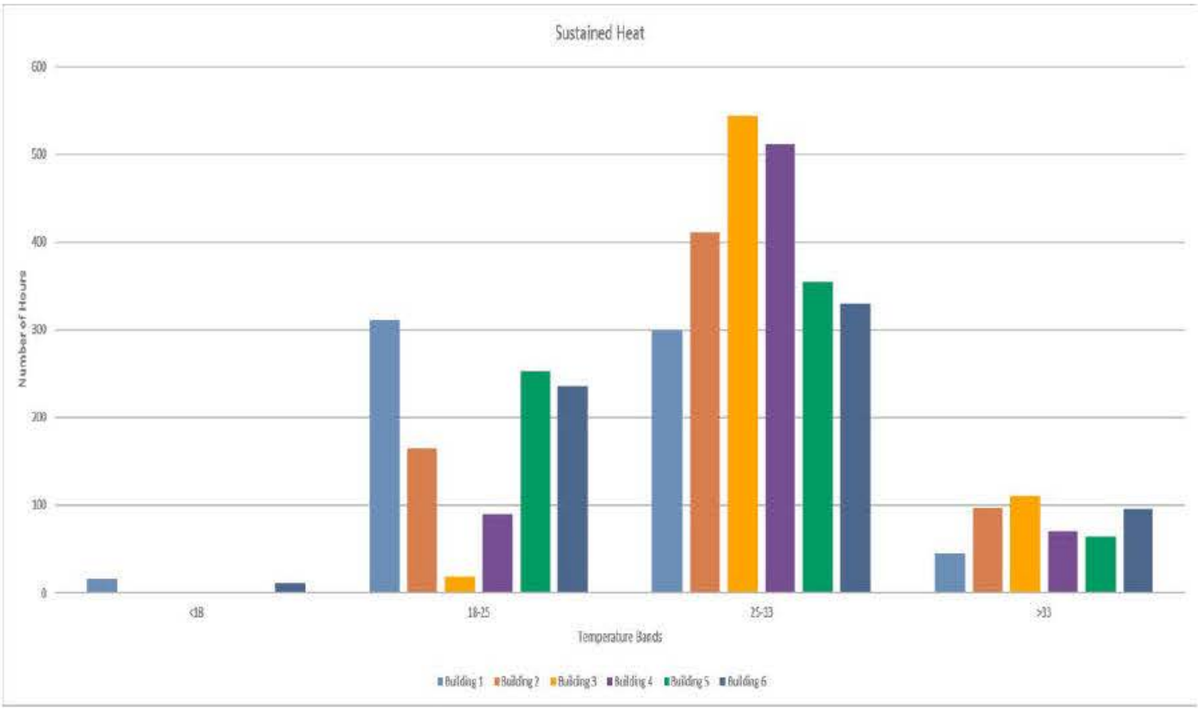


The graph above shows the period between the 27th of January to the 31st of January 2009. This period has been selected because it clearly shows 3 consecutive days where the temperature exceeds 40 degrees. The red dashed line represents the recorded external temperature while the solid lines show the simulated average indoor temperatures for the buildings under study. It can be observed that every building behaves quite differently, depending on their size, construction systems, and passive thermal strategies.

Number of Hours Within Temperature Bands

The second set of results is the number of hours during which the average temperature of each of the apartments/studios is within specific temperature bands across the 4 weeks under study. The temperature bands range from 18 to 45 degrees Celsius, in 1 degree increments.

The data for each model have again been plotted against one another and plotted individually for clarity.



This graph shows a more summarised version of the temperature distributions. The temperature bands have been set according to the following rationales:

- Temperatures below 18°C are usually considered below the accepted comfortable temperature range
- Temperatures between 18°C and 25°C are widely accepted as the comfortable temperature band in environments where adaptive comfort is used.

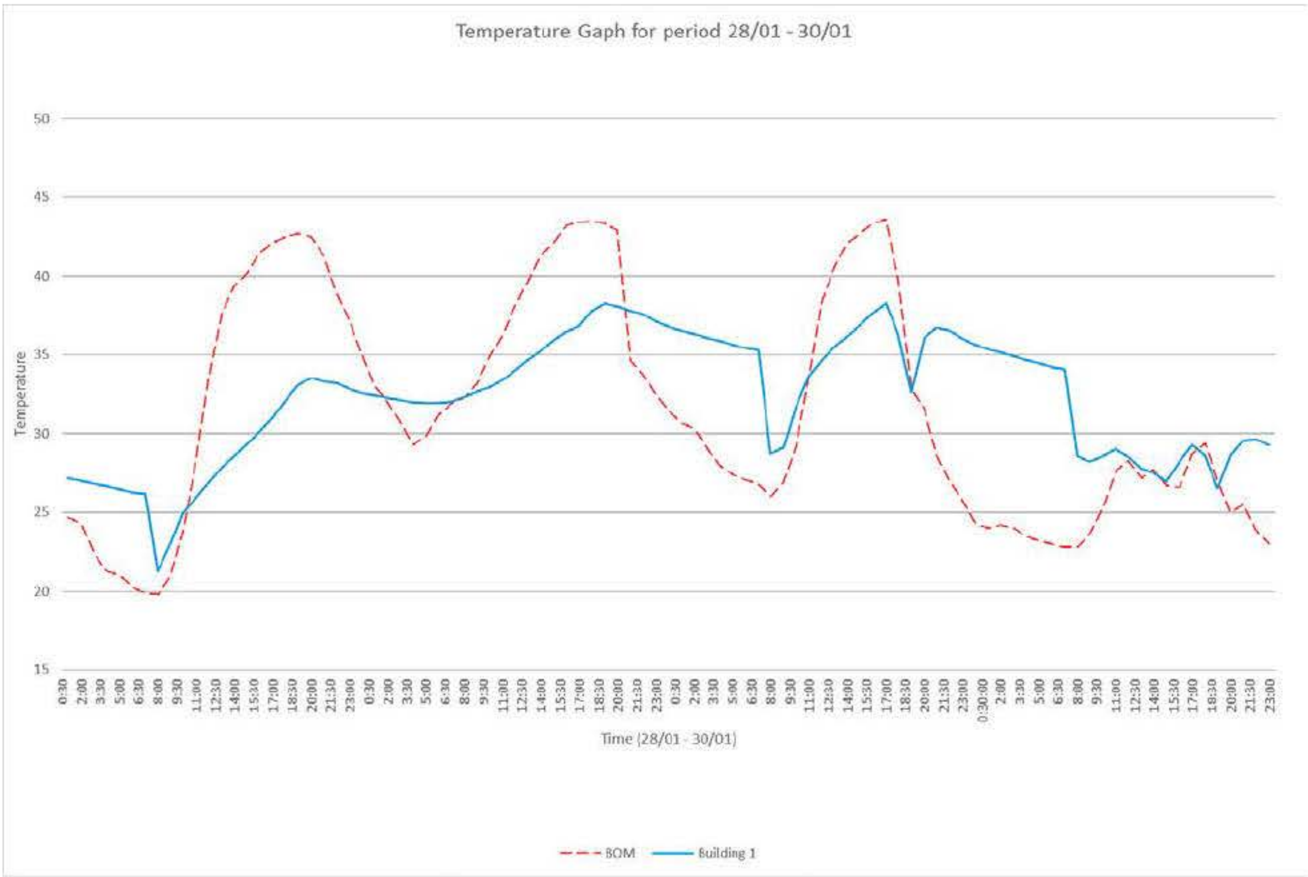
Sustained heat refers to a heat level that exceeds the comfortable temperature bands for sustained periods of time, and is represented in the graph at the right hand end of the graph. Temperatures recorded during long periods of heat wave may not necessarily always be extremely high, but sustained periods above a certain temperature threshold can pose serious health hazards.

Sustained heat and short extreme temperatures can both result in dehydration, confusion, dizziness, and in extreme cases death. Both sustained heat and peak temperature need to be addressed in order to create healthy and comfortable environments.

From this, it can be observed that as far as sustained heat is concerned, Building 1 performs the best as it has the most hours within the comfortable range, and the least number of hours in both the 25-33°C and >33° ranges. Conversely, Building 3 is the worst performer as it has the least number of hours within the comfortable range, and the most hours in both the 25-33°C and >33° ranges.

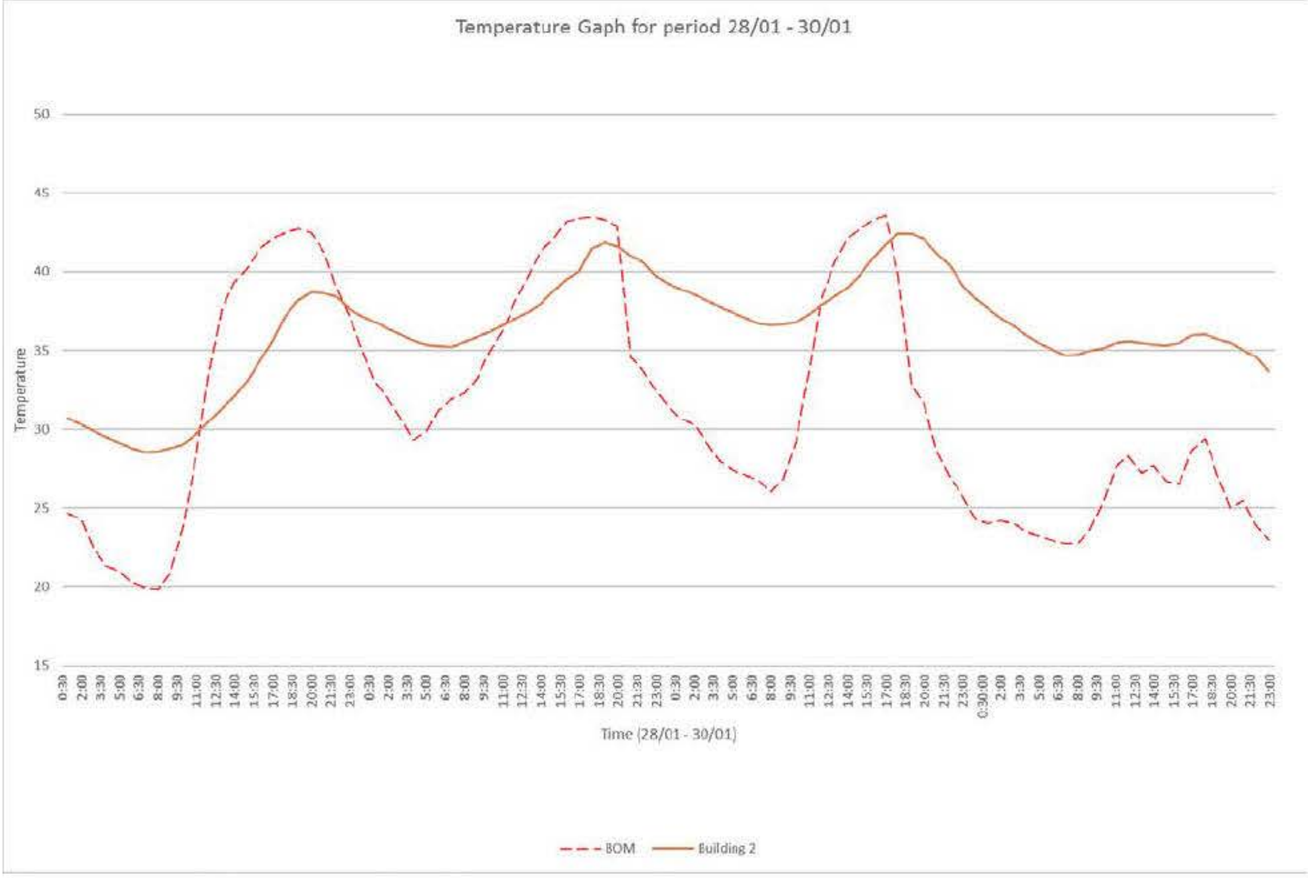
Appendix 2 Individual Apartment Temperature profile in heat wave

Apartment 1



Apartment 1's main thermal strategy when it comes to passive cooling is the use of cross ventilation. The profile of the windows has been set so that they would open when the outside temperature is lower than the inside temperature. Even though temperatures rises to the high 30s on the second and third day of heatwave, the combination of small well sealed windows, external insulation and cross ventilation manages to keep the internal temperatures under 40 degrees. The absence of large amounts of thermal mass inside the building also means that the temperature drops fairly quickly at night time and after the heat wave.

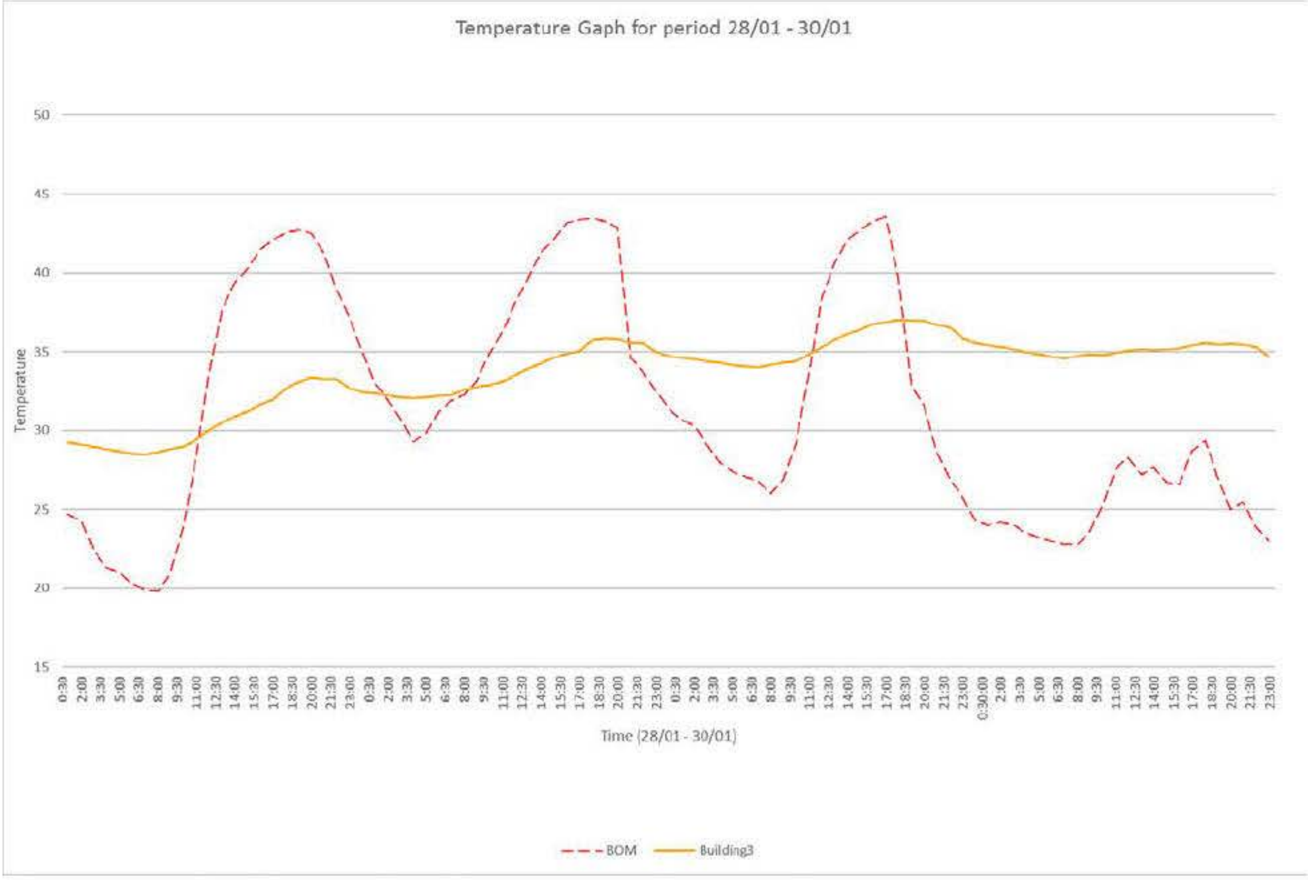
Apartment 2



Apartment 2 contains a large volume of uninsulated thermal mass, but no other thermal strategies besides that. The windows are modelled as always closed, so there is no opportunity for natural ventilation. The large volume of thermal mass will mitigate sudden temperature fluctuations, i.e. the building will take more time to heat up, but also more time to cool down, compared to a lightweight building.

It is worth noting that prior to this test period, the external daytime temperature was already in the mid-30s – that would explain why the internal temperature quickly rose to the high 30s on the first day itself, as the thermal mass had already been preheated over the previous warm days. The same reason lies behind why the peak daytime temperature also progressively rise over the three days – the thermal mass does not have time to cool down enough at night and gets even hotter the following day. The thermal mass also remains very warm for a long time after the heatwave.

Apartment 3

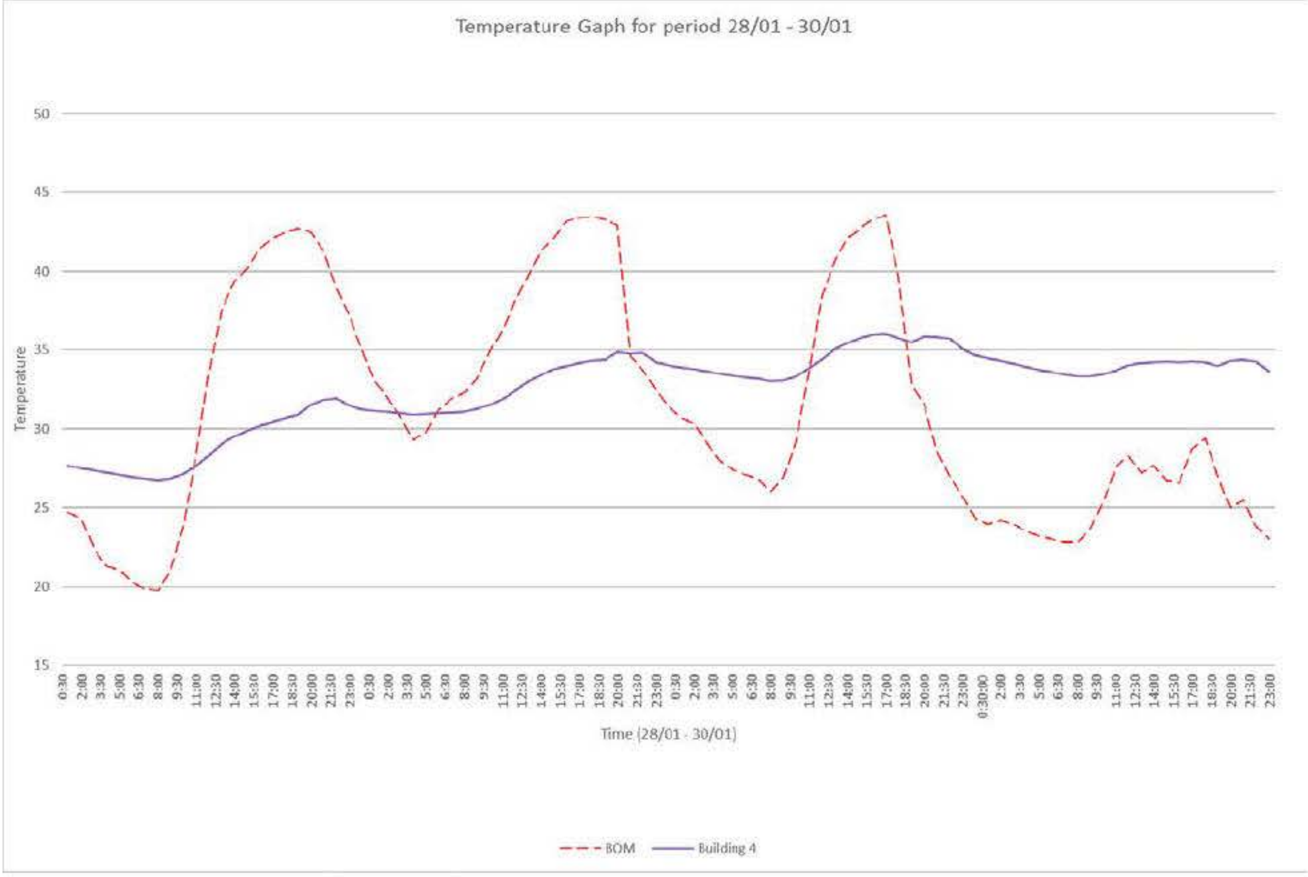


Apartment 3 (which is the same as Building 2) has large volumes of uninsulated thermal mass, but no other thermal strategies besides that. The windows are modelled as always closed so there is no opportunity for natural ventilation. The large volume of thermal mass will mitigate sudden temperature fluctuations, i.e. the building will take more time to heat up, but also more time to cool down, compared to a lightweight building.

Even though Apartment 2 and Apartment 3 are inside the same building, apartment 3 is significantly larger and has a larger surface area of contact between the air and the thermal mass. The result is an even more stable temperature – the internal temperature only reaches the high 30s on the third day, but remains in the mid-30s for over 24 hours after the heatwave has passed. While Apartment 3 may seem to mitigate the temperature extremes better than Apartment 2 - a performance which is seen as more desirable – it is important to note that the temperature remains also remains in the mid-30s for longer (more details on the sustained heat section)

The behaviour of the temperature becoming progressively higher across the 3 days can also be observed here.

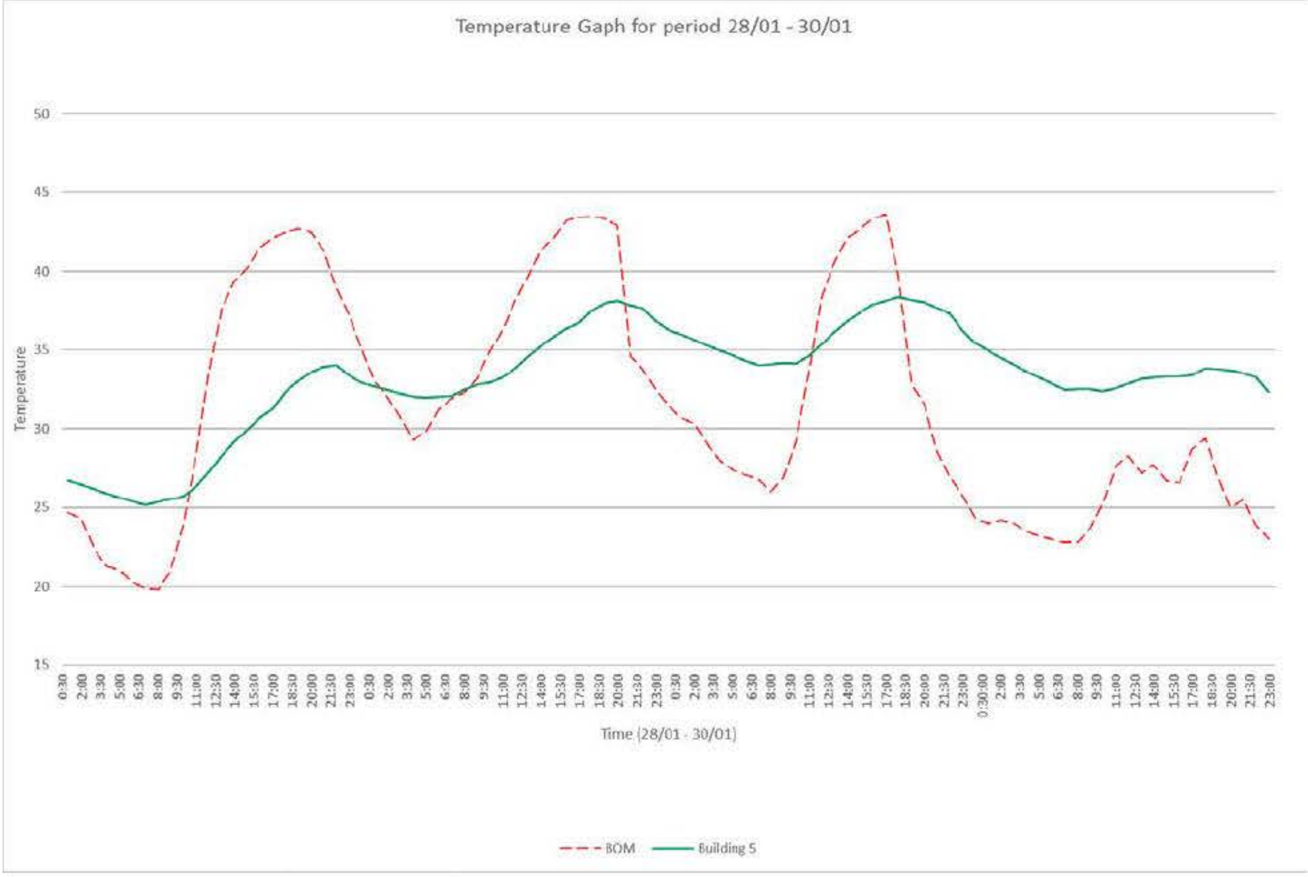
Apartment 4



Apartment 4 also has large volumes of thermal mass with windows facing only one direction. The external and tenancy walls and ceiling are insulated. The most interesting characteristic of Apartment 4 is that it is sandwiched between other tenancies and only has 15% of its walls are external walls. The fact that 85% of its boundary walls are adiabatic has a huge impact on thermal performance of the apartment – this means that no heat exchange, be it gain or loss, can happen through the shared walls.

The combination of thermal mass, insulation and a small area available for heat exchange means that Apartment 4 will not be significantly affected by its external environment. This is demonstrated on the graph above, where the temperature just passes the 35 degrees mark on the third day of the heat wave. Like for Apartment 3, the internal temperature remains quite high after the heatwave, and this is attributed to the thermal mass, and the very few mechanisms Apartment 4 has to expel the excessive heat built up as a result of both external and internal gains.

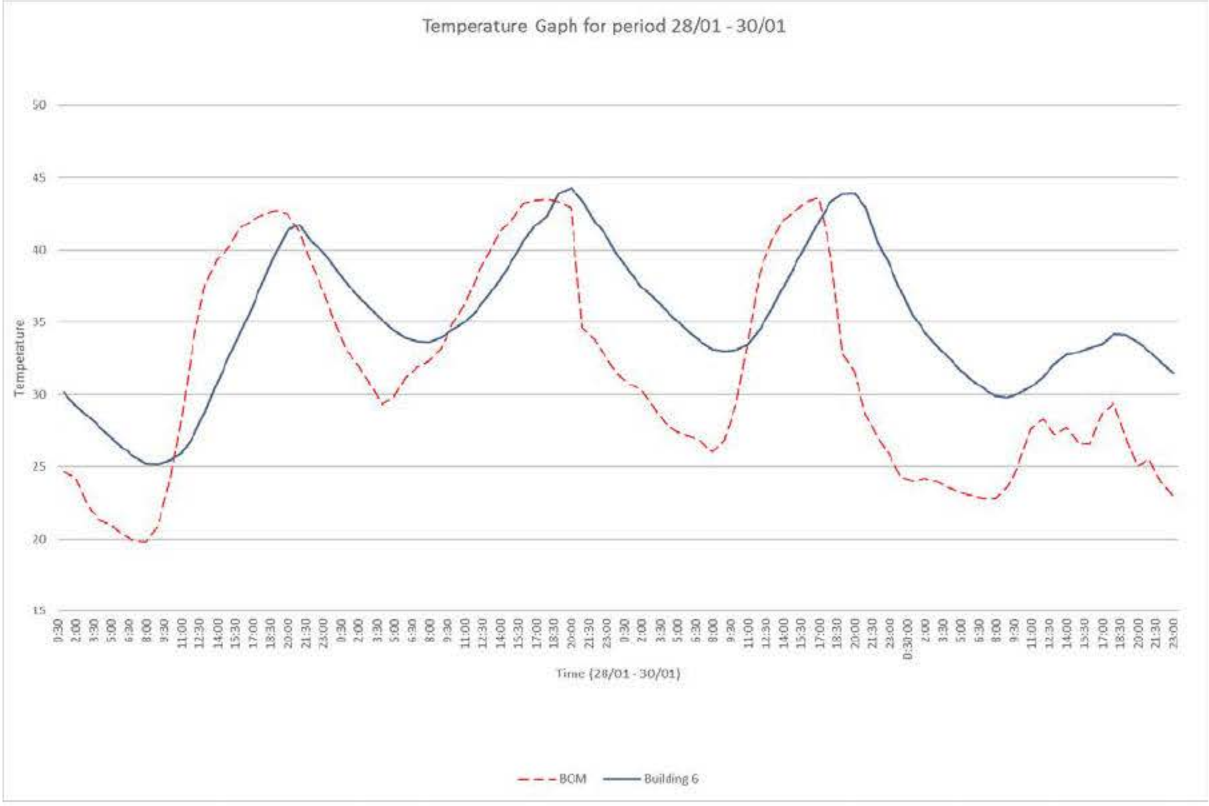
Apartment 5



The external envelope of Apartment 5 consists of triple brick walls, and the internal walls are a combination of double brick walls and lightweight partitions. The external walls are not insulated and the building shares about 50% of its walls with adjacent tenancies or shared corridors.

Even though the low performing glass and absence of insulation will allow more heat transfer between the inside of the apartment and the outside, the presence of the thermal mass manages to prevent the temperature from rising excessively during daytime. However, unlike Apartment 2, 3 and 4, the smaller volume of heavy partitions allows the temperature to drop more significantly at night and after the end of the heat wave.

Apartment 6



The external envelope of Apartment 6 consists of poorly insulated brick veneer walls with lightweight internal partitions. The shared wall between the apartment and the communal stairwell is double brick. Compared to the other apartments, Building 6 has a large proportion of its boundary walls set as external walls, and is therefore more prone to heat exchanges with the outside environment, and these said exchanged are further facilitated by the fact that the envelope of the apartment is poorly insulated.

The graph above shows that, save from the slight time delay, the internal temperature follows very closely the external temperature. The uninsulated, mostly lightweight construction of the apartment means that there is nothing to damper the temperature fluctuations – the effect of the bricks as thermal mass is negligible because they are external and are to a degree insulated from the inside air by the structural frame and the internal wall cover. Because of this limited contact between the internal air and the thermal mass, the internal temperature also drops relatively quickly as the external temperature drops.

The case studies outlined above make one thing very clear: in free running mode, thermal mass is extremely effective at mitigating sudden extreme rises in temperature. The downside of this is that the thermal mass of the concrete will hold on to that heat for longer, and will slowly radiate this heat back into the apartments, unless there are mechanisms in place to flush said heat out during cooler periods. This is where strategies like natural ventilation, as seen used in Apartment 1, can be more effective when combined with strategically utilised thermal mass. The graphs above suggest that Apartment 6 is the worst performer, and Apartment 4 is the best performer during a heat wave.

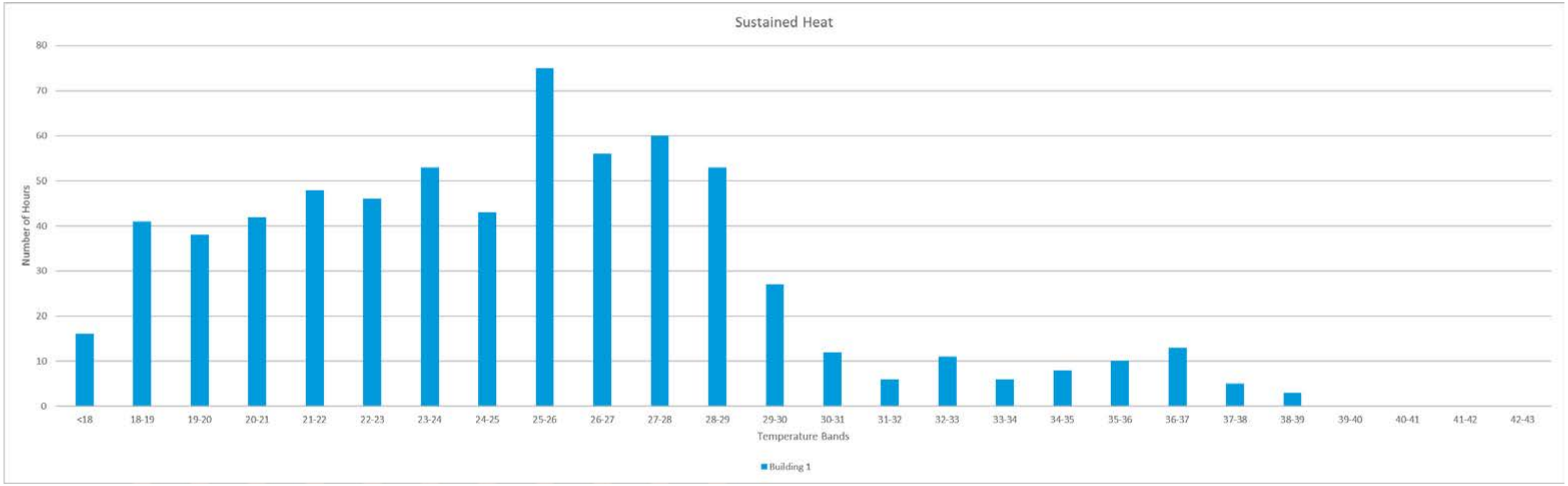
Appendix 3 – Individual Apartment Sustained Heat Profiles

Sustained Heat

The sustained heat study will look at a longer period than the peak temperature graph, namely the 19th of January to the 15th of February. The reason behind the choice of this period is because it was the hottest four-week period of 2009. Temperatures were recorded every hour and plotted on a chart at 1°C increments.

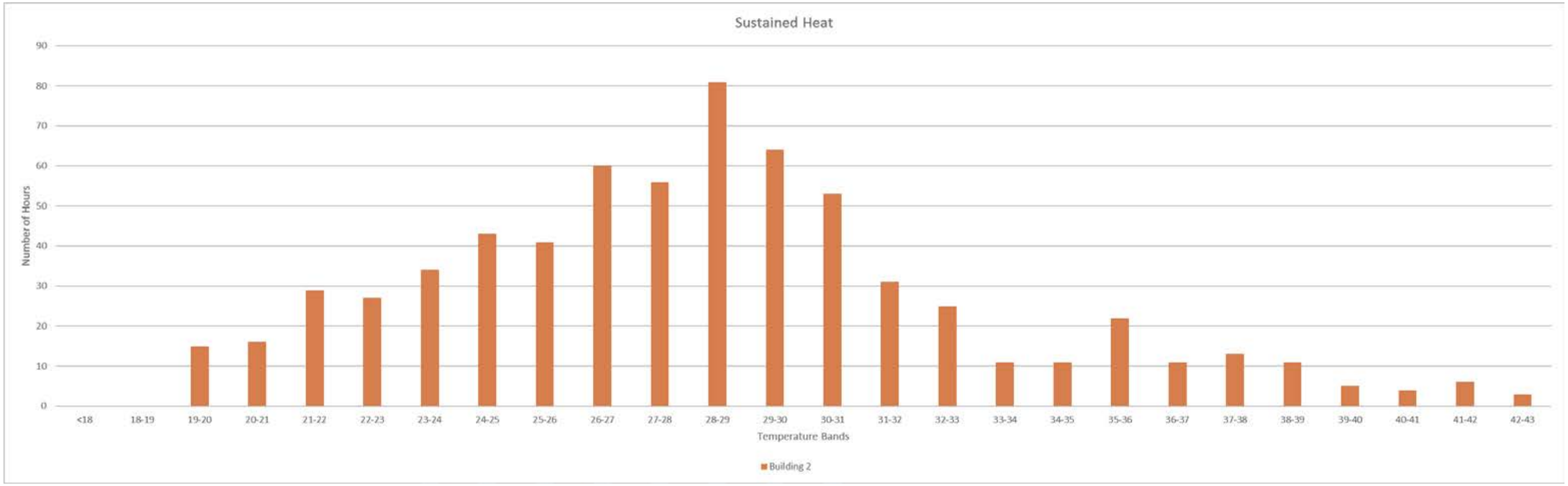
The graph above shows the temperature distribution of 5 apartments during that twenty-eight-day period. This period includes the three-day heatwave that was the focus of the above maximum temperature analysis (28/01 – 30/01) as well as Black Saturday (7/02) where temperature peaked at 46°C.

Apartment 1



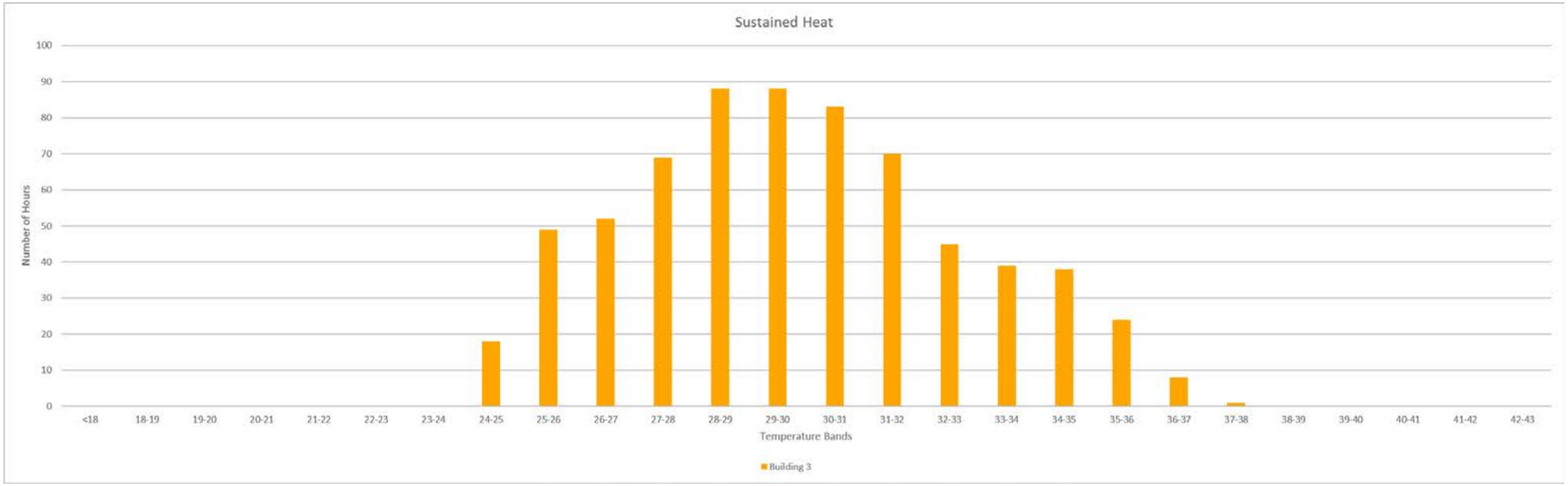
Apartment 1 has a relatively wide distribution of temperatures with the mode of the distribution being between 25 and 26 degrees, most of the hours under 30°C and maximum internal temperatures reaching 39°C. As seen previously, the main thermal strategy used by Apartment 1 is natural ventilation. While the lack of thermal mass resulted in fairly high temperature peaks. However, the combination of window operation and more thermally reactive lightweight construction also implied that the heat built up internally could easy be flushed out to attain more comfortable temperatures.

Apartment 2



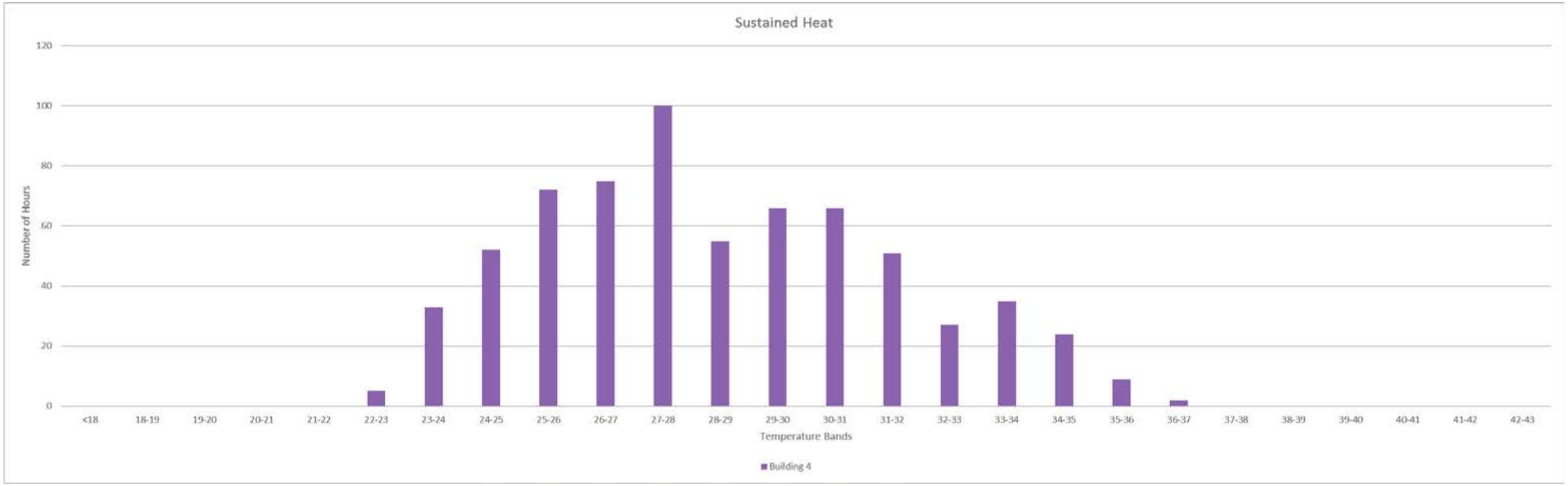
Apartment 2 also has a fairly wide distribution of temperatures, but with a non-negligible portion of the distribution towards the hotter end. The mode of the distribution is 29°C with maximum internal temperatures reaching 43°C. The large volume of thermal mass in the apartment resulted in warmer temperatures compared to Apartment 1 as the heat accumulated during hot days would radiate back into the internal space, and the absence of ventilation strategies would prevent that heat to easily be flushed out. The result was internal temperatures that would remain moderately high for several days, even when outside conditions would become more comfortable.

Apartment 3



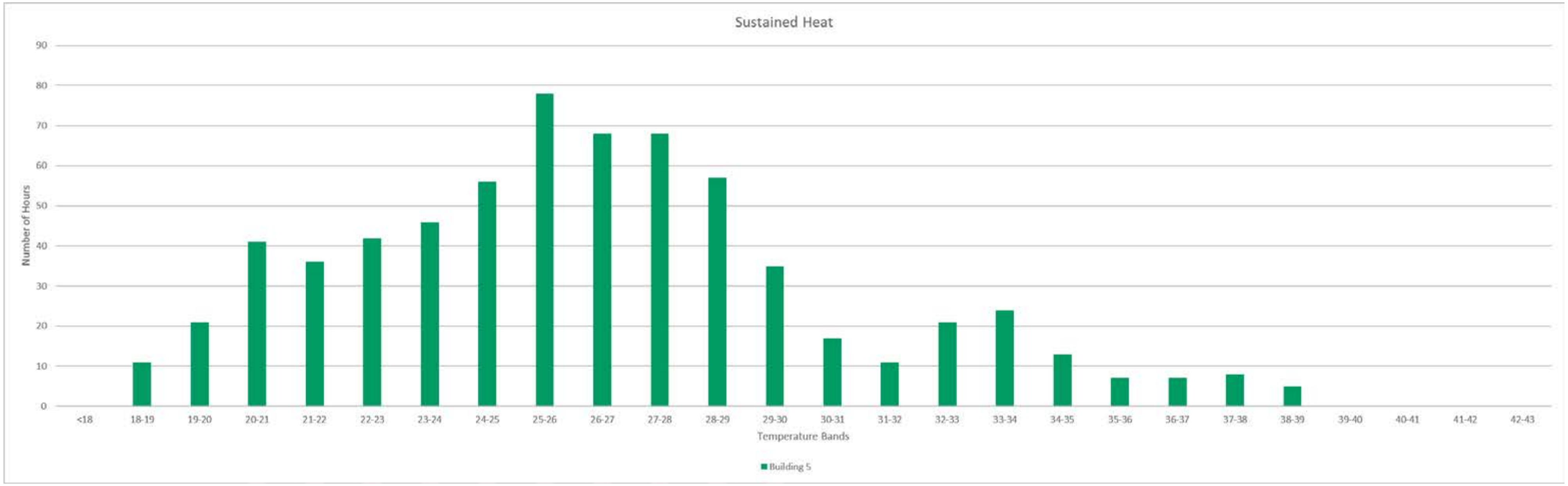
Apartment 3 has a much narrower distribution of temperature. This is entirely attributed to the large volume of thermal mass in the apartment, which has mitigated the temperature extremes, both high and low. However, because the large amounts of thermal mass is not used in conjunction with other thermal strategies, such as insulation and natural ventilation, the distribution of temperature is skewed towards the hotter end of the temperature bands – even if temperatures never exceed the high 30s, most of the hours within the four-week period is above the comfortable threshold. Although having the exact same construction system as Apartment 2, Apartment 3 also has more occupants – the increased internal gain is then reflected in the higher sustained internal temperature.

Apartment 4



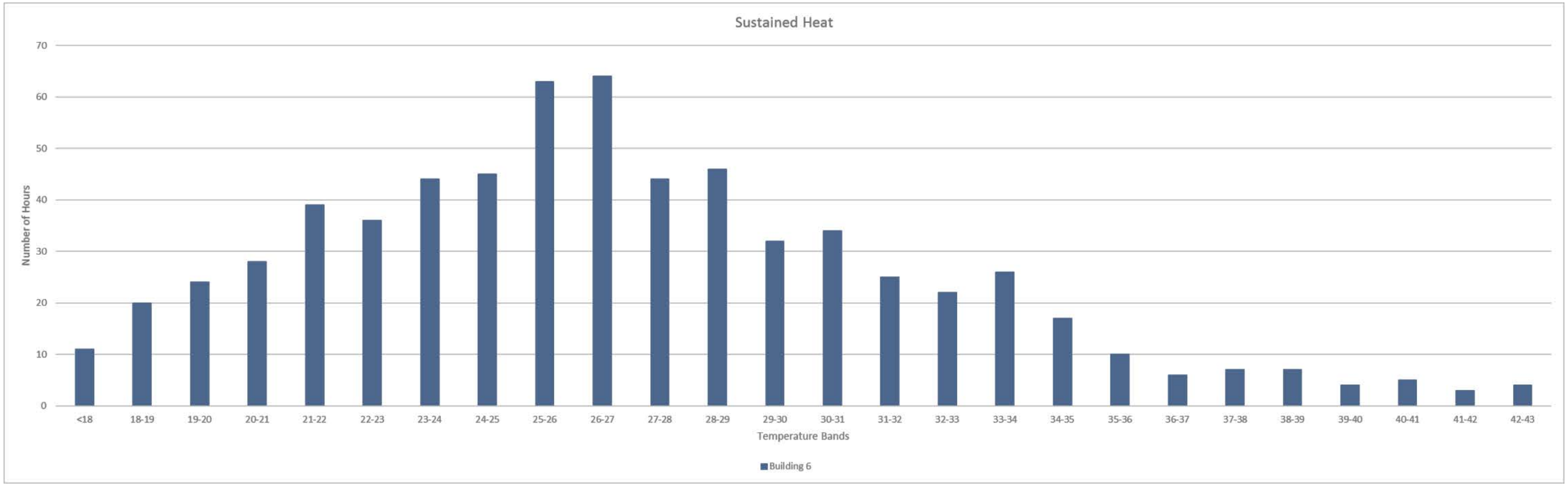
The distribution for Apartment 4 is very similar to that of Apartment 3, in that it covers a narrower temperature band, attributed primarily to the amount of thermal mass inside the apartments. The major difference between Apartments 3 and 4 is that Apartment 4 is insulated, so is more protected from external solar and conduction gain. The result is that the mode of the distribution is at 28°C with a slightly lower maximum temperature. Apartment 4 also almost completely enclosed by adiabatic walls, and has a single window, meaning that whatever heat accumulated inside the apartment would stay in the apartment.

Apartment 5



Apartment 5 has a heavy wall construction with a combination of heavyweight and lightweight internal partitions. In terms of how much thermal mass is has, Apartment 5 sits between Apartment 1 and Apartment 4, This can be observed on the chart above. Its temperature distribution is narrower than that of Apartment 4, but wider than apartment 1, reflecting the relative amount of thermal mass it has. The mode of the distribution is at 26°C and the maximum is 39°C.

Apartment 6



Apartment 6 has the most widespread temperature distributions over this 4-week period. The mode of the distribution is 26°C and the peak is well within the mid 40s. The wide distribution is attributed to the uninsulated lightweight construction that reacts quickly to changes in external temperature and the absence of other thermal strategies that might mitigate heat gains and heat losses.