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Measured and simulated thermal behaviour in rammed earth houses in a hot-arid climate. Part B: Comfort

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Abstract

Heating and cooling of residential buildings consumes around ten percent of the world's energy. One approach for reducing these costs is solar passive design using building materials with high thermal mass such as Rammed Earth (RE). Several studies have examined the performance of small RE structures or individual rooms within RE dwellings and have demonstrated the material's capacity to passively provide comfortable internal conditions.However, there is a lack of scientific evidence about the performance of full RE houses in real-world settings spanning several seasons.This research investigated the thermal performance of RE structures prior to occupancy and over the course of an occupied year. Two custom-designed houses were built in the hot-arid city of Kalgoorlie-Boulder, Western Australia: one with traditional solid RE walls and the other with walls with an insulating polystyrene core (iRE). Otherwise the houses were identical in orientation and design.

This study is presented in two Parts. Part A examined the houses' performance without occupants: This Part examines their occupied behaviour in terms of the occupants' thermal comfort. Comfort was examined using qualitative and quantitative data from sensor measurements as well as occupant surveys and simulated results using state-of-the-art assessment software *BERS Pro*. Comfort scores for measured and simulated data were determined using rules built into *BERS Pro*'s engine *Chenath* and a modified version of the ANSI/ASHRAE Standard 55-2010 SET* method.

Real-world thermal comfort of both houses outperformed their simulated behaviours: occupants reported comfortable conditions throughout Summer (outdoor maxima 45°C) and Winter (minima 1°C) with no artificial cooling and with minimal heating. The *Chenath* and SET* methods agreed with comfort performance in Summer but scored Winter performance poorly. Similarly, simulations predicted poor performance in Winter. Consequently, predicted energy demands due to heating were likely far higher than those needed in reality. This paper therefore argues from measured evidence of RE and iRE houses for the suitability of RE as a sustainable building material able to curb domestic energy demands. Collected data has been made publicly available for future analyses.

Keywords: rammed earth, thermal comfort, environmental monitoring, rural housing

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Contents

1. Introduction

Rammed earth (RE) is a high thermal mass construction method relied upon for millennia to passively provide comfortable living conditions [13]. In RE, soil is compacted into formwork in layers to produce thick, freestanding high density ($\sim$2000kg/m^3) walls. Depending on its quality and grading, soil can be claimed directly from the site, making RE an ideal choice for construction where transportation costs can be prohibitive, as is the case in rural Australia and other communities around the world [5]. However, the global RE industry is at a critical juncture. On the one hand, it has the potential to offer sustainable, low-embodied energy construction and to curb domestic energy demands. On the other, its use is threatened by new and/or inappropriate regulations on its thermal properties and design. One such example are those imposed by the Australian Nationwide House Energy Rating Scheme (NatHERS), which often rates RE thermal performance poorly despite vernacular evidence to the contrary. Recent research has identified shortfalls in these regulations [6–8]. However, more evidence is needed to adapt them to better reflect actual RE thermal performance. As a leader in RE construction (e.g. Ciancio and Beckett [4]), adaptations to Australian regulations will encourage similar changes around the world.

In this series, we contrast the unoccupied and occupied thermal behaviour of two houses, one built with traditional solid RE walls (RE) and the other with walls with an insulating polystyrene core (iRE). The houses are hereafter referred to as the "monolithic" and "insulated" houses respectively. The houses were built in Kalgoorlie-Boulder, Western Australia (WA) and designed to optimise passive solar behaviour, making extensive use of thermal mass, optimised ventilation and orientation. Performance prior to occupancy was discussed in Part A of this series. That paper described the houses' construction and instrumentation, our experimental approach and the strategies used for data collection and management. Unoccupied performance was quantified in terms of thermal stability (the ability to resist large changes in diurnal temperature) and thermal lag (the ability to offset peak temperatures): features important to controlling thermal comfort. Performance in all rooms was measured using a suite of sensors and simulated using NatHERS softare *BERS Pro* (v4.3). We showed that thermal stability and lag were similar in both houses despite differences in their construction: the more costly iRE did not provide a notable benefit in the WA climate. Notably, *BERS Pro* simulated thermal stability and lag did not match measured values: stability scores were significantly poorer and lags significantly longer in rooms with lower and higher thermal mass envelopes respectively.

Part B of this series expands on Part A's findings to examine the houses' occupied performance over twelve months. Again, performance was evaluated using measured data and simulated data from *BERS Pro*. Comfort scores based on the *Chenath* assessment method (used within *BERS Pro*) applied to measured data were compared to occupant feedback, obtained through regular surveys, to examine *Chenath*'s ability to match reported data and identify causes for discrepancies. *Chenath* scores were also contrasted against those from the ANSI/ASHRAE Standard 55-2010 SET* method to examine strengths and weaknesses in the assessment criteria [1]. Data presented in both Parts of this study have been made publicly available and can be downloaded from `http://datascience.ecm.uwa.edu.au:55555/`. A timeline describing the unoccupied and occupied analyses covered during this series is given in Table 1.

(Insert Table 1 somewhere near here)

Table 1: Analysis timeline. MMT: Mean Monthly Temperature (°C)

Year	2014				2015												2016		
Month	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M
Max MMT	24.6	29.3	30.0	32.7	34.9	36.8	29.1	22.4	20.0	19.5	17.3	18.5	23.5	30.9	31.0	32.9	32.8	31.6	27.8
Min MMT	10.4	14.5	15.5	16.8	18.8	20.8	16.7	12.3	8.0	7.2	6.2	7.7	8.2	15.7	16.6	16.8	19.0	18.0	17.1
Period	Unoccupied							Occupied											
Season	Unoccupied										Winter					Summer			
Dates	01/09/14-30/11/14										14/06/15-23/09/15					21/11/15-02/03/16			

2. Data Management

This study's experimental programme was explained in detail in Part A of this series. Here, we describe the techniques used to adapt the installed instrumentation to accommodate occupants and the simulation methodology.

2.1. Virtual Sensors

The aim of this research is to investigate the thermal behaviour of hybrid RE and iRE houses under real-world conditions. Head-level room temperatures and humidities are key data for the assessment. However, it was not feasible to have sensors hanging at head-level while the houses were occupied. To address this problem, we developed a machine learning algorithm that learned models for accurate, long-range estimation of sensor readings [2]. At any time such "virtual sensors" estimated their readings using those from the permanent sensors mounted in the ceilings and walls. Data gathered during the unoccupied period, discussed in the first Part of this series, was used to train virtual sensors for head level temperature and humidity. Although a simple linear regression appeared to give reasonably correlated results, its fit to extreme temperatures, most notably daily maxima, was poor. For testing periods of 7 to 14 days, in 90% of the cases the error for linear regression models was within 1°C. However, as the testing period increased, the estimation accuracy decreased. On the other hand, virtual sensing was extremely accurate and stable for long periods: for up to 95% of the sensor readings it achieved estimation errors within 0.5°C. "Best", "high" and "low" virtual sensor values were computed for both houses, corresponding to the median, upper and lower quartiles of the prediction model. These virtual sensor observations were used for thermal comfort analyses during the occupied period.

2.2. Simulations

A common grievance of occupants of Australian low-energy dwellings is that NatHERS energy assessments fail to accurately capture their use of the structure and so its efficiency [8]. Commentators on the accreditation process claim that the disparity is due to shortfalls in the *Chenath* engine's comfort-rating criteria. Daniel et al. [6, 7, 9], Miller et al. [14] showed that the *Chenath* engine is able to capture the thermal behaviour of unoccupied high thermal mass structures. However, it is less able to model occupant behaviour or comfort interpretation in houses designed to function passively [8].

In this study, house performance was simulated using *BERS Pro* v4.3 (incorporating *Chenath* v3.13, released September 2015) to compare predicted unoccupied and occupied performance to measured data and to identify disparities in any sources of discomfort. Simulations were based on 30-year average annual temperature data (as required by the rating system) and provided a simulated year's worth of data for each condition (i.e. unoccupied or occupied). Wall material thermal properties used in *BERS Pro* are given in Table 2.

(Insert Table 2 somewhere near here)

For unoccupied performance, simulations assumed external doors and windows remained shut and no artificial heating or cooling (including cooking, bathing etc.) was permitted. Occupied simulations assumed normal occupant activity (cooking, bathing, sleeping etc.) and the opportunity to employ artificial heat-

Table 2: Material and component thermal properties used in *BERS Pro* simulations

Material/component	Density (dry) (kg/m^3)	Resistance (m^{2}K/W per metre)	Capacitance (kJ/m^{3}K)	R-value (m^{2}K/W)
Rammed earth (RE)	2000	0.80	1940.0	-
Extruded polystyrene (EP)	32	35.72	340	-
Concrete	2400	0.69	2112.0	-
Steel	N/A	0.02	3900.0	-
Timber (softwood)	N/A	10.00	1057.5	-
External surface	-	-	-	0.04
Internal surface	-	-	-	0.12
Total RE wall	300mm RE			**0.40**
Total iRE panel	125mm RE, 50mm EP, 125mm RE			**2.14**

ing and cooling. The *Chenath* engine simulates cooling hierarchically. First, the effect of opening windows in that room was calculated. If that was not sufficient, occupants were assumed to activate forced air movement (e.g. from ceiling fans). Finally, if neither approach sufficiently reduced perceived temperatures, active cooling was applied in the model. Unlike cooling, no hierarchy existed for heating; if temperatures dropped below the heating threshold, artificial heating was applied [12].

3. Thermal performance metrics

3.1. Occupant surveys

The monolithic house was occupied by a family of five: two adults and three children under the age of ten. The insulated house was occupied by two adults. Both were Aboriginal families who volunteered to take part in the study and who had had no prior contact with the research team. Either family was free to withdraw at any point with no repercussions (i.e. they would not be asked to leave the houses).

Both families resided in the houses for the duration of the study, excepting short absences for holidays in Winter. The occupants were surveyed monthlyand asked:

- how they would rank the thermal comfort during the day (very poor/poor/normal/excellent);
- how they would rank the thermal comfort during the night (as above);
- whether they had used the ceiling fans or heaters (and, if so, when);
- whether they had experienced any day or set of days that were too hot or cold (and, if so, when);
- how many people had occupied the house (normal tenants/moreor fewer), with details;
- whether they were happy to continue with the study.

Occupants were surveyed by a local liaison officer, known in the community, to reduce potential bias in their responses. Responses were obtained for the majority of the surveyed months for both houses (some absences in winter). Occupants were not contacted directly by the research team, except if access was needed to repair equipment.

3.2. Thermal comfort

Thermal comfort was assessed by 'scoring' each house according to the percentage of time that hourly temperature was within comfortable thresholds. Comfort thresholds were calculated using two methods: the comfort rules used within *BERS Pro* (the *Chenath* engine) as part of the NatHERS rating system; and the ANSI/ASHRAE Standard 55-2010 SET* method. Scores from both methods were compared to qualitative feedback from the occupants. Hourly contributions to Time Outside Comfort, TOC, were also examined, calculated as the percentage time that a given hour fell outside the comfort boundaries. TOC values were used to identify times in the day most responsible for poor comfort performance for both methods.

3.2.1. Chenath assessment

The *Chenath* engine specifies different minimum and maximum permissable temperatures for every hour of the day and rates that hour as either too hot, too cold or within tolerance. The cooling threshold (i.e. the upper comfort limit per hour), T_{upper}, varies by activity but not by room use and is defined as

$$T_{upper} = T_n + 2.5 + \Delta T \tag{1}$$

where T_n is the "trigger temperature" based on the psychrometric chart and ΔT is an offset accounting for air movement and humidity [3, 11]. T_n changes per location: in Kalgoorlie-Boulder, $T_n = 26°\text{C}$. T_n also varies depending on activity: if during a sleeping period, defined as 00:00–07:00, T_n is reduced by 1.5°C [15]. ΔT is found via

$$\Delta T = \left[1.6 + 6(v - 0.2) - 1.6(v - 0.2)^2\right] + (2.67 - 0.053r) \tag{2}$$

where v is the indoor air speed (which must be between 0.2 and 2m/s) and r is relative humidity in %. The relative humidity reduces or increases acceptable temperatures for r >50% or r <50% respectively. A further modification is applied depending on the comfort condition of the previous hour: T_{upper} is reduced by 2°C if the previous hour exceeded its calculated T_{upper} [15]. This modifica-

Table 3: Hourly *Chenath* heating and cooling temperature thresholds. *Reduced by 2°C if previous hour was outside comfort limits

Threshold	Rooms	Times	Temperature limits (°C)
Cooling	All rooms	00:00–07:00	$T_{upper} - 1.5$*
		07:00–00:00	T_{upper}*
Heating	Living rooms	00:00–07:00	N/A
		07:00–00:00	20
	Bedrooms	01:00–07:00	15
		07:00–08:00	18
		16:00–00:00	18

tion forces *Chenath* to apply more rigorous cooling (if possible) to rapidly return conditions to within comfort levels.

The heating threshold (i.e. the lower comfort limit) varies by room use and activity. In living rooms, heating is required if temperature falls below $T_{lower} = 20$°C from 07:00–00:00. Comfort outside of those hours is not considered as the rooms are assumed to be vacant. In bedrooms, heating is required if temperature falls below $T_{lower} = 15$°C from 01:00–07:00 or $T_{lower} = 18$°C from 08:00–09:00 and 16:00–00:00. Otherwise, bedrooms are assumed to be empty. Unlike cooling, no penalty is applied to T_{lower} if the previous hour fell below its heating threshold. Hourly *Chenath* heating and cooling thresholds are summarised in Table 3.

(Insert Table 3 somewhere near here)

3.2.2. SET assessment*

The SET* method is a simpler alternative to the *Chenath* comfort rules which can easily be applied to any room of a structure. As such, its use can provide insight into what benefits the more complex *Chenath* method provides. SET* uses a thermo-physiological simulation of the human body to define a range of comfortable temperatures according to mean monthly outdoor temperature (MMOT).

The input temperature, T_{SET^*}, is defined as

$$T_{SET^*} = T_i - \Delta T \tag{3}$$

where T_i is the indoor dry bulb temperature and ΔT is as per Eqn 2. T_{SET^*} is deemed uncomfortable if it falls outside of the comfort limits for its corresponding MMOT. de Dear and Brager [10] suggested an improvement to MMOT, being the "thermal expectation", T_{RM}, which includes effects of the preceding week of temperatures on perceived comfort:

$$T_{RM} = 0.34T_1 + 0.23T_2 + 0.16T_3 + 0.11T_4 + 0.08T_5 + 0.05T_6 + 0.03T_7 \tag{4}$$

where, for a given day of observation, T_j (for $j = 1$ to 7) is the mean temperature (i.e. the average of the day's maxima and minima) for the jth preceding day. For *BERS Pro* simulations, T_{RM} was calculated for the first day of each month using 30-year average daily temperature data for Kalgoorlie-Boulder (BoM). This value was used in place of MMOT with the ANSI/ASHRAE Standard 55-2010 acceptable operative temperature range chart. Measured outdoor dry bulb temperatures from April 2015 to April 2016 were used to calculate T_{RM} for the measured data set. Resulting monthly 80% acceptable minimum and maximum temperatures for both data types are given in Table 4: 80% limits were used rather than the tighter 90% limits to provide as broad a range of potential comfort as possible. Unlike *Chenath*, SET* limits are not affected by room type. However, ANSI/ASHRAE Standard 55-2010 assumes standard daytime occupant activities: T_{SET^*} is not designed to apply to nighttime comfort.

(Insert Table 4 somewhere near here)

Table 4: SET* monthly 80% acceptance cooling and heating thresholds for measured data (2015–2016 hourly temperatures) and *BERS Pro* simulated performance (30-year mean hourly temperatures)

Data	Threshold	January	February	March	April	May	June
Measured	Cooling (°C)	29.9	29.0	30.5	27.6	26.3	25.1
	Heating (°C)	22.9	22.0	23.5	20.6	19.3	18.1
		July	August	September	October	November	December
	Cooling (°C)	24.8	25.8	26.2	27.8	29.2	28.8
	Heating (°C)	17.8	18.9	19.3	20.9	22.2	21.8
		January	February	March	April	May	June
Simulated	Cooling (°C)	29.9	29.8	28.6	27.2	25.7	26.0
	Heating (°C)	22.9	22.8	21.7	20.2	18.7	19.0
		July	August	September	October	November	December
	Cooling (°C)	25.0	26.0	25.8	26.5	26.2	28.5
	Heating (°C)	18.0	19.0	18.8	19.5	19.3	21.5

4. Results and Discussion

This section assesses the thermal performance of the Kalgoorlie-Boulder rammed-earth houses during Summer and Winter. The following questions were addressed:

1. How differently did the houses perform?
2. Did the residents perceive the houses to be thermally comfortable or not?
3. For how much of the time and when were the houses thermally comfortable according to either simulations or measured data?
4. What were the sources of differences between the comfort scores and occupant feedback?

4.1. Surveys

Survey results showed that both houses were comfortable *throughout Summer and Winter*. In Summer, occupants did not use any artificial cooling (e.g. mobile air conditioning) but did make use of ceiling fans. Artificial heating was used in both houses in Winter: although fixed heating units were not installed, occupants were free to use mobile heaters. Both houses were occupied for the entirety of Summer but were reported vacant for short intervals during Winter; these periods were not included in comfort analyses. Although not part of the survey, occupants reported a reduction in their annual energy bills compared to previous homes and excellent acoustic insulation owing to the houses' thick walls.

4.2. Outdoor temperatures

Outdoor hourly temperatures during Summer and Winter are compared in Figure 1. An unpaired Welch Two sample t-test was used to assess differences between measured and simulated climate data; all seasons were significantly different between measured and simulated values (unpaired p values: Summer$= 3.995e-17$; Winter$= 5.712e-04$). Simulated outdoor median, lower and upper quartile temperatures were *cooler* than measured values for all seasons. Temperature ranges were similar for Winter but smaller for Summer. Consequences of these differences on thermal comfort are discussed in the following sections.

(Insert Figure 1 somewhere near here)

4.3. Indoor temperatures

Hourly temperatures were measured or simulated for each room in both houses throughout Summer and Winter. Here, we predominantly focus on those in the southern bedroom both for brevity and as it was the room with the largest RE or RE/iRE envelope (by metre of wall). Measured and simulated dry bulb temperature in the southern bedroom and outdoors during Summer are shown in Figures 2 to 4. The same results for Winter are shown in Figures 5 to 7.

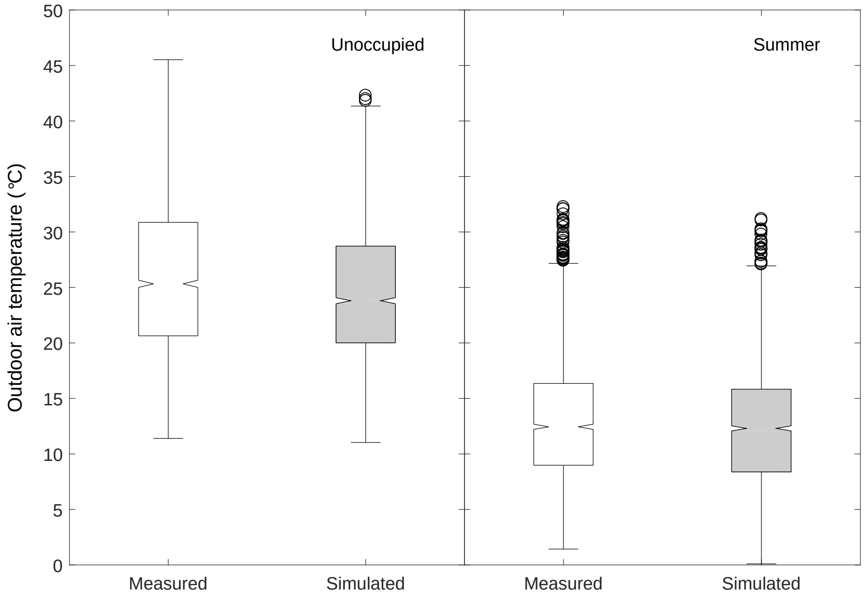

Figure 1: Boxplots of measured and simulated outdoor hourly temperature in Summer and Winter

4.3.1. Summer

Figure 2 shows that internal temperature variation was significantly less than that outside for both houses in Summer. Internal temperature variation was broader for a given hour in the monolithic house than in the insulated (Figure 3). The insulated house had marginally higher temperatures overall, most significantly from 21:00–09:00.

BERS Pro simulated internal temperatures were lower than measured as a consequence of lower outdoor temperatures predicted for the period (Figure 1). Temperature ranges per hour were similar throughout the day in both houses. However, daily temperature variation was larger than for measured values, as were hourly variations (likely due to the houses' poorer simulated thermal stability, covered in Part A of this series). Opposite to measured behaviour, simulated variations were the largest from 10:00–21:00.

(Insert Figure 2 somewhere near here)

(Insert Figure 3 somewhere near here)

(Insert Figure 4 somewhere near here)

4.3.2. Winter

As for Summer, Figure 5 shows that internal temperature variations were significantly less than those outdoors in Winter for both houses. However, surveys revealed that occupants used portable heaters on various occasions, demonstrated by sharp temperature spikes in Figure 5. Such spikes did not represent mean air temperature. Rather, heaters were (unintentionally) positioned below ceiling sensors in some rooms, generating false readings. Severe spikes were removed during data cleaning. Remaining spikes were included in comfort assessments as their presence was useful to indicate heating episodes. Again, internal temperatures

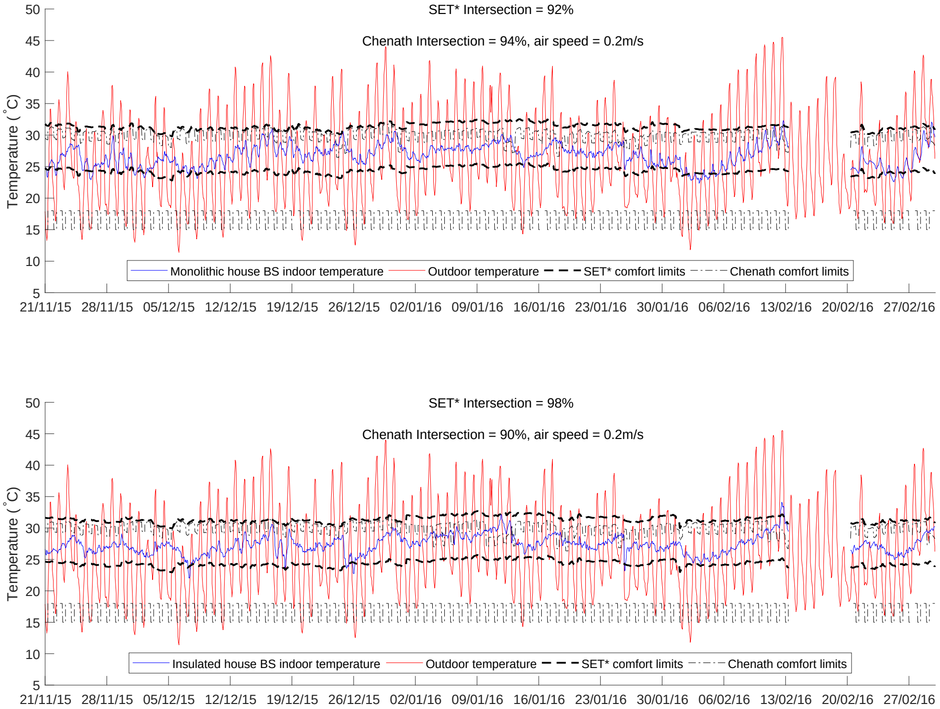

Figure 2: Head-level southern bedroom (BS) indoor and outdoor dry bulb temperatures during Summer, compared to *Chenath* and SET* comfort limits

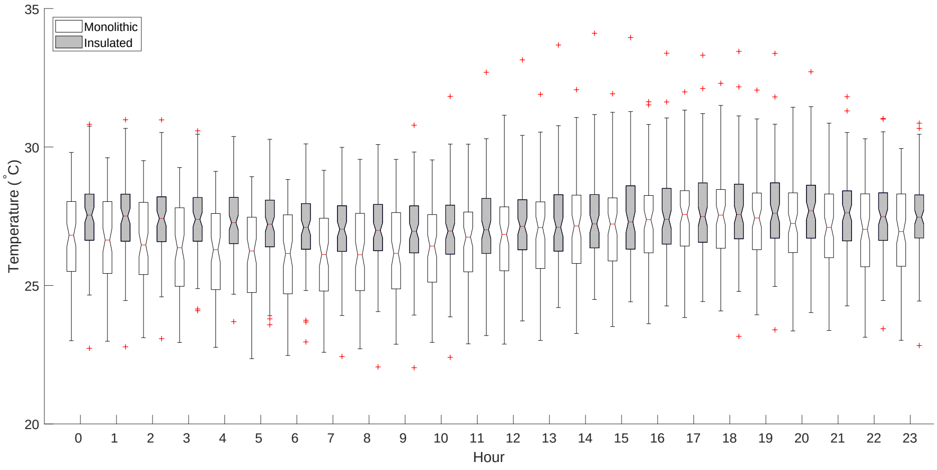

Figure 3: Measured ("best") Summer monolithic and insulated house hourly temperatures in the southern bedroom. Box necks show the 95% confidence interval on the mean (roughly 90 samples per analysed hour). + symbols are outliers

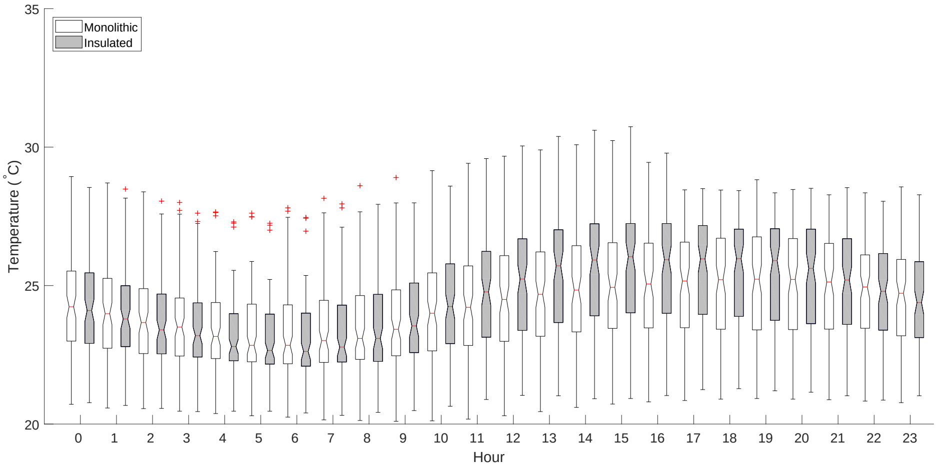

Figure 4: *BersPRO* simulated Summer monolithic and insulated house hourly temperatures in the southern bedroom. Format as per Figure 3

were warmer in the insulated house and temperature ranges per hour were smaller (Figure 6). However, all temperature outliers (the majority positive) occurred for the insulated house, indicating greater random variation (i.e. irregular heating).

Simulated results in Figure 7 demonstrate *BERS Pro*'s assumption of near-constant heating in Winter: hourly ranges were significantly narrower than measured values due to tight heating control. Temperatures were also warmer than measured values. Positive outliers occurred in both houses at every hour, corresponding to heating episodes enforced by the comfort criteria: this is discussed in more detail in the following sections. As a consequence of heating, temperatures in both houses were highly similar. However, simulated temperature ranges in the insulated house were somewhat broader and warmer from 10:00–16:00. These hours were centred about the diurnal maximum (around 13:00–14:00) and corresponded to warmer Winter days during the overall period when heating was not applied. Part A demonstrated that the insulated house's thermal stability was marginally worse than the monolithic's, hence its more notable reaction to higher outdoor temperatures.

(Insert Figure 5 somewhere near here)

(Insert Figure 6 somewhere near here)

(Insert Figure 7 somewhere near here)

4.4. Thermal comfort

Thermal comfort scores for both houses using the *Chenath* and SET* methods in Summer and Winter are given in Tables 5 and 6. "Best", "high" and "low" comfort calculations assumed airspeeds of 0.2m/s (minimum value in Eqn 2). An additional "best" calculation was completed at 0.3m/s to examine the effect of higher airspeeds on overall scores.

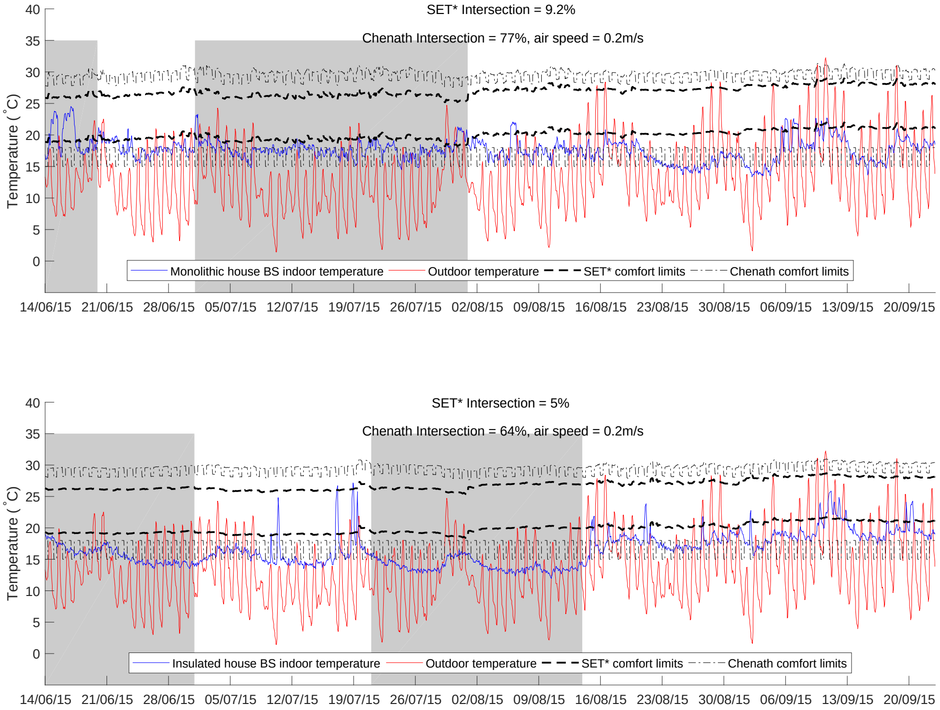

Figure 5: Head-level southern bedroom (BS) indoor and outdoor dry bulb temperatures during Winter, compared to *Chenath* and SET* comfort limits. Shaded regions denote times when houses were reported unoccupied

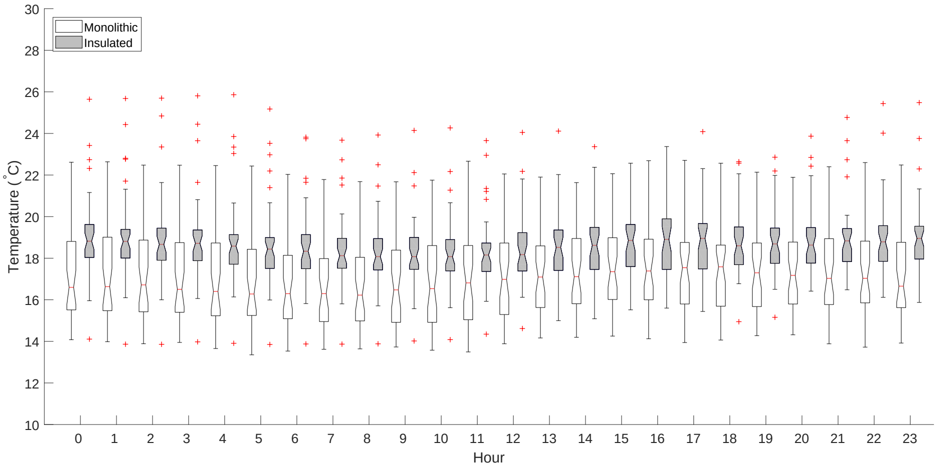

Figure 6: Measured Winter ("best") monolithic and insulated house hourly temperatures in the southern bedroom. Format as per Figure 3

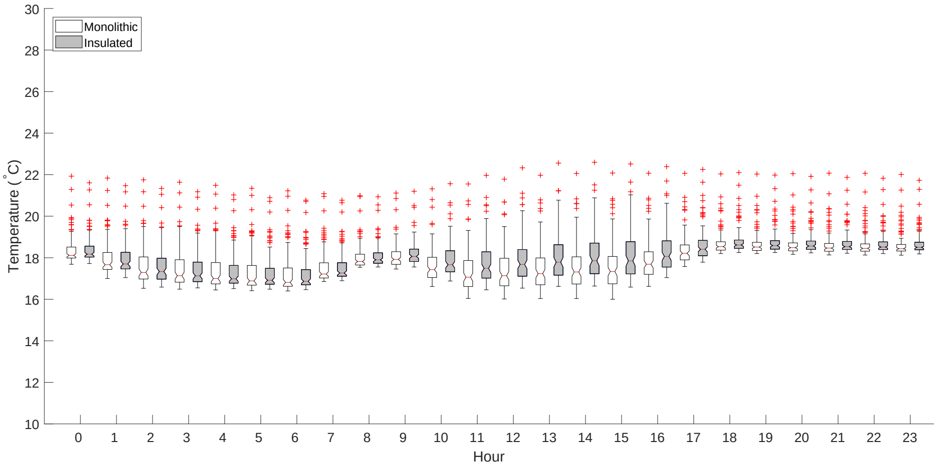

Figure 7: *BersPRO* simulated Winter monolithic and insulated house hourly temperatures in the southern bedroom. Format as per Figure 3

Table 5: *Chenath* method thermal comfort scores. “Best”, “High” and “Low” are results for different estimation methods. Bold entries show highest scores per analysis. [a]: calculated for airspeed of 0.2m/s. [b]: airspeed of 0.3m/s

Season	Room	Best		Best 0.3m/s		High		Low		Simulated	
		RE	iRE	RE	iRE	RE	iRE	RE	iRE	RE	iRE
Summer	Liv	88	**89**	**96**	95	**85**	84	**97**	**97**	**84**	83
	BE	**93**	89	**98**	97	**91**	87	**97**	**97**	92	**94**
	BS	**94**	90	**98**	97	**92**	88	**98**	97	**94**	**94**
	BW	**88**	87	**96**	95	**86**	84	**97**	**97**	**92**	**92**
	Kit	**89**	**89**	**96**	95	**86**	85	**98**	96	**91**	**91**
	Average	**90**	89	**97**	96	**88**	85	**97**	**97**	**91**	**91**
Winter	Liv	**44**	40	**44**	40	**46**	42	**40**	37	**96**	**96**
	BE	**79**	65	**79**	65	**80**	67	**74**	62	95	**97**
	BS	**77**	64	**77**	64	**79**	66	**74**	61	96	**97**
	BW	**84**	67	**84**	67	**86**	68	**77**	62	96	**97**
	Kit	**43**	41	**43**	41	**45**	42	**39**	38	**97**	**97**
	Average	**65**	55	**65**	55	**67**	57	**61**	52	96	**97**

(Insert Table 5 somewhere near here)

(Insert Table 6 somewhere near here)

4.4.1. Summer

Measured behaviour

Chenath comfort scores were over 80% in all rooms. Scores in the monolithic house were marginally higher than in the insulated for all analyses. At no time did hourly indoor temperatures fall below the heating threshold. Hence, “low” and “high” estimates produced the highest and lowest scores due to the assumption of lower or higher temperatures respectively.

Chenath and SET* TOC results for the southern bedroom (“best” estimation) are shown in Figure 8. Note that Figure 8 shows the percentage time a given hour was uncomfortable for that hour: the total detriment to the comfort score (i.e. 100-score) is the average of the hourly values. Similar analyses were

Table 6: SET* method thermal comfort scores. Legend as for Table 5

Season	Room	Best		Best 0.3m/s		High		Low		Simulated	
		RE	iRE	RE	iRE	RE	iRE	RE	iRE	RE	iRE
Summer	Liv	94	**99**	91	**98**	94	**99**	89	**97**	**63**	**63**
	BE	94	**98**	89	**98**	94	**98**	90	**97**	65	**66**
	BS	93	**98**	87	**97**	94	**98**	89	**96**	60	**61**
	BW	95	**98**	91	**98**	95	**98**	90	**98**	66	**67**
	Kit	93	**99**	90	**98**	94	**98**	87	**98**	**61**	**61**
	Average	94	**98**	89	**98**	94	**98**	89	**97**	63	**64**
Winter	Liv	**15**	6	**10**	5	**19**	7	**9**	4	51	**52**
	BE	**10**	6	**7**	4	**12**	6	**8**	4	8	**10**
	BS	**10**	5	**7**	4	**10**	6	**7**	4	**4**	**4**
	BW	**14**	6	**8**	5	**15**	7	**9**	4	8	**11**
	Kit	**14**	6	**9**	5	**17**	7	**7**	4	**54**	**54**
	Average	**13**	6	**8**	4	**15**	7	**8**	4	25	**26**

completed for remaining rooms. By the *Chenath* method, 00:00–07:00 was the least comfortable period in all rooms in the insulated house. TOC was higher during that interval due to the lower value of T_n for sleeping periods in Eqn 1. This was also the least comfortable period in the monolithic house's southern and eastern bedrooms.Given that living rooms and kitchens were likely to be unoccupied from 00:00–07:00, specifying "comfort" at these times was misleading; removing restrictions on T_n when sleeping, as for heating in living rooms, would more accurately reflect their use and improve scores. Notably, TOC results in the monolithic house's western bedroom, living room and kitchen between 15:00–23:00 were as high as those for 00:00–07:00. Part A showed that these rooms had poorer thermal stability than the eastern and southern bedrooms due to their orientation and lower thermal mass envelopes respectively. These rooms also experienced thermal lags of roughly 1 hour. As such, temperatures in these rooms were higher in the afternoon and evening than in the other bedrooms, exceeding the *Chenath* waking cooling threshold. However, increasing "best" airspeed improved comfort scores significantly: an airspeed of 0.3m/s produced similar comfort levels to the “low” estimate due to more-positive values of ΔT in Eqn 1. All rooms achieved 100% comfort at 0.6m/s, which could, for example, be provided by a pedestal or ceiling fan. Use of air movement also benefitted from low daily humidities (around 50%); if humidity was higher then higher airspeeds, perhaps outside the fans’ range, would have been needed. *Chenath* scores of 100% could therefore realistically be achieved in all rooms, agreeing with occupant feedback.

SET* Summer comfort scores were higher than *Chenath* scores: over 90% in both houses. Contrary to *Chenath*, SET* scores were higher in the insulated house by 4–9%: indeed, scores were close to 100% in the insulated house. This difference was due to marginally higher temperatures in the insulated house, as previously discussed: the majority of uncomfortable hours in both houses were *too cold* according to the SET* comfort thresholds. Hence, the “low” estimation method received the lowest score. Similarly, increasing airspeed was detrimental. For the few hours that fell below comfort, 06:00–07:00 was the least comfortable time in all rooms in the monolithic house, corresponding to daily diurnal minima. Discomfort was also high around 16.00 in the living areas, corresponding to those days with high external maximum temperatures (close to 40°C) combined with the room’s thermal lag, as discussed above. All TOC values were similar in the insulated house according to the SET* thresholds.

Overall, both the *Chenath* and SET* gave high comfort scores in Summer, agreeing with occupant feedback. However, as occupants did not report any instances of being too cold, the SET* method was less appropriate despite achieving higher comfort scores in some cases. Specifying separate waking and sleeping comfort criteria in *Chenath* was therefore beneficial for describing Summer performance.

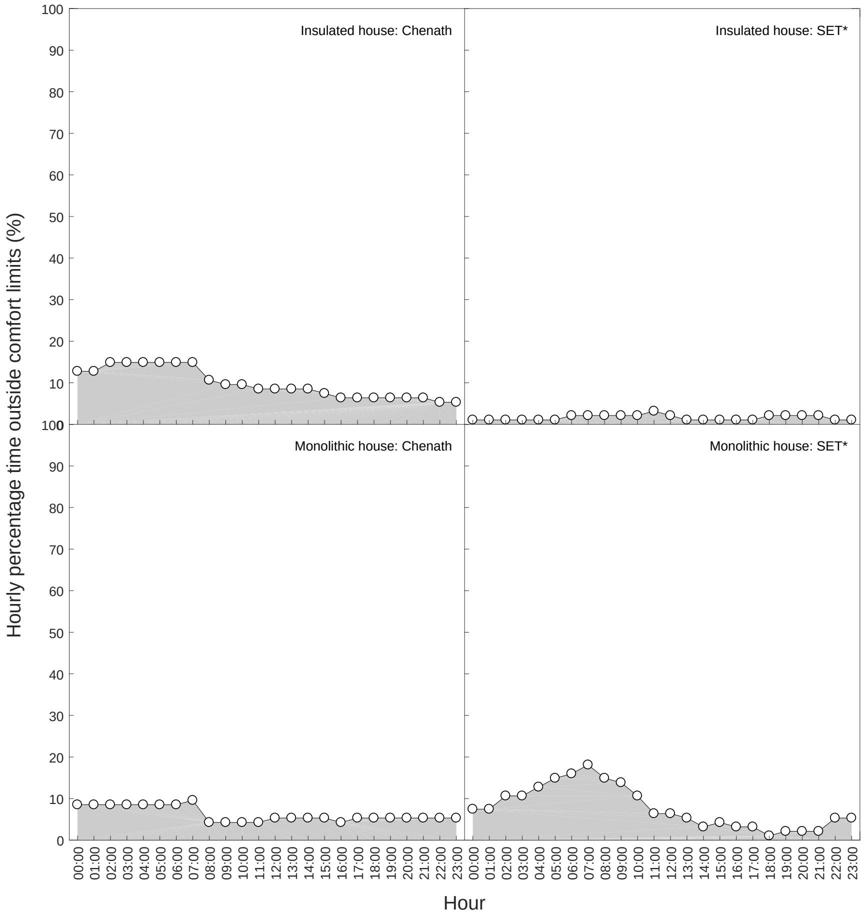

Figure 8: *Chenath* and SET* measured ("best" estimate) percentage TOC per hour for summer in the southern bedrooms

(Insert Figure 8 somewhere near here)

Simulated behaviour

BERS Pro hourly humidity values were not available. Therefore, humidity was set to 50% in Eqn 2, removing its contribution to ΔT. 50% was representative of 30-year annual average humidity in Kalgoorlie-Boulder (Australian Bureau of Meteorology). An indoor airspeed of 0.2m/s was also assumed.

Chenath comfort scores were >80% for all rooms in both houses in Summer, similar to measured "best" scores. No hourly temperatures fell below the heating threshold. However, it is unclear from temperature values alone whether this was due to the houses' passive performance or infrequent instances of artificial heating, allowed under the *BERS Pro* comfort hierarchies. Most hours fell within the comfort boundaries: discomfort did not vary significantly between hours for those that did not. Based on measured data, including humidity effects in Eqn 2 would increase the cooling threshold by 1–2°C, almost eliminating discomfort. Without accounting for air humidity, increasing airspeed to 0.6m/s also achieved 100% comfort for all rooms. *Chenath* comfort scores for both houses were therefore notionally 100%: as *BERS Pro* is built on *Chenath*, such a result was expected.

Both houses received similar SET* scores for *BERS Pro* data. However, scores up to 30% lower than those for measured values Unlike *Chenath*, no temperatures exceeded the SET* cooling threshold but intermittently fell below the heating threshold, accounting for the lower scores. Peak discomfort occurred between 06:00–07:00 in all rooms (e.g. Figure 9 for the southern bedroom), corresponding to outdoor temperature diurnal minima. As uncomfortable hours were deemed too cold, including humidity effects or increasing airspeed *lowered* comfort scores. Given the (sometimes) extreme outdoor temperatures, such a result was unrealistic: as found for measured behaviour, the SET* method's poorer performance was due to its high Summer heating threshold.

(Insert Figure 9 somewhere near here)

4.4.2. Winter

Measured behaviour

Sleeping and living areas scored differently in Winter under *Chenath* as the method applies different heating comfort criteria to each. Overall Winter *Chenath* scores were higher in the monolithic house by roughly 10%. The greatest differences were between the bedrooms: monolithic scores were around 80% but insulated scores around 60%. Such a result may be unexpected, given the higher mean hourly temperatures in the insulated house's bedrooms (e.g. Figure 6). However, no hourly temperatures exceeded the cooling threshold.Hence, higher upper quartile temperatures in the monolithic house *during sleeping periods* produced higher scores. Figure 10 shows that the least comfortable hours in the bedrooms were 08:00 and 18:00–00:00 for both houses. *Chenath* assumes that bedrooms were unoccupied from 09:00 to 16:00, hence no uncomfortable hours occurred during this period. The jump in discomfort at 08:00 was due to the transition to a higher 07:00–08:00 heating threshold. Such a sudden shift in perceived comfort is unlikely: removing it by extending the 00:00–07:00 heating threshold to 08:00 marginally improved overall bedroom comfort scores by 1.5% in the insulated house and 3% in the monolithic house. Discomfort prior to 08:00 was lower due to the lower sleeping period heating threshold.

(Insert Figure 10 somewhere near here)

Chenath Winter scores in the living rooms and kitchens were low in both

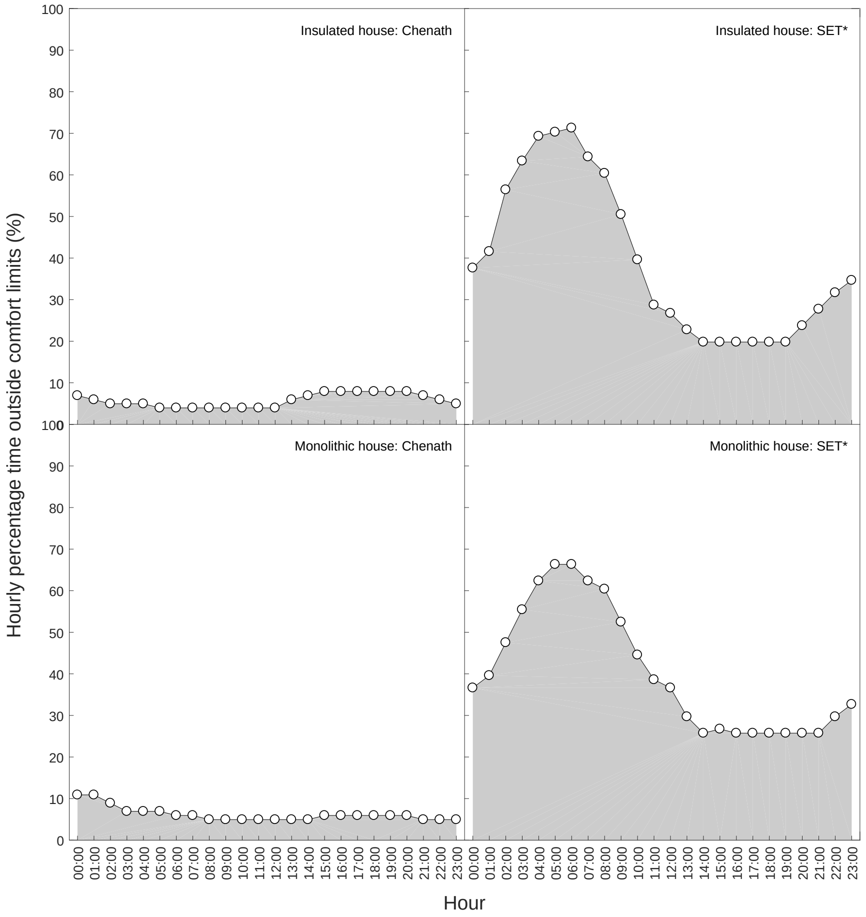

Figure 9: *BERS Pro Chenath* and SET* percentage TOC per hour in summer in the southern bedroom

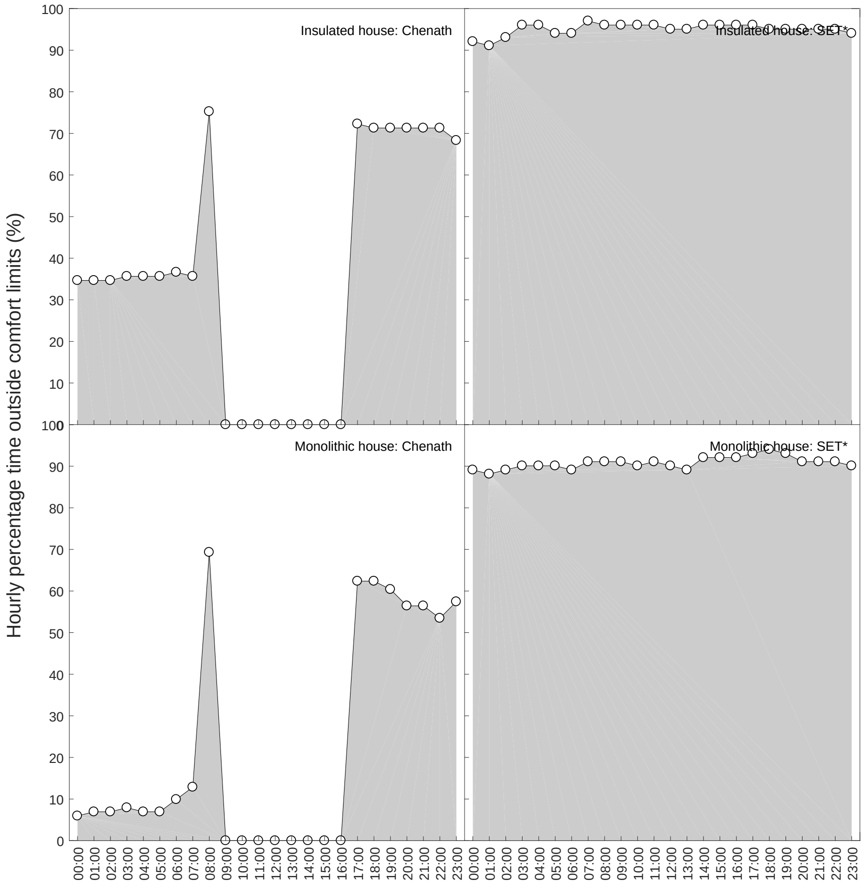

Figure 10: Southern bedroom measured TOC (*Chenath* and SET* methods, "best" estimate) in Winter

houses: roughly 40%. Again, no hourly temperatures exceeded the cooling threshold. Hourly TOC in the living rooms is shown in Figure 11: distributions were different to those in the bedrooms, due to the different heating threshold requirements. Living rooms and kitchens were assumed to be unoccupied from 00:00 to 07:00: TOC was zero during those times. A single heating threshold of 20°C was applied at 08:00. In the insulated house, all hours 08:00–00:00 were similarly uncomfortable: occupants did not heat the living room up to the assumed *Chenath* heating threshold. Discomfort marginally dropped in the monolithic house around 14:00, corresponding to outdoor temperature diurnal maxima; as discussed in Part A, the monolithic house, sited to the East of the insulated, marginally benefitted from less shading.

(Insert Figure 11 somewhere near here)

(Insert Table 7 somewhere near here)

SET* Winter comfort scores were poor in both houses: <15% in the monolithic house and <10% in the insulated. No temperatures in the monolithic house exceeded the cooling threshold. Isolated incidents of temperatures exceeding the cooling threshold occurred in the insulated house due to heating spikes. “Low” estimates and increased airspeeds increased the heating and cooling thresholds and so reduced comfort scores. Hourly TOC was similar throughout the day in all rooms in both houses, shown in Figures 10 and 11. Again, an exception was around 14:00 in the monolithic house’s living room, where discomfort marginally reduced due to outdoor diurnal maxima. As for Summer, poor scores stemmed from a heating threshold that was much higher than that adopted by the occupants.

Overall, the *Chenath* method was able to approximate occupant feedback but imposed heating thresholds were too high, leading to lower scores. As for Summer,

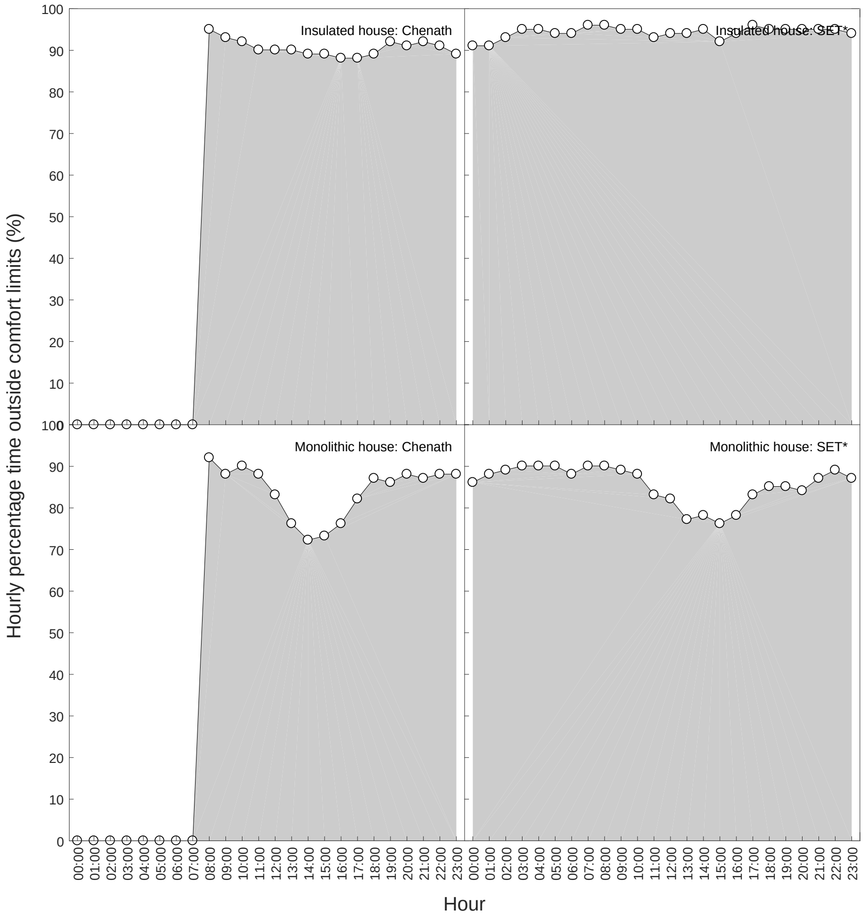

Figure 11: Living room measured TOC (*Chenath* and SET* methods, "best" estimate) in Winter

specifying different criteria for sleeping and waking times was advantageous, but using rigidly-defined values and heating times was detrimental. This was reflected in scores from the SET* method, whose high heating threshold made it entirely entirely inappropriate for judging Winter comfort, given that occupants did not report any uncomfortable times. To highlight the effect of high heating thresholds on comfort scores, scores corresponding heating thresholds reduced by only 2°C are given in Table 7: *Chenath* kitchen and living room scores improved by 32% in the monolithic house and by 16% in the insulated house, almost matching bedroom scores in both cases, and all SET* scores improved by up to 40%.

Simulated behaviour

All rooms required heating in Winter when simulated using *BERS Pro*, as shown previously in Figure 5. Two separate heating events occurred per day in the bedrooms, coinciding with the start of the two comfort-specified periods (00:00–08:00 and 17:00–23:00). One heating event occurred in the living rooms, starting at 08:00.

Chenath comfort scores were >95% in all rooms. Rapid changes in comfort criteria led to some instances of temperatures falling below the heating threshold.In the bedroom, sudden TOC peaks occurred at 08:00 and 17:00 (Figure 12). Similarly, a single peak occurred at 08:00 in the living room (Figure 13). Such peaks did not reflect expected occupant comfort; rather, they reflected discontinuities in *Chenath*'s heating thresholds. Providing a more continuous heating threshold definition would likely remove these instances. Rarely, indoor hourly temperatures exceeded the heating threshold. Such instances occurred when outdoor peak temperatures exceeded 25°C On these days, heating was not required and the house ran freely.

Table 7: Effect of reducing heating thresholds by 2°C on *measured* data *Chenath* and SET* Winter comfort scores. Unaffected rooms shown in *italics*. RT: Reduced Threshold. Other labels as for Table 5

House	Room	*Chenath*			SET*		
		Original (%)	RT (%)	Change (%)	Original (%)	RT (%)	Change (%)
Insulated	Liv	40	55	16	6	25	19
	BE	*65*	*65*	*0*	6	24	19
	BS	*64*	*64*	*0*	5	23	18
	BW	*67*	*67*	*0*	**6**	**28**	21
	Kit	41	56	16	6	25	19
	Average	55	62	6	6	25	19
Monoithic	Liv	44	76	32	**15**	**58**	43
	BE	*79*	*79*	*0*	10	49	38
	BS	*77*	*77*	*0*	10	46	36
	BW	*84*	*84*	*0*	14	56	42
	Kit	43	74	31	14	55	41
	Average	65	78	13	13	53	40

SET* comfort scores exceeded 50% in the living rooms and kitchens but largely fell below 10% in the bedrooms. In the bedrooms, almost all hours fell below the heating threshold; neither *BERS Pro* heating episode was sufficient to elevate temperatures above the SET* heating threshold. In the living rooms and kitchens, a single heating episode was sufficient to elevate temperatures above the SET* heating threshold. However, as discussed in Part A of this series, these rooms' thermal stabilities were poorly captured by *BERS Pro*. Consequently, temperature rose rapidly at the onset of heating and fell rapidly at its termination, so that hourly TOC fell dramatically around 14:00, corresponding to the combined maximum heating effect and outdoor diurnal maxima. Such rapid changes were not representative of those rooms in reality.

(Insert Figure 12 somewhere near here)

(Insert Figure 13 somewhere near here)

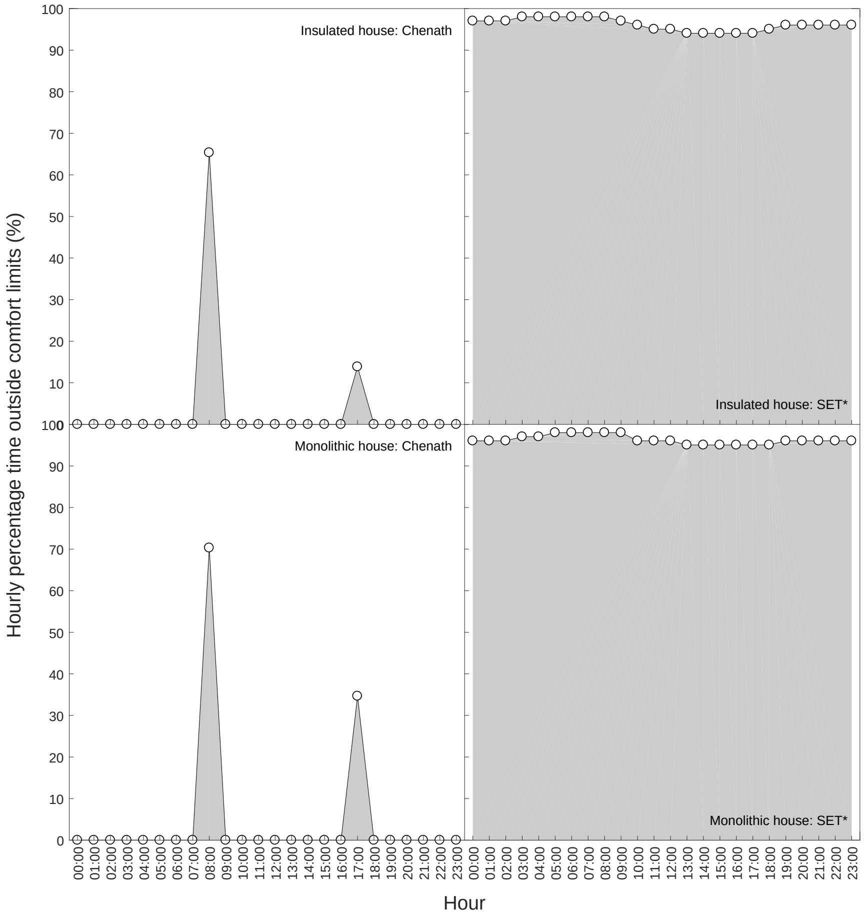

Figure 12: Southern bedroom *BERS Pro* TOC (*Chenath* and SET* methods, “best” estimate) in Winter

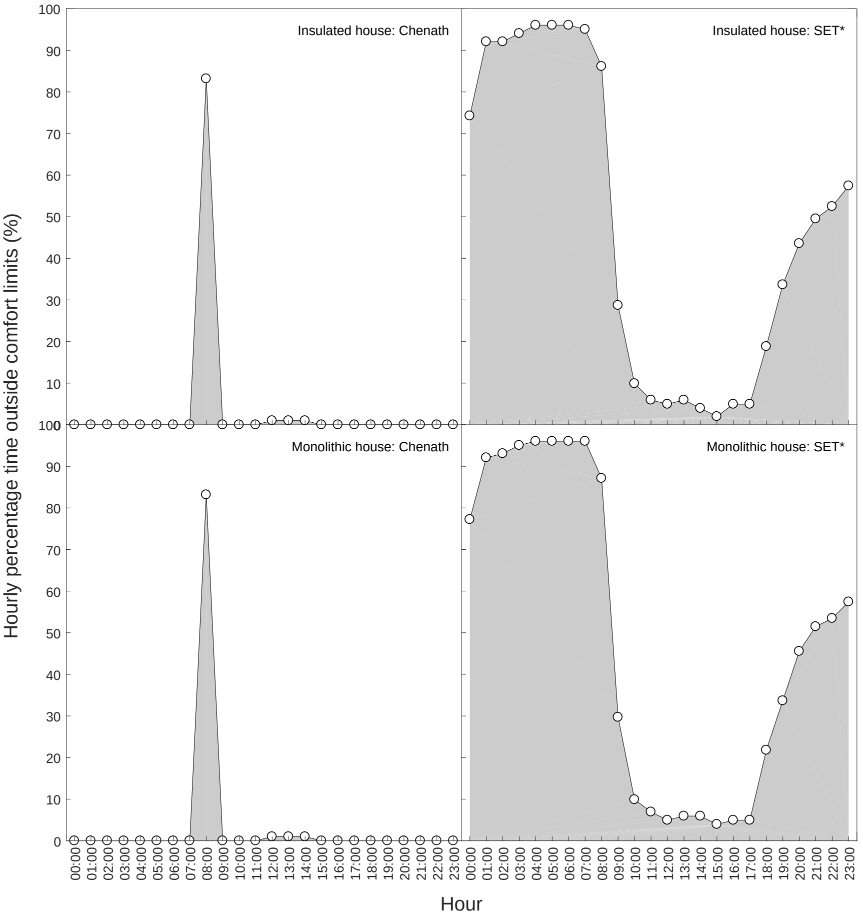

Figure 13: Living room *BERS Pro* TOC (*Chenath* and SET* methods) in Winter

4.5. Comfort model consequences on energy efficiency

heating takes a lot of energy due to high thermal mass (density and specific heat cap)

Several differences between measured and simulated performance were apparent. The most critical was *BERS Pro*'s requirement for near-constant heating in Winter. Heating was needed in reality, however rooms were not heated up to the *Chenath* (or SET*) thresholds. Given RE and iRE's high thermal mass (high density and specific heat capacity), additional heating represents a large energy demand. Winter heating demands should therefore have been significantly lower than predicted. Simulations also assumed that artificial cooling was required in the living rooms and kitchens in Summer. In reality, this was not the case as these rooms were significantly more thermally stable (discussed in Part A of this series). Summer cooling energy demands should therefore have been lower (if not zero) for both houses. A consequent quantitative reduction in simulated energy demand cannot be determined; however, the discussion provided above demonstrates that the houses' energy efficiency, predominantly in Winter, was considerably higher than those predicted by *BERS Pro*.

5. Conclusions

This series examined the performance of two RE houses in Kalgoorlie-Boulder, Western Australia. The houses were built to optimise passive solar properties and comprised mixes of RE, iRE and lightweight insulated walls. A substantial sensor and logging array was installed in each house to monitor unoccupied and occupied performance. Performance was also simulated using the state-of-the-art thermal modelling software *BERS Pro* v4.3 and assessed qualitatively through monthly occupant surveys. Indoor and outdoor data was gathered over the course of two years and the cleaned data used in this series has been made freely available for future research. This paper investigated the houses' thermal performance when occupied during Summer and Winter.

The houses' performance in Winter was poorly reflected by the *Chenath* and SET* method comfort criteria. Occupants reported that both houses were comfortable in Summer and largely comfortable in Winter, although infrequent heating was required. In Summer, *Chenath* and SET* comfort scores largely agreed with occupant perceptions. *BERS Pro* simulations were also similar to measured performance in Summer. However, Winter scores for measured data were poor and did not reflect occupant feedback. Simulations also demanded artificial heating in all rooms throughout Winter. Contrasting the *Chenath* and SET* methods and hourly TOC demonstrated that poor Winter performance was due to high heating thresholds. The effect of reducing heating threshold demands by 2°C, in agreement with occupant behaviour, on perceived comfort was demonstrated: comfort scores improved by up to 40% in some cases. Given that heating constitutes the greatest energy demand for these houses, *BERS Pro* simulated energy demands were likely far higher than in reality. However, results presented here are for a case study only: as a subjective quantity, we cannot claim that occupant comfort judged here reflects that of all occupants in low-energy homes in this or other climates.

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