Measured performance of a lightweight straw bale passive house in a Mediterranean heat wave

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1 Introduction

Rising temperatures and heatwaves across Europe in recent years are highlighting the need to pay close attention to overheating in the design of highly energy efficient buildings. The trends are clear to see in Figure 1 and Figure 2. Buildings that are not equipped to deal with such conditions put their occupants at risk: during the 2003 summer heatwave, as many of 70,000 additional deaths were reported across Europe [1].

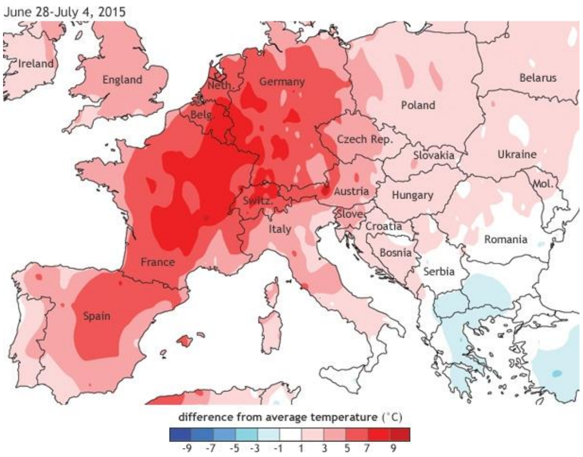

Figure 1: Temperature anomalies for Europe during June 28-July 4, 2015 [2]

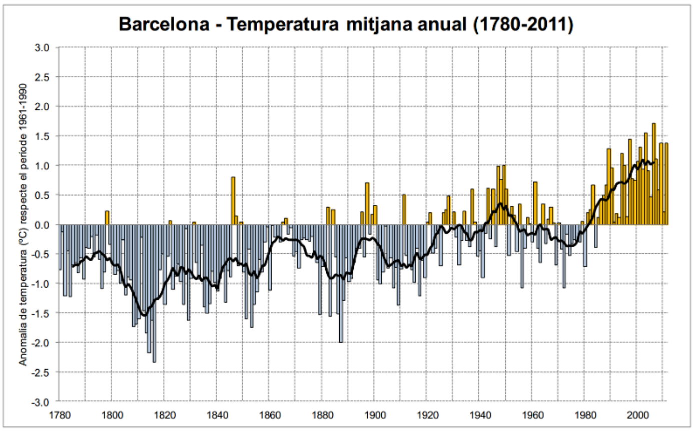

Figure 2: Annual temperature in Barcelona (1780-2011) [3]

The summer performance of passive houses in Mediterranean European climates has been documented, showing very good results [4]. However, recent press coverage in the UK with headlines to the tune of "Residents roast in eco-homes' greenhouse effect" [5, 6] underlines the need to address overheating if the quality assurance associated with the Passivhaus standard is to be maintained.

Can a comfortable indoor climate be achieved in super insulated, airtight, lightweight passive houses with no active cooling systems, under heatwave conditions? This paper takes the case study of a lightweight Mediterranean passive house, and through quantitative data analysis, looks at the measured performance of the home during the heat wave of July 2015.

2 Case Study: Larixhaus

The Larixhaus is a small single-family home located in the town of Collsuspina, near Barcelona, Spain (Figure 3, Figure 4, Figure 5). It was designed, prefabricated and built over a period of 8 months, from May - December 2014. The Larixhaus is the first prefabricated timber and straw bale dwelling on the Iberian Peninsula to achieve Passivhaus certification. The home is located at an altitude of 888 metres above sea level, therefore summer temperatures are typically not extreme, averaging 21 ºC in July and August, when average monthly solar radiation is usually > 200 kWh/m^2. The Köppen climate category is CfB, maritime temperate, with warm summers. PHPP climate zone is [ES] Barcelona, adjusted for altitude.

Figure 3: Bailing machine

Figure 4: Wall module during pre-fabrication

Figure 5: View of the the Larixhaus from the south west

A monitoring system was installed in the Larixhaus and came online June 6th 2015. Wireless air temperature and relative humidity sensors record data at 5-minute intervals. Figure 6 and Figure 7 show floor plans and indoor sensor locations. Figure 8, Figure 9 and Figure 10 show the outdoor temperature sensor in its housing, and indoor sensors on the ground and first floor (bedrooms are located on the ground floor, with living room and kitchen on the 1st floor).

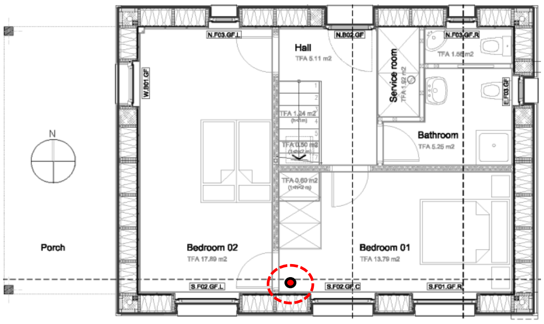

Figure 6: Ground Floor plan & sensor location

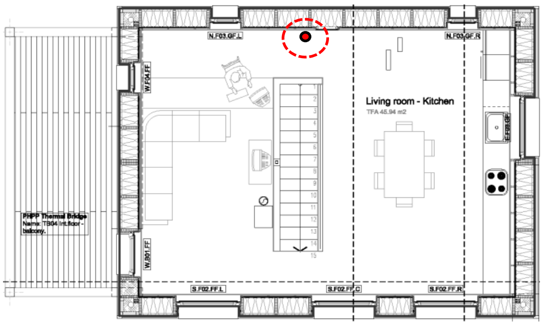

Figure 7: 1st Floor plan & sensor location

Figure 8: Outdoor sensor

Figure 9: Ground Floor sensors

Figure 10: 1st floor sensors

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3 Summer design strategies

Table 1 shows the summer design strategies used to combat overheating.

Design strategy	Description
Reduction of solar heat gains through opaque envelope	• Roof: 40cm straw insulation (λ = 0.059 W/m·K[1]), ventilated cavity • Walls: 40cm straw insulation (λ = 0.059 W/m·K), ventilated cavity
Reduction of solar heat gains through transparent envelope	• External shading devices: venetian blinds on southern openings; retractable awnings on western openings; roller blinds on eastern openings • Glazing solar factor: g = 47 %
Reduction of transmission and infiltration heat gains	• Thermal insulation; airtightness (n50 = 0.32 ac/h); controlled mechanical ventilation + heat recovery & automatic summer bypass
Ground coupling	• XPS insulation (λ = 0.034 W/m·K) under floor slab limited to 13 cm
Natural ventilation	• Night ventilation through tilted windows, providing simple, cross and stack ventilation
Reduction of internal heat gains	• Efficient lighting and appliances • DHW pipe runs kept to minimum (no recirculation)

Table 1: Summer design strategies

PHPP was used extensively in the design phase for energy balancing between summer and winter performance. The project brief was to prioritise bio-based insulation (straw) and structural materials (timber), therefore the building was designed with very little thermal mass, estimated as 60 Wh/K per m^2 TFA.

4 Methodology

4.1 Occupant behaviour & calibrated PHPP model

The PHPP model used in the design and certification stages showed an overheating index of 7.5 %. For the current study, the model was calibrated to reflect the exact habits of the occupants, relating to mechanical ventilation, external shading devices and window operation during the summer, shown respectively in Table 2, Table 3 and Table 4. The average monthly outdoor air temperatures were also adjusted in the climate file according to the measured data. Solar radiation, sky temperature and dew point temperature were not measured so these were left as they were in the climate file. The resulting PHPP overheating frequency was 4.6 %.

[1] Calculated lambda value for large format straw bales, positioned vertically in the walls, with dimensions 120 cm (h) x 40 cm (w) x 70 cm (d).

	h/d	Fan speed	Flow rate [%]	Flow rate [m³/h]	Air change rate [1/h]
22:00 - 08:00	14	1	28%	96	0.42
08:00 - 22:00	10	2	49%	170	0.74
Rarely used	-	*3*	*96%*	334	*1.46*
Nominal flow rate ventilator [m³/h]			350	-	-
Total volume for ventilation [m³]			229	-	-
Average air flow rate [m³/h]				**139**	
Average air change rate [1/h]					**0.61**

Table 2: Typical user operation of mechanical ventilation system

	Ground Floor	1st Floor
08:00 - 10:00	All T&T[2] windows tilted open	All T&T windows tilted open
10:00 - 20:00	All windows shut	All windows shut
20:00 - 22:00	All T&T windows tilted open	All T&T windows tilted open
22:00 - 08:00	All windows shut	All T&T windows tilted open [on v. hot nights]

Table 3: Typical user operation of windows

	Venetian blinds [south]		**Roller blinds** [east]		**Retractable awning** [west]	
	Ground Floor	**1st Floor**	**Ground Floor**	**1st Floor**	**Ground Floor**	**1st Floor**
08:00 - 20:00	Shut (slat angle 45º)	Shut (slat angle 45º)	Shut	Shut	*None*	In place
20:00 - 08:00	Open	Open	Open	Open	*None*	In place

Table 4: Typical user operation of external shading devices

4.2 Comfort models for overheating analysis

Summer comfort and overheating has been analysed through three comfort models, shown in Table 5.

Thermal comfort model	**Description**
PHPP overheating frequency (DIN 1946-2)	• Operative temperature > 25 ºC for < 10 % occupied hours • PHPP overheating frequency for use in buildings where no active cooling is specified, based on DIN 1946-2 [7]
Schnieders (based on ISO 7730)	• Operative temperature ≤ 26 ºC @ 60 % relative humidity • Relative humidity ≤ 70 % • Follows ISO 7730 for category B, where PMV ≤ + 0.5 (≤ 10 % PPD), operative temperature ≤ 26 ºC @ 60 % relative humidity, 1.2 Met and 0.6 Clo [7]
Adaptive comfort model (EN 15251)	• Occupants' comfort is adaptive, a function of the exponentially weighted running mean of the daily mean external air temperature [8]

Table 5: Comfort models used for overheating analysis

[2] T & T = tilt & turn windows

4.3 Period analysed

The period analysed is 6th June - 6th October. Occupants were on holiday from the 6th – 13th July and 8th – 12th August. The monitoring system was off-line from the 8th – 24th August due to technical problems.

5 Results and analysis

The results are presented according to each comfort model described above (the sensors used in the Larixhaus are air temperature sensors and do not measure radiant heat, therefore indoor air temperatures have been used in place of operative temperatures for the analyses).

The summary of results can be seen in Table 6. While maximum outdoor temperatures rose to 37.6 ºC, the maximum indoor air temperature was 26.2 ºC. Relative humidity remained between 35 % and 79 %, averaging 55 %.

	Min.	Ave.	Max.
Outdoor air temp. [ºC]	7.3 ºC	19.6 ºC	**37.6 ºC**
Indoor air temp. [ºC]	20.7 ºC	23.4 ºC	**26.2 ºC**
Indoor relative humidity [%]	35 %	55 %	79 %

Table 6: Minimum, maximum and average temperatures & relative humidity, occupied hours, 6th June – 6th October 2015

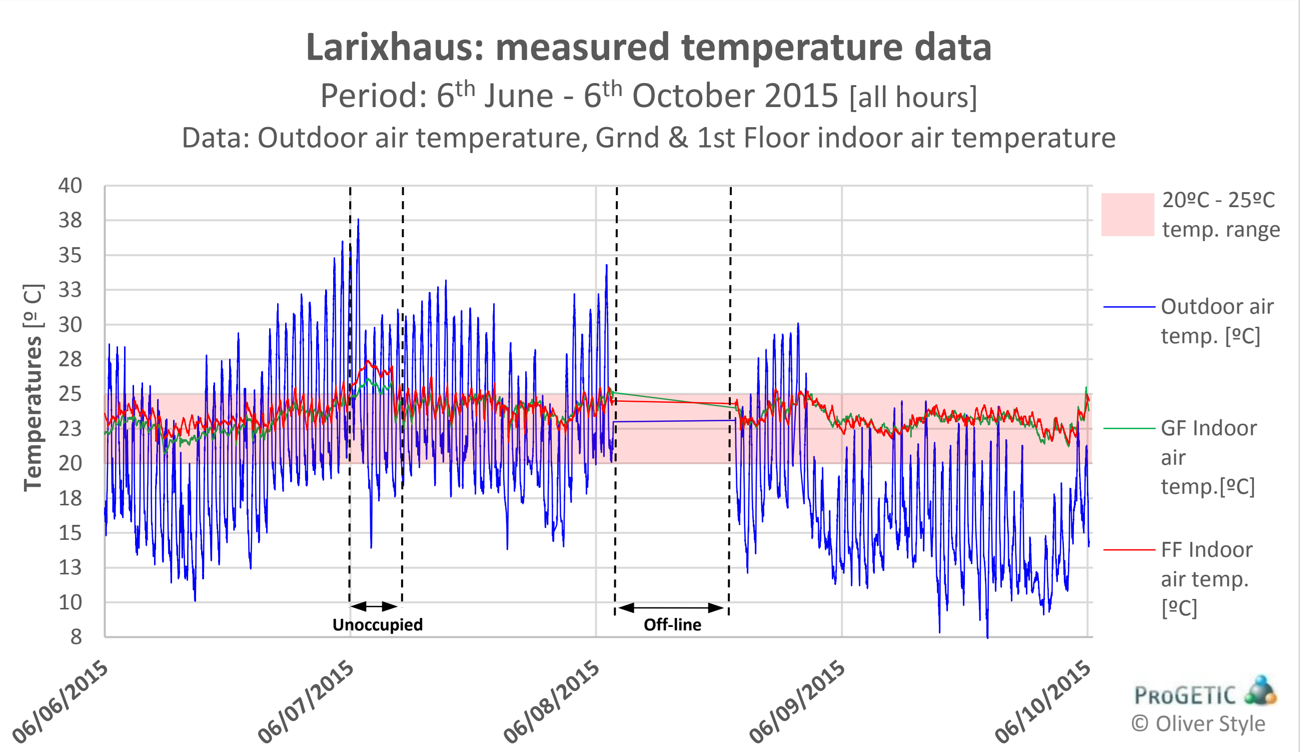

Figure 11: Outdoor and indoor air temperatures, all hours, 6th June – 6th October 2015

Figure 11 shows the outdoor and indoor air temperatures from 6th June – 6th October. It can be seen that indoor air temperatures only significantly exceeded 25 ºC when the building was unoccupied (6th – 13th July), coinciding with the peak outdoor temperature of 37.6 ºC. Otherwise, they remain largely within the 20 ºC to 25 ºC temperature band.

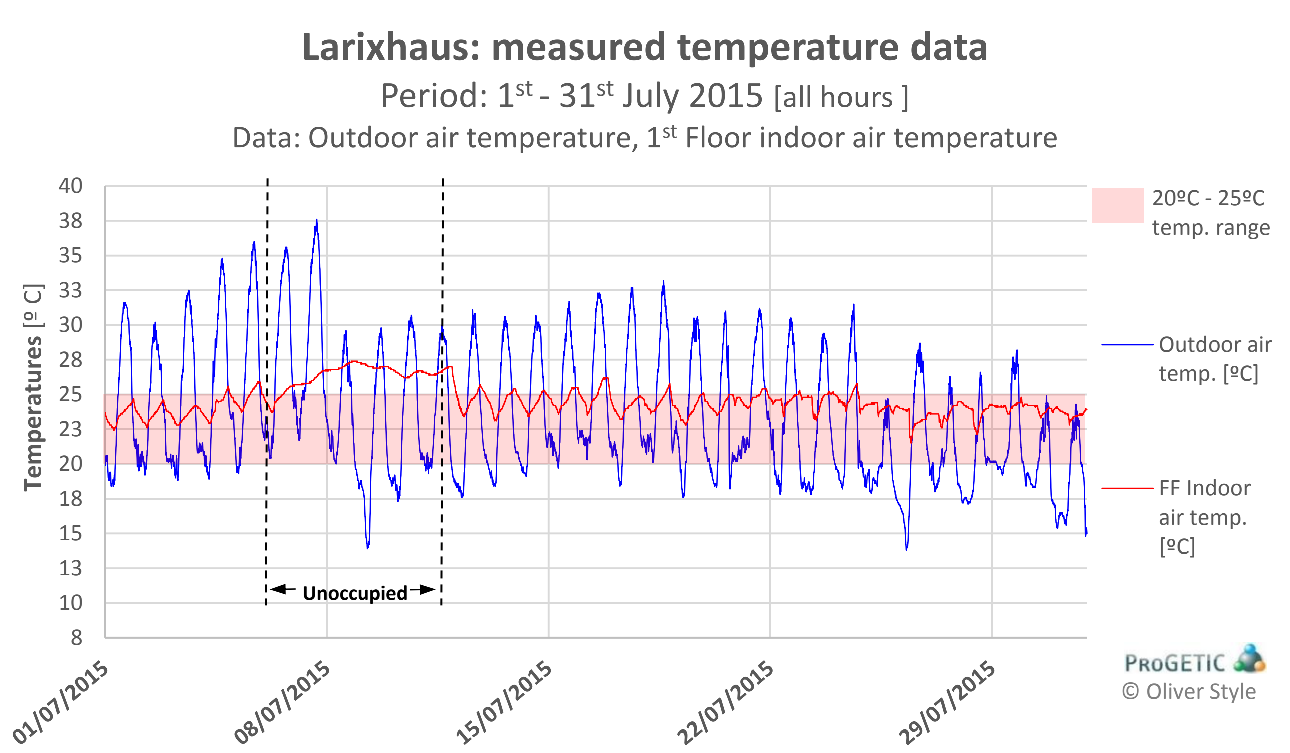

Figure 12: Outdoor & 1st floor air temperatures, all hours, 1st – 31 July, 2015

Figure 12 shows the 1st floor temperatures during the month of July. The importance of natural night ventilation can be seen during the unoccupied week of 6th – 13th June (at this time there were no internal occupancy gains and minimal solar and equipment gains): indoor temperatures rise to 27.4 ºC and oscillate between 26 ºC – 27 ºC until the occupants return and activate the natural night ventilation, keeping peak temperatures below 25 ºC most of the time.

5.1 PHPP overheating frequency model (DIN 1946-2)

The measured overheating frequency during occupied hours was 1.3 %, shown in Table 7. This compares with a predicted PHPP overheating frequency of 4.6 %.

Overheating limit [ºC]	25.49 ºC
Total nº data points	105120
Overheating nº data points	1339
Measured overheating frequency [%]	**1.3 %**
Predicted PHPP overheating frequency [%]	**4.6 %**

Table 7: Calculated overheating frequency vs. measured results, 6th June – 6th October 2015

5.2 Schnieders comfort model

The Schnieders comfort model results are shown in Figure 13 (for the 1st floor only, being the most susceptible to overheating). It can be seen that during occupied hours, temperatures remain within the inner comfort range; relative humidity moves into the extended comfort range for a small number of hours (> 70 %), but at all times remain below 80 %. Temperatures only move into the extended comfort range during unoccupied hours, due to the fact that the occupants are not around to open windows and activate natural night cooling.

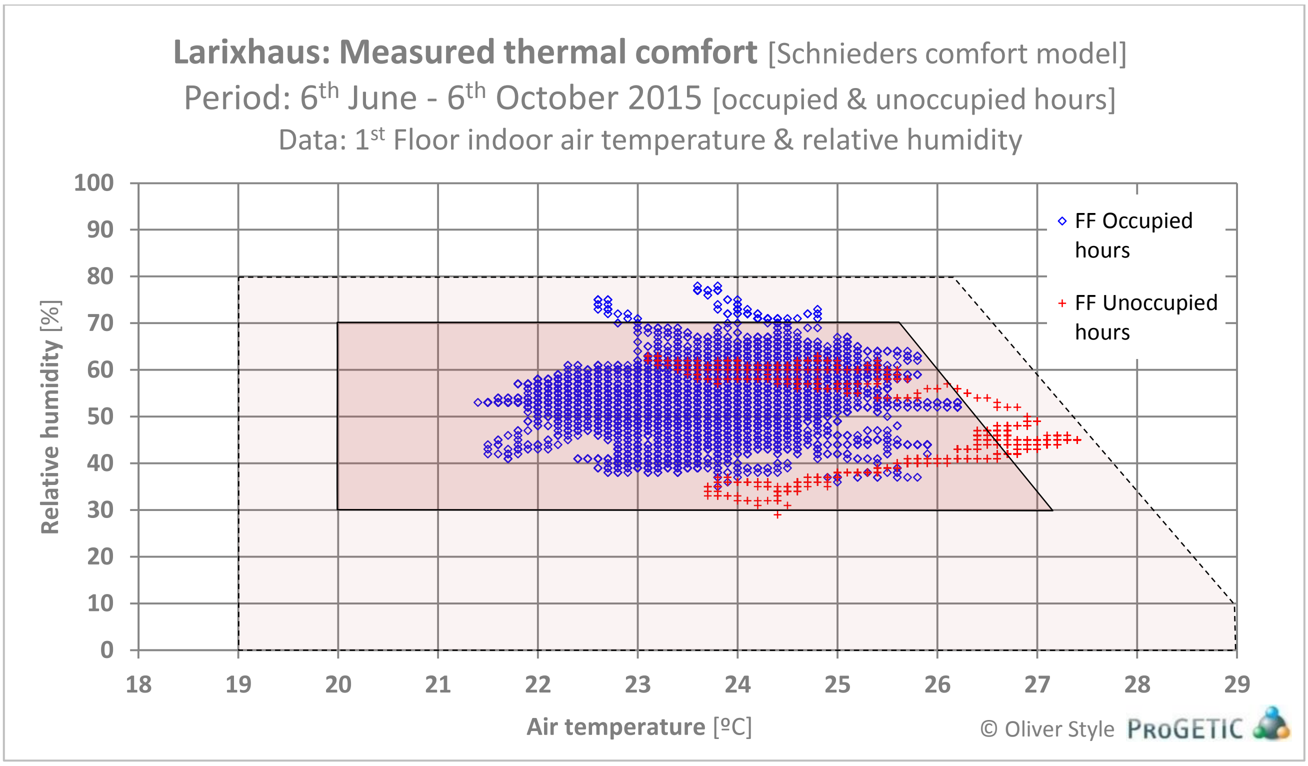

Figure 13: Indoor air temperature & relative humidity, 1st floor, Schnieders comfort model, 6th June - 6th October, 2015

5.3 Adaptive comfort model (EN 15251)

The adaptive comfort analysis was limited to the month of July only, with daily average indoor temperatures and corresponding running mean outdoor temperatures, shown in Figure 14. A constant of α = 0.8 was used for the calculation of the external running mean temperature [$\Theta_{rm} = (1-\alpha)\,\Theta_{ed-1} + \alpha.\,\Theta_{rm-1}$] following EN 15251. For almost every day in the month, indoor temperatures remain within Category II, very close to the lower limit (the Category II upper limit is calculated as: $\Theta_{i\,max} = 0{,}33\,\Theta_{rm} + 18{,}8 + 3$; lower limit: $\Theta_{i\,max} = 0{,}33\,\Theta_{rm} + 18{,}8 - 3$).

This implies that indoor temperatures could be significantly higher without causing discomfort, assuming occupants adapt to higher outdoor temperatures.

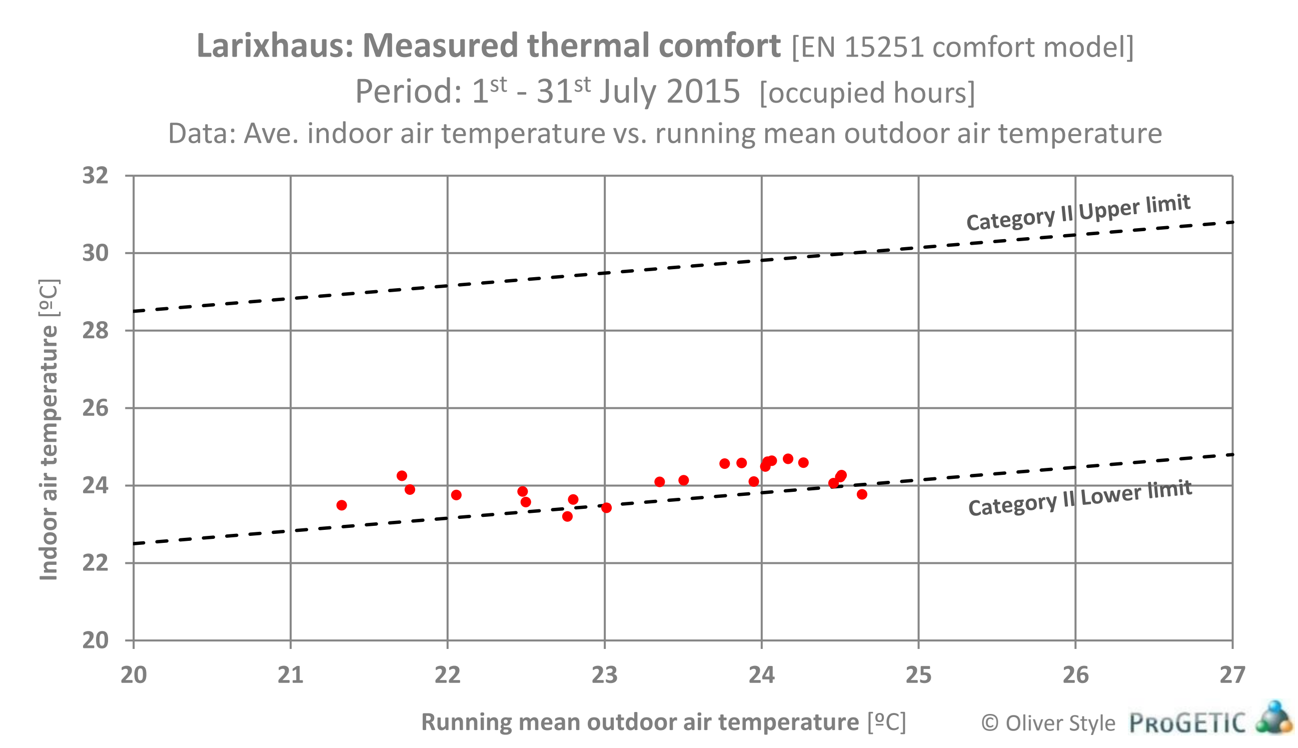

Figure 14: Indoor air temperature as a function of running mean outdoor temperature, Adaptive Comfort model, 1st – 31st July, 2015.

6 Conclusions

The results indicate no overheating and show impressive summer performance. This is in line with the qualitative feedback from occupants that they were comfortable at all times during the summer. The Larixhaus is clearly an isolated case study that must be situated within a broader analysis. However, the author offers the following conclusions:

- PHPP is an accurate tool for summer overheating analysis. The measured performance of the Larixhaus was significantly better than the predicted PHPP results. However, given the margin of uncertainty in the model and together with highly conscientious occupants, the predicted and measured results show reasonable agreement. The model appears to provide results on the safe side.

- Close attention to summer design strategies is important during the design phase to ensure overheating is adequately tackled. Equipment gains must be carefully dealt with, especially given the high level of thermal protection and extended time constants of Passivhaus buildings. In warm climates, mechanical plant is often best located outside the thermal envelope. DHW systems need careful design to make sure they do not generate excessive heat which then requires removal to maintain comfort.

- Bio-based insulation materials offer effective thermal protection in warm climates and are fully compatible with high-comfort, low-energy construction. The low embodied energy and of these materials can help reduce the environmental impact of a building and provide healthy and comfortable indoor conditions.

- In climates with high outdoor temperatures and humidity (especially where night time temperatures remain > 20 ºC), it is likely that passive cooling alone will not maintain comfort.
- For the climates similar to that of the Larixhaus, with adequate external shading devices, good natural night ventilation, and careful operation of the building by occupants, it would appear that lightweight, super-insulated, air-tight passive houses with no active cooling can provide a comfortable indoor climate during heatwaves.

7 References

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