

Long-term evaluation of residential summer thermal comfort: Measured vs. perceived thermal conditions in nZEB houses in Wallonia

Keywords: Summer thermal comfort; Overheating; nZEB houses; Measurements; Post-occupancy evaluations.

Abstract

In a context of global warming, summer thermal comfort is a key issue for the design and operation of nearly zero-energy buildings (nZEBs). Although there are various methods and benchmarks for the long-term evaluation of summer thermal conditions in free-running buildings, their application to the residential sector is still debated. Based on data from post-occupancy measurements and survey campaigns, this paper evaluates the compliance with commonly used overheating criteria defined by existing standards (CIBSE and Passive House Institute) of 23 nZEB houses in Wallonia (Belgium). The quantitative relationship between measured and perceived comfort is statistically analysed, and building characteristics leading to the most critical overheating situations are qualitatively discussed. The results show that summer thermal discomfort is frequent in nZEB houses in Wallonia, despite its temperate climate. In living rooms, the long-term appraisal of thermal conditions appears to be related to the frequency of extreme temperatures, while occupants' thermal perception in bedrooms seems to be more affected by smaller temperature deviations. These results imply a critical review of the capacity of the criteria commonly used for the evaluation of overheating risks in free-running residential buildings to predict the satisfaction of occupants with their summer thermal comfort. More generally, the findings reinforce the importance of a better integration, even in temperate climates, of environmental controls – and their required operation by the occupants – to properly mitigate overheating risks in nZEB houses.

Highlights

- Existing overheating criteria and benchmarks are compared with comfort perception
- Summer thermal discomfort is common in Walloon nZEB houses, especially in bedrooms
- In living areas, summer perception is more influenced by extreme temperature episodes
- In bedrooms, summer thermal comfort is driven by smaller temperatures deviations
- Better understanding of how environmental controls are operated by the occupants is needed

1. INTRODUCTION

Summer thermal comfort in buildings is today an emerging challenge also in countries characterised by temperate climates. Climate change, in fact, leads to warmer summers and more frequent heat waves [6], these having an increasingly more critical impact particularly in consideration of the higher sensitivity [7] of an ageing population [8]. Conversely, the evolution of building construction techniques (e.g., with higher insulation, airtightness and enhancement of solar gains) driven by the evolution of energy performance standards [9-11] can also severely impinge on the summer thermal behaviour of buildings [12, 13].

While in temperate countries such as the UK, the study of summer thermal indoor conditions in new buildings has acquired a consistent tradition [14-18], in Belgium – which shares a similar climate to the UK – and more particularly in Wallonia, this domain of research is at its infancy. the *MEASURE* project [19], which conducted POE surveys in 149 Walloon residential high energy efficient single-family houses, recently revealed a high frequency of complaints related to overheating discomfort. Among other results, 73% of occupants (n= 149) reported states of discomfort, mainly in living rooms and bedrooms [20].

In this context, the criteria for the assessment of summer thermal comfort in buildings that are not mechanically conditioned are particularly crucial. When used at the design stage for the analysis of dynamic thermal simulation results, they can provide guidelines for the optimization of strategies to mitigate overheating risks [21]. Conversely, when used for the analysis of monitoring data, they can offer benchmarks for the verification and comparison of indoor conditions [14]. The criteria recommended by CIBSE (Chartered Institution of Building Services Engineers) [22] and PHI (Passive House Institute) [23] are among the most commonly used for the study of summer thermal comfort in free-running residential buildings in temperate climates [15, 16]. Nevertheless, their capacity to predict the satisfaction of occupants with their summer thermal comfort [24], the applicability of adaptive principles in residential buildings (especially in bedrooms [4]), the limits of this adaptivity [5] and the consequences of the criteria formulation [1] are still debated.

Building on the granular data, directly collected in 23 surveyed single-family houses, analysed through common overheating criteria, this paper aims to offer an overview of measured and perceived summer thermal conditions encountered in nZEB houses in Wallonia and, on such bases, provide a critical evaluation of the capacity of current criteria to predict the satisfaction of occupants with their summer thermal comfort.

2. METHOD

As part of the POE (Post-Occupancy Evaluation) campaigns launched by the *MEASURE* project, 23 nZEB houses in Wallonia (Belgium) were continually monitored during an entire year (2016). Air temperatures were recorded every 10 minutes in the living rooms and in the main bedrooms of each house, resulting in approximately 52,560 data points for each room. The results of the monitoring are first analysed in the light of commonly used criteria for the long-term evaluation of overheating risks in free-running residential buildings. The fulfilment of these criteria is then compared to the general appraisal of summer indoor thermal conditions as perceived by the occupants, obtained by mean of questionnaire-based interviews. The

overheating situations encountered are finally discussed qualitatively based on buildings characteristics.

The study was submitted for approval to the Belgian Data Protection Authority. In this context, an informed consent form was obtained from all participants. Building characteristics and methods for data collection are illustrated in detail in the following paragraphs.

2.1. Buildings characteristics

The majority of the dwellings included in this study were detached single-family houses (20 out of 23 cases). In Belgium, single-family houses represent the 79.7% of the housing stock [25], of which 30% are detached houses [26]. The houses were all situated in the Cfb climatic zone (temperate oceanic climate) of Wallonia (southern part of Belgium, corresponding to a latitude of around 50° North) according to the Köppen-Geiger climate classification system [27]. They were all located in rural to semi-rural environments on relatively unobstructed sites, with little or no surrounding environmental shading.

Requirements for nZEB houses in Wallonia rely on the definition provided in the European Directive 2010/31/EU on the energy performance of buildings [9], and primarily focus on reducing heating requirements. The volumetric and thermal characteristics of the envelope of the buildings analysed are described in Table 1. Heating floor areas, mean U-values, air tightness, yearly heating needs, and SHGC (Solar Heat Gain Coefficient) of windows were taken from the requirements for Belgian EPBD (Energy Performance of Buildings Directive) calculation [28] (further buildings' characteristics can be found in [29]).

These houses had been occupied for a minimum of 3 years before the beginning of the present study. This selection criterion was established in order to avoid the potential bias that can appear during the first years of occupation of a building [30]. Dwellings were mostly occupied by families with children. The number of children is presented in Table 1 based on their age category. Houses 4 and 17 were occupied by recently-retired couples. All houses were owner-occupied.

The size of the sample was defined by the practical need to offer an in-depth and accurate knowledge of the technical characteristics of the buildings and of the specific requirements of occupants influencing their summer thermal behaviour. The relatively limited number of nZEB houses included in the analysis, in fact, allowed direct on-site measurements and verifications of key buildings' characteristics (e.g. orientation, house and construction type, solar shading, location of the bedroom, airtightness of the thermal envelope, ventilation rates, etc.) as well as focused discussions with the occupants about, among other aspects, their habits and behaviours (e.g., presence during the day, windows opening). The data gathered are reported in Table 1.

All houses were equipped with a heating system (of variable type) and were mechanically ventilated (with a summer bypass in the presence of a heat recovery system). None of the ventilation systems was found to be sized to allow effective purge ventilation in summer (that is, maximum air change per hour less than 1 per hour).

Internal sources of heat gains have not been detailed but no extreme case was encountered (e.g., high internal gains due to specific appliances or large indoor hot water storage). Also, no mechanical cooling system or fixed ceiling fan was detected in any of the houses.

118 2.2. *Measurements*

119 Following recommendations from the literature [15], air temperature sensors were placed by
120 the research team on top of existing furniture at a minimal height of 80cm, away from windows
121 (to avoid direct solar radiation) and from any other internal heat sources. Data were recorded
122 using a dedicated wireless/4G router. The Belgian Building Research Institute (BBRI)
123 conducted preliminary calibration tests of the measuring devices before the measurement
124 campaign and verified compliance with the maximum errors declared by the manufacturer.
125 These tests confirmed a maximum error of $\pm 0.3^{\circ}\text{C}$ after calibration.

126 Real room occupancy was found to considerably vary across days and houses. As a
127 consequence, similar to many other studies [15, 31, 32], based on the discussions with the
128 households and due to the absence of continuous high resolution spatio-temporal models of
129 occupants' localisations, realistic occupancy assumptions had to be made. A general occupancy
130 between 7am and 10pm in the living rooms, and between 10pm and 7am in the bedrooms, was
131 thus assumed for the 7 cases that were occupied during working hours. Conversely, for the 16
132 houses that were not occupied during the day, occupancy of the living rooms was limited to
133 7am-9am and 5pm-10pm on business days. The implications of these assumptions might
134 depend on the type (e.g., percentage based, maximum temperature, daily weighted exceedance)
135 and the evaluation period for each criterion (year/summer) and they cannot be easily quantified
136 with certainty. It would be interesting to conduct sensitivity analyses on real cases to weigh
137 these implications, but these are beyond the scope of this study.

138 Known periods of prolonged absence (e.g., vacations) were removed from the data in order to
139 limit the bias that could be induced by periods of uncontrolled and non-evaluated thermal
140 conditions (see section 2.4).

Table 1. Main characteristics of the buildings analysed

ID	House type*	Construction Type*	Number of occupants**	Presence during working hours**	Heated floor area**	Window-to-floor surface ratio***	Mean U-value (windows included)*	Air change rate at 50 Pa (n ₅₀)*	Main window SHGC*	Heating needs*	Living room			Bedroom			
											Main windows orientation*	Solar shading Type*	Windows opening **	Main windows orientation*	Under roof location*	Solar shading type*	Windows opening **
	[-]	[-]	[-]	[-]	[-]	[%]	[W/m².K]	[1/h]	[-]	[kWh/m².y]	[-]	[-]	[-]	[-]	[-]	[-]	[-]
1	Attached	Masonry	5	No	330.0	15.2	0.24	1.25	0.51	14.8	O	In	Day and Night	W	No	No	Day and Night
2	Semi-attached	Masonry	4	Yes	119.7	13.2	0.15	0.82	0.54	8.8	S	In	Never	S	No	In	Day and Night
3	Semi-attached	Masonry	3	No	151.7	19.0	0.15	0.68	0.54	5.0	S	In	Never	S	No	No	Day
4	Detached	Masonry	2	Yes	275.3	12.1	0.35	3.50	0.63	29.4	NE	Out	Day and Night	SW	No	In	Day
5	Detached	Masonry	3	No	364.7	16.3	0.32	6.03	0.62	18.6	S	Out	Never	E	No	In	Never
6	Detached	Wooden Frame	5	Yes	212.6	22.6	0.43	5.24	0.64	26.9	SE	In	Day and Night	SW	No	No	Day and Night
7	Detached	Masonry	4	No	201.1	24.0	0.19	0.74	0.5	7.6	SO	No	Day and Night	SW	Yes	No	Day
8	Detached	Wooden Frame	3	No	186.5	26.0	0.25	1.77	0.49	14.3	SO	Out	Never	SW	Yes	In	Never
9	Detached	Masonry	4	No	156.6	20.9	0.28	0.70	0.45	14.0	SE	No	Never	SW	Yes	No	Day
10	Detached	Masonry	2	Yes	149.8	19.1	0.43	2.91	0.63	31.0	SE	In	Day and Night	W	Yes	No	Day and Night
11	Detached	Masonry	4	No	198.4	19.9	0.32	1.40	0.63	16.7	O	No	Never	W	No	Out	Day
12	Detached	Masonry	4	No	196.4	15.0	0.47	4.21	0.65	29.5	E	No	Day and Night	SW	Yes	No	Day and Night
13	Detached	Masonry	6	No	216.8	27.0	0.15	0.54	0.51	3.6	SO	Out	Day and Night	SW	No	Out	Day and Night
14	Detached	Wooden Frame	4	No	194.2	28.0	0.42	2.18	0.56	26.0	NE	Out	Day and Night	NE	No	No	Never
15	Detached	Masonry	2	No	160.7	18.0	0.37	2.32	0.63	19.8	NO	In	Day and Night	NW	Yes	In	Day and Night
16	Detached	Masonry	5	Yes	233.8	19.9	0.31	1.01	0.63	17.8	E	In	Never	E	No	In	Never
17	Detached	Wooden Frame	2(>65 y/o)	Yes	203.0	18.7	0.35	3.80	0.65	20.3	S	In	Day and Night	W	Yes	In	Day and Night
18	Detached	Masonry	5	No	239.5	14.3	0.39	7.88	0.63	30.1	S	In	Never	SW	Yes	In	Never
19	Detached	Masonry	4	No	265.3	18.2	0.16	0.82	0.52	6.1	E	In	Never	E	No	No	Day and Night
20	Detached	Masonry	1	No	190.6	31.7	0.40	2.24	0.5	19.4	N	No	Never	NW	Yes	In	Day
21	Detached	Masonry	3	Yes	467.8	13.3	0.35	4.76	0.6	20.8	SO	In	Day	W	No	In	Day
22	Detached	Wooden Frame	4	No	160.0	15.6	0.28	2.34	0.65	14.5	S	In	Never	S	No	No	Never
23	Detached	Wooden Frame	4	No	186.59	24.7	0.40	3.69	0.63	23.8	SO	In	Day	NW	Yes	Out	Day

Source of data: * On-site verification/measurements ; ** Questionnaire-based interviews; *** Belgian EPBD calculation

Outdoor temperatures were monitored for each dwelling to calculate a local running mean temperature θ_{rm} . This calculation was done according to the EN15251 standard [33] using the following equation based on the daily mean external temperature θ_{ed-i} of the previous days (31 previous days were used with a constant α of 0.8):

$$\theta_{rm} = (1 - \alpha) \cdot (\theta_{ed-1} + \alpha \cdot \theta_{ed-2} + \alpha^2 \cdot \theta_{ed-3} + \dots) \quad (1)$$

As reported by the Royal Meteorological Institute of Belgium [34], the weather data over the measurement period (calendar year 2016) can be considered broadly in line with the average of the last 30 years, both in terms of temperatures and solar radiation. The average temperatures of most months of the year, particularly during the meteorological summer period, is generally consistent with seasonal norms, although a remarkably hot month of September was recorded (Figure 1). Over the year, 97 days exceeded 20°C, 25 days recorded maximum temperatures higher than 25°C, and 6 days exceeded 30°C.

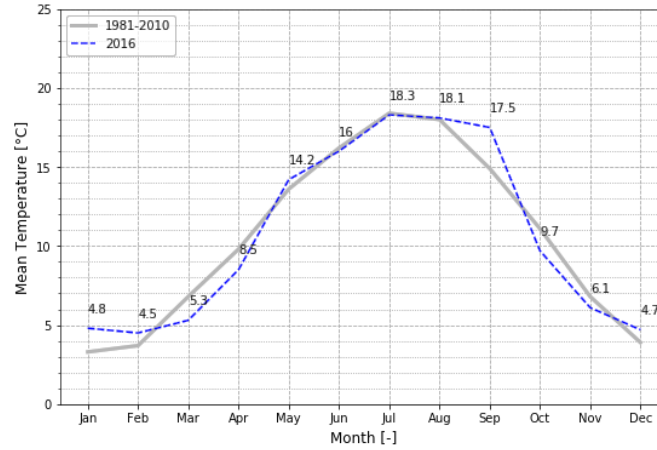


Figure 1. Comparison of monthly mean temperatures of 2016 with the climate normal (1981-2010).

2.3. Criteria for overheating assessment

Two groups of long-term summer comfort qualification criteria exist according to the type of threshold not to be exceeded: *static* (based on a fixed temperature) and *adaptive* criteria. The latter are based on a comfort temperature evolving in function of the history of outdoor temperatures in accordance with the theory of adaptive comfort [35]. Various limits, accepted frequencies, and periods of calculation can be found in the literature (see for example the work of [1]), discussing the different overheating criteria and the strengths or weaknesses of their formulation (discontinuity, etc.).

Among the criteria based on a static temperature limit, the Belgian Passive House Platform (PHP) recommends not to exceed 5% of the time of occupancy above 25°C [36], while the Passive House Institute (PHI) brings this threshold to 10% of occupancy time [37]. The Chartered Institution of Building Services Engineers (CIBSE) in UK, in the previous version of its environmental Guide A [38], suggested the use of maximum 1% of the time above 28°C for living rooms and 26°C in bedrooms. These criteria, which needed to be evaluated over the

period of a year, were mainly conceived to inform the design phase of a building. It should also be noticed that the assessment of the Passive House criteria is based on a single thermal zone modelling of the building using the Passive House Planning Package (PHPP) [39]. Nevertheless, these criteria are also often used for the analysis of measured temperatures, since they are simple to apply and allow easy comparisons between different cases and studies [13-15, 18, 31, 32]. These criteria rely on a static characterisation of thermal comfort based on thermal neutrality [40]. The accuracy of such model in real buildings is, however, largely questioned [41].

It has for long been recognized in the scientific literature that the adaptive capacity of occupants (afforded by physiological, psychological and behavioural factors) can allow a wider thermal tolerance in free running buildings [42]. In this case, comfort temperature can be defined in function of a running mean temperature, which is linked to the evolution of daily outdoor temperatures. The adaptive thermal comfort model is embedded in standards such as the EN15251 in Europe [35]. This standard [33] defines different comfort categories corresponding to a percentage of dissatisfied people as a function of the difference between operative and comfort temperatures. This allows calculating the time of occupancy spent in each comfort category at design stage by simulation or by the analysis of data collected in existing buildings.

Although defined primarily for office buildings, adaptive capacities – for example, linked to the possibility of opening windows or adjusting solar protection devices – also exist in other building types where the adaptive thermal comfort approach can be applied [22, 43]. Despite some limiting factors depending on the surrounding environment (e.g., presence of noise, safety, pollution, etc.) or to the mobility of the occupants, studies have postulated that single-family dwellings might effectively entail more adaptive opportunities than offices [5, 44].

In the most recent 8th edition of environmental Guide A [45], CIBSE introduced the use of the adaptive comfort categories defined by EN15251 for the quantification of the risk of overheating. This document refers to the Technical Memoranda TM52 [22] presenting three criteria founded upon *hours of exceedance* (T_{max+1}), a *daily weighted exceedance* (W_e), and an *upper limit temperature* (T_{upp}). These criteria are based on the frequency, duration, and intensity of the deviations from the EN15251 comfort categories and, more generally, take consideration of the upper limit of the comfort Category II, which is recommended for new buildings and major refurbishments in absence of very sensitive and fragile persons [46]. In residential buildings, as specified in its Technical Memoranda TM59 [47], CIBSE only imposes compliance with the first criterion, *hours of exceedance*, for living rooms, kitchens and bedrooms, although at least two criteria must be met for other types of buildings [22].

Some authors have argued, however, that the adaptive capacity is limited during the night [4] and that the quality of sleep decreases at temperatures above 24 degrees Celsius [48]. For this reason, CIBSE adds for bedroom a criterion based on an absolute threshold of 26°C [38, 47]. The general CIBSE approach is widely used for overheating analysis both in cases of monitoring studies and simulations [16, 49-53].

In our study, static and adaptive *hours of exceedance*, as well as the number of *daily weighted exceedance* and *upper limit temperature* criteria, have been analysed for both living rooms and bedrooms. Table 2 presents a summary of the discussed criteria and clarifies their application.

These criteria are generally based on the evaluation of the operative temperature (T_{op}), which can be seen as the manifestation of the combined effect of mean radiant temperature and air

temperature in a space [45]. As in many other studies [15-18, 31, 32, 51, 54], since only air temperatures could be consistently measured in our POE campaign, these data were used for comparison with the different thresholds described in Table 2.

Table 2. Common overheating criteria for non-air-conditioned residential buildings

Type	Thresholds	Overheating criterion	Source
Hours of exceedance	25°C	10% of annual occupied hours over temperature of 25 °C	PHI
		5% of annual occupied hours over temperature of 25 °C	PHP
Hours of exceedance	28°C living areas	1% of annual occupied hours over operative temperature of 28 °C (living areas)	Guide A, CIBSE 2006
	26°C bedrooms	1% of annual occupied hours over operative temperature of 26°C (bedrooms)	TM59, CIBSE 2017 (bedrooms only)
Hours of exceedance	$(T_{op} - T_{max})^* > 1K$	3% of occupied hours during the non-heating period (May to September included) when T_{op} exceeds EN15251 Cat. II upper limit by 1K**	TM52, CIBSE 2013
	$T_{op} - (EN15251 \text{ Cat. II upp. limit}^*) > 1K$		Guide A, CIBSE 2015
Daily weighted exceedance	$T_{op} - (0.33 T_{im} + 21.8^\circ C) > 1K$	Max 6 in any one day during occupied hours ***	TM59, CIBSE 2017
	$We = \sum (he) \times WF$ with $WF = \min(0; T_{op} - T_{max})$ and he : corresponding time [h]		TM52, CIBSE 2013
Upper limit temperature	$T_{upp} = T_{max} + 4K$	Absolute maximum value during occupied hours ***	TM52, CIBSE 2013

* rounded to the nearest unit

** For spaces that are occupied by very sensitive and fragile persons upper limit of Category I is recommended.

*** May fail to be met in dwellings (TM59, CIBSE 2017).

Although this might represent a limitation, it was assumed, similar to other studies [32, 51] that in highly insulated nZEB houses the temperature of the walls can be very close to the air temperature, even if some local discomfort caused by radiative exchanges (due, for example, to high solar exposition of glazing) could also influence instantaneous thermal sensation. Air velocity was also not recorded and, therefore, it was not considered in the analysis, although this is also a parameter that could affect the reported thermal sensation. Other important factors that could influence thermal perception, such as activities and clothing levels, were discussed with the occupants and were found to be in accordance with the conditions for application of the overheating criteria (that is, sedentary activities and possibility to freely adapt the clothing to the thermal environment) [33]. Results of the applications of these criteria are presented in Table 3. Appraisal of indoor thermal conditions and fulfilment of overheating criteria in the living rooms (7am-10pm or 7am-9am and 5pm-10pm on business days). and

2.4. Questionnaire-based semi-structured interviews

Face-to-face semi-structured interviews were conducted on the basis of a questionnaire that had been previously sent to all the occupants. All interviews were conducted by the same researcher who personally reported the results directly on-site. The questionnaire, focusing on the general perception of indoor environmental quality, was conceived to capture both the satisfaction of the occupants and the main parameters that could influence their evaluations (e.g., socio-economic profiles, habits, etc.). It was developed in French in the context of a Post Occupancy Evaluation (POE) project funded by the Walloon region in Belgium [19].

At the end of the summer period, and without knowing the results of the measurement campaign, occupants were requested to provide a general evaluation of the indoor thermal conditions they had experienced. This intended to offer a retrospective appraisal of the thermal conditions over the entire summer season, and not an instantaneous thermal sensation vote, as it is commonly captured using the ASHRAE thermal sensation scale [55]. A single concerted vote per household, representing the perception of the whole family, for each room was requested in response to the question: *How do you evaluate thermal comfort during last summer in the living room and in the main bedroom?* The evaluation was reported on a 5-point scale, presented in Figure 2, which was designed on the basis of the Bedford comfort scale [56]. The implementation of this scale was decided following preliminary focus group tests with building occupants. Compared to the original Bedford scale, the “comfortably warm” and “comfortably cool” votes were grouped within a single “comfortable” vote, for this to be more easily understood by the respondents and to allow focusing specifically on their (eventual) reported degrees of discomfort. The main implication of using this scale consisted in the need to adopt statistical tests suitable for the analysis of ordinal data (see **Error! Reference source not found.**).

Too cold	Slightly too cold	Comfortable	Slightly too hot	Too hot
☐	☐	☐	☐	☐

Figure 2. Scale used for indoor thermal conditions appraisal (administered in its French translation).

Since people seldom report the same thermal experience, and that inter (and intra)- individual differences of perception would require a much larger sample to be quantified, these methodological choices (single family vote reported on a scale with a limited number of points) were made to limit the influence of extreme individual evaluations. The votes obtained (n=23) are reported in the first column of Table 3. Appraisal of indoor thermal conditions and fulfilment of overheating criteria in the living rooms (7am-10pm or 7am-9am and 5pm-10pm on business days). and **Error! Reference source not found.**, respectively for living rooms and bedrooms. Habits and behavioural actions taken by the occupants that can influence thermal conditions were also discussed during the questionnaire-based interviews. In this context, the presence of solar shading was verified in each room, while presence during the day and general adaptive responses were recorded (*“Do you open windows to cool down the living room/bedroom? If yes, when? (day and/or night)”*). This information is reported in Table 1.

2.5. Statistical analysis

Statistical tests were applied to analyse the relations between the data gathered. As the data resulting from the application of overheating criteria to the measurements had distributions that were significantly different from normal (p -value of Kolmogorov-Smirnov test < 0.001 [57]), non-parametric statistical tests were used, based on ranked values. Due to the limited size of the sample, and therefore the risk that an effect could not be detected when it actually exists (Type II error), the analysis of data calculated for each test both the statistical significance (p -value at the alpha level of 0.05) and the effect size of the differences detected. Without being subjected to some of the limitations of null hypothesis significance testing (NHST), the effect size offers a standardised method to estimate the magnitude and the substantive relevance of the differences or deviations between groups of data [58].

The relationships between the frequency of temperature deviations in bedrooms and in living rooms were analysed using the Spearman Rho test [59]. The test calculates the correlation between two quantitative data and the probability that the same correlation can occur between the two if the relation does not exist in the population. In this case, the Rho value of the test was used for an estimation of the effect size of the influence detected.

The relationships between occupants' thermal appraisal and compliance of the building with the overheating criteria were analysed through the Jonckheere-Terpstra test [60, 61]. This test evaluates the probability that the (ascending or descending) trend of the median values of the overheating criteria through the ordinal groups of thermal conditions appraisal (vote of the occupant on the Likert scale mentioned in section **Error! Reference source not found.**) could have occurred by chance. Inferences from the data were based on statistical and practical significance of the influences detected, and were made based on the estimation of the Pearson's r effects size [62].

For both the Spearman Rho and the Pearson's r effect sizes, the benchmarks proposed by Cohen [63] were used in this study: ≥ 0.1 = small effect, ≥ 0.3 = medium effect; ≥ 0.5 = large effect.

3. RESULTS AND DISCUSSION

3.1. Fulfilment of overheating criteria

The following tables show, respectively, for the living rooms (Table 3) and the bedrooms (Table 4), the results concerning the fulfilment of the criteria presented in Table 2 for the 23 houses. The time exceeding comfort Category II of the EN15251 is also presented.

It is worth noting a relatively high base temperature in these buildings: mean of 8.9% (median, mdn: 6.4% ; standard deviation, sd: 8.1%) of the time of occupancy above 25°C in the living room and a mean of 8% of occupancy time (mdn: 6.4% ; sd: 7.5%) in bedrooms. The criteria based on static lower temperatures appear, therefore, more demanding to achieve. Eighteen (18) cases do not meet the criterion of less than 5% of time of occupancy above 25°C for at least one room (8 cases, if we consider 10% of the time of occupancy as set by the PHI). This criterion is not met in 14 living rooms (6, if we consider 10% of time of occupancy) and 14 bedrooms (5, if we consider 10% of time of occupancy). Three (3) cases (IDs 6, 7 and 23) present a percentage of the time of occupancy above 28°C exceeding 1% in the living room. In terms of

bedrooms, 18 cases do not meet the criterion of 1% of occupancy time above 26°C. If excluding building ID 12, these cases do not meet the criterion of 5% of occupancy time above 25°C for at least one room.

In comparison, only four cases do not fulfil at least one of the CIBSE TM52 adaptive criteria for the living room (cases ID 1, 7 and 23 regarding *hours of exceedance $T_{max}+1$* , *daily weighted exceedance (We)* and *upper limit temperature (T_{upp})* and case ID 22 regarding We). In the bedrooms, 4 cases do not fulfil at least one of the CIBSE adaptive criteria ($T_{max}+1$ is not met for cases IDs 3, 7 and 23; We for cases IDs 3, 7, 18 and 23; and T_{upp} is never reached).

Case ID 3 is particular in the sense that, although having a very high percentage of time above 25°C in the living room (24.4%), it fulfils the CIBSE TM52 criteria for this room. In the bedroom, on the contrary, this is the case with the highest daily weighted exceedance We and proportion of time above 26°C.

Only 5 buildings (IDs 2, 4, 5, 16 and 17) finally meet all the criteria suggested by CIBSE, mainly because the temperatures in the bedroom exceed 26°C for more than 1% of time of occupancy.

These results confirm a tendency documented in the recent literature [18, 52], which suggests that nZEB houses in temperate climates might be particularly at risks when dealing with overheating

Table 3. Appraisal of indoor thermal conditions and fulfilment of overheating criteria in the living rooms (7am-10pm or 7am-9am and 5pm-10pm on business days).

ID	Occupants' thermal appraisal	PHI % of time > 25°C Period: year [%]	CIBSE 2006 % of time > 28°C Period: year [%]	EN15251 % of time > Cat. II Period: May to September [%]	% of time > Cat. III (>T _{max} +1K) Period: May to September [%]	CIBSE TM52 2013 Number of daily weighted exceedance We Period: May to September [-]	Number of Tupp exceedance Period: May to September [-]
8	Comfortable	6.3	0.0	0.2	0.0	0	0
13	Comfortable	7.8	0.4	0.8	0.0	0	0
14	Comfortable	8.7	0.4	1.1	0.1	0	0
15	Comfortable	15.3	0.2	1.4	0.1	0	0
16	Comfortable	0.9	0.0	0.0	0.0	0	0
20	Comfortable	6.6	0.5	0.8	0.0	0	0
22	Comfortable	3.6	0.4	0.9	0.3	1	0
1	Slightly too hot	5.0	0.3	2.2	1.1	2	1
2	Slightly too hot	3.4	0.0	0.0	0.0	0	0
3	Slightly too hot	24.4	0.0	0.5	0.0	0	0
4	Slightly too hot	3.6	0.8	0.8	0.1	0	0
5	Slightly too hot	12.0	0.5	0.1	0.0	0	0
10	Slightly too hot	3.9	0.0	0.0	0.0	0	0
11	Slightly too hot	6.0	0.1	0.1	0.0	0	0
12	Slightly too hot	4.2	0.4	0.1	0.0	0	0
17	Slightly too hot	1.5	0.0	0.2	0.0	0	0
18	Slightly too hot	3.8	0.8	1.0	0.1	0	0
19	Slightly too hot	4.3	0.0	0.0	0.0	0	0
21	Slightly too hot	11.1	0.3	0.2	0.0	0	0
6	Too hot	8.1	1.0	2.3	0.5	0	0
7	Too hot	33.9	6.0	15.7	7.7	20	5
23	Too hot	22.3	7.2	20.9	14.4	40	68
	<i>Mean</i>	8.9	0.9	2.1	1.1	2.7	3.2
	<i>Mdn</i>	6.4	0.4	0.4	0.0	0.0	0.0
	<i>Sd</i>	8.1	1.8	5.2	3.3	9.1	14.2
	<i>Min</i>	0.9	0.0	0.0	0.0	0	0
	<i>Max</i>	33.9	7.2	20.9	14.4	40	68
<i>Jonckheere–Terpstra test:</i>							
	<i>p-value</i>	n.s.	n.s.	n.s.	n.s.	n.s.	<0.05*
	Pearson's r effect size	0.23	0.39	0.08	0.24	0.28	0.45

*** $p \leq 0.001$, ** $p \leq 0.01$, * $p \leq 0.05$, n.s. = not significant ($p \geq 0.05$); $r < 0.10$ = negligible; $0.10 \leq r < 0.30$ = small; $0.30 \leq r < 0.50$ = moderate; $r \geq 0.50$ = large

Data reported in bold italic correspond to failed criteria

Table 4. Appraisal of indoor thermal conditions and fulfilment of overheating criteria in the main bedrooms (10pm-7am).

ID	Occupants' thermal appraisal	PHI	CIBSE 2006, 2017	EN15251		CIBSE TM52 2013	
		% of time > 25°C	% of time > 26°C	% of time > Cat. II	% of time > Cat. III (>T _{max} +1K)	Number of daily weighted exceedance We	Number of Tupp exceedance
		Period: year	Period: year	Period: May to September	Period: May to September	Period: May to September	Period: May to September
[-]	[-]	[%]	[%]	[%]	[%]	[-]	[-]
5	Comfortable	2.2	0.0	0.1	0.0	0	0
15	Comfortable	9.0	3.1	0.8	0.1	0	0
1	Slightly too hot	1.7	1.1	0.0	0.0	0	0
2	Slightly too hot	0.7	0.0	0.0	0.0	0	0
4	Slightly too hot	2.4	0.8	0.0	0.0	0	0
8	Slightly too hot	10.3	5.2	1.2	0.3	0	0
11	Slightly too hot	6.4	2.3	0.0	0.0	0	0
12	Slightly too hot	4.4	2.5	0.0	0.0	0	0
14	Slightly too hot	5.4	2.6	0.0	0.0	0	0
16	Slightly too hot	1.6	0.5	0.0	0.0	0	0
17	Slightly too hot	2.0	0.6	0.3	0.0	0	0
19	Slightly too hot	8.7	1.6	0.0	0.0	0	0
21	Slightly too hot	4.5	1.9	0.0	0.0	0	0
22	Slightly too hot	12.2	4.1	0.3	0.0	0	0
23	Slightly too hot	18.5	12.1	7.6	1.2	4	0
3	Too hot	31.7	20.5	17.5	1.5	7	0
6	Too hot	6.4	2.7	0.1	0.0	0	0
7	Too hot	23.1	15.0	7.3	2.9	6	0
9	Too hot	7.8	4.4	1.3	0.3	0	0
10	Too hot	5.2	2.3	0.0	0.0	0	0
13	Too hot	7.1	3.0	0.7	0.0	0	0
18	Too hot	9.1	5.1	2.9	0.1	1	0
20	Too hot	3.9	1.1	0.1	0.0	0	0
<i>Mean</i>		8.0	4.0	1.7	0.3	0.8	0
<i>Mdn</i>		6.4	2.6	0.1	0.0	0.0	0.0
<i>Sd</i>		7.5	5.1	4.0	0.7	2.0	0
<i>Min</i>		0.7	0.0	0.0	0.0	0	0
<i>Max</i>		31.7	20.5	17.5	2.9	7	0
<i>Jonckheere–Terpstra test</i>							
<i>p-value</i>		n.s.	<0.05*	n.s.	n.s.	n.s.	-
Pearson's r effect size		0.31	0.43	0.35	0.26	0.38	-

*** $p \leq 0.001$, ** $p \leq 0.01$, * $p \leq 0.05$, n.s. = not significant ($p \geq 0.05$); $r < 0.10$ = negligible; $0.10 \leq r < 0.30$ = small; $0.30 \leq r < 0.50$ = moderate; $r \geq 0.50$ = large

Data reported in bold italic correspond to failed criteria

3.2. Appraisal of indoor thermal conditions

Figure 3 shows the results of the appraisal of indoor thermal conditions as provided by the occupants. The appraisal is divided according to the season (winter and summer) and the room (living room and bedroom). Six (6) cases experience “slightly too hot” to “too hot” conditions in the living room, and a vast majority (20 out of 23) of the surveyed households report these conditions in the bedrooms. Frequencies of “too hot” conditions are also higher in bedrooms compared to living rooms (8 out of 23 vs. 4 out of 23). This situation differs from the winter season for which participants indicated comfortable thermal conditions in 17 cases in bedrooms (6 cases as “slightly too cold”) and in all cases in living rooms. Bedrooms appears, thus, to present the most variables conditions between winter and summer. In only 2 cases (IDs 5 and 15), the bedroom summer thermal conditions were appraised by participants as “comfortable”.

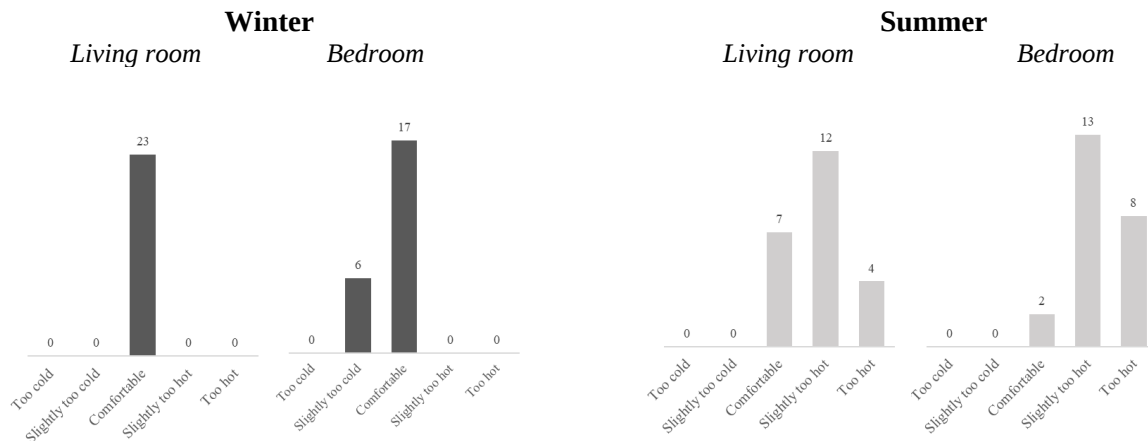


Figure 3. Appraisal of indoor thermal conditions provided by the occupants according to the season and the room

The results of the survey support the evidence found in the literature leading to postulate that occupants are not always satisfied with summer thermal conditions in nZEB houses and that the lowest satisfaction is often found in bedrooms during summer [30]. Further investigations could be conducted to identify when this discomfort is specifically reported by the occupants (e.g., before or during sleep, or when waking up).

3.3. Relationship between summer thermal conditions in living rooms and in bedrooms

Table 4 presents the results of the statistical non-parametric tests on the percentages of time of occupancy above certain thresholds in bedrooms and in living rooms. The Spearman Rho analysis investigated the significance and effect size of the relationships between the frequency of temperature deviations in bedrooms and in living rooms. Statistically significant (p -value < 0.05) correlations of large magnitude ($Rho > 0.5$) could be detected for small temperature deviations (that is, percentage of time of occupancy exceeding 25°C and comfort Category II of EN15251). Conversely, larger temperature deviations (that is, percentage of time of occupancy exceeding 28°C and Category III of EN15251) led to non-significant and weaker ($0.214 < Rho < 0.273$) correlations between thermal conditions in living rooms and in bedrooms. Despite a certain homogeneity of temperatures in nZEB houses can be expected, local variations have therefore to be carefully considered. This supports the interest towards an evaluation of the frequency of occurrence of small and large temperature deviations from the comfort zone by room in order to offer a better understanding of buildings' summer thermal behaviour (e.g.

combining percentage of the time over 25°C and 28°C (EN15251 Cat. II and III) as done in previous studies [15, 31]).

Table 4. Non-parametric correlations between percentages of time of occupancy above 25°C, 28°C and class II and III of EN15251 in bedrooms and in living rooms.

		Bedrooms			
		% of time > 25°C	% of time > 28°C	% of time >EN15251Cat. II	% of time >EN15251Cat. III
Living rooms	% of time > 25°C	Spearman Rho	0.544	0.476	0.491
		<i>p</i> -value	<0.01	<0.05	<0.05
	% of time > 28°C	Spearman Rho	0.253	0.362	0.389
		<i>p</i> -value	n.s.	n.s.	n.s.
	% of time >EN15251Cat. II	Spearman Rho	0.440	0.453	0.508
		<i>p</i> -value	<0.05	<0.05	<0.05
	% of time >EN15251Cat. III	Spearman Rho	0.265	0.214	0.273
		<i>p</i> -value	n.s.	n.s.	n.s.

*** $p \leq 0.001$, ** $p \leq 0.01$, * $p \leq 0.05$, n.s. = not significant ($p \geq 0.05$)

$Rho < 0.10$ = negligible; $0.10 \leq Rho < 0.30$ = small; $0.30 \leq Rho < 0.50$ = moderate; $Rho \geq 0.50$ = large

The combination of criteria suggested by CIBSE TM52 [22] appears globally in line with this finding.

Alternatively, cumulative indexes (in K.h for example) could be used by room to quantify the intensity (in degrees Kelvin) and the duration of the temperature deviation (in hours), as suggested by the EN15251 standard [33] in order to simplify the use of indicators.

3.4. Relationship between the appraisal of summer thermal conditions and overheating criteria

a) Living rooms

As presented in Table 3. Appraisal of indoor thermal conditions and fulfilment of overheating criteria in the living rooms (7am-10pm or 7am-9am and 5pm-10pm on business days), four cases were appraised by occupants as being “too hot”. Among them, cases IDs 7 and 23 were particularly extreme as they did not meet any criterion and reached the highest proportion of time spent outside of comfort Category III (up to 14.4% of occupancy time). This fraction of time is more limited (0% (case ID 9) and 0.5% (case ID 6)) in the other two cases that fulfil other adaptive criteria (*daily weighted exceedance T_{max+1} and upper limit temperature T_{upp}*). Among the 12 cases considered as “slightly too hot”, only case ID 1 exceeded the adaptive CIBSE criteria (*hours of exceedance T_{max+1} , daily weighted exceedance W_e and upper limit temperature T_{upp}*) but in a more moderate way when compared to cases ID s 7 and 23. The other cases presented limited percentage of the occupied time outside Category III (ranging from 0% to 0.1% of time (case IDs 4 and 18)) and fulfilled all the CIBSE adaptive criteria. The 7 cases reported as “comfortable” by the occupants showed very limited percentage of the occupied time outside of comfort Category III (ranging from 0% to 0.3% of time (case ID 2)). Apart from case ID 22 that did not fulfil the *daily weighted exceedance* criterion ($W_e=1$), all other CIBSE adaptive criteria were met.

The results of the Jonckheere–Terpstra tests, evaluating the relationships between occupants’ thermal appraisal and compliance with overheating criteria, are presented in the rows at the bottom of Table 3. Appraisal of indoor thermal conditions and fulfilment of overheating criteria in the living rooms (7am-10pm or 7am-9am and 5pm-10pm on business days).. The only test

for which statistical significance was detected is related to the *adaptive upper limit temperature* T_{upp} criterion (a criterion that may fail to be met in residential buildings [47]). This means that, in the sample analysed, the frequency of these extreme values clearly increases with the perceived discomfort. The size of the effect detected is practically relevant, with moderate magnitude ($r= 0.45$). The effect size related to the statistical tests applied to the 28°C criterion test (although this was found as statistically non-significant) also detected a moderate magnitude of influence ($r= 0.38$). This reflects the importance of considering the frequency of extreme events when evaluating the long-term summer thermal conditions in living rooms. Li et al. have recently found similar results in air conditioned offices buildings [24].

No other statistical test led to the detection of significant differences in the data, this reflecting the similarity of the values encountered in the sample for the other overheating criteria in the “comfortable” and “slightly too hot” categories of appraisal, as showed above. This leads to question the thresholds and the acceptable frequency of the criteria.

In general, the occurrence of perceived discomfort in living rooms (“slightly too hot” or “too hot” votes) was found to be similar to the number of buildings that did not meet the static criteria *percentage of the time of occupancy above 25°C exceeding 5%*. However, among these 14 buildings, five were reported as being “comfortable”, this suggesting a thermal satisfaction, or a possible adaptation from the part of the occupants, which is not captured by static criteria [42].

On the other hand, the CIBSE TM52 adaptive overheating risk assessment methodology was only able to identify dwellings presenting the most severe overheating situations. It should be considered here that CIBSE adaptive criteria [22] are based on the difference between T_{op} and T_{max} (here, represented by the upper limit of EN15251 comfort Category II). This difference has to reach 1-degree K (rounded value) for it to be considered. To some extent, this could be seen as considering the percentage of time outside of comfort Category III, a category that should only be exceeded for a limited part of the year [46]. This situation, which is tolerated up to 3% of the occupied time, appears therefore not to be limiting in the cases encountered. The removal of the tolerated difference of 1K, or a lower accepted frequency, should allow to be more in line with the number of complaints found under these conditions.

Finally, the noticed absence of a strong link with the percentage of time exceeding the adaptive EN15251 Category II also leads to question the applicability of these comfort categories in a residential context. In this regard, de Dear et al. found, in a humid subtropical climate, a larger tolerance to temperature ranges but a lower acceptability to higher thresholds in homes compared to what the ASHRAE adaptive model would define for offices [5].

These results reflect, therefore, the need to re-evaluate, in the case of residential buildings in a temperate climate, the acceptable temperature thresholds in living rooms based on larger samples where significant and practically relevant differences in individual preferences and adaptation can be detected and measured.

b) Bedrooms

As presented in

, only 2 bedrooms (case IDs 5 and 15) were considered “comfortable” in summer. Case ID 15 was the only one to be deemed comfortable although presenting a temperature above 26°C for more than 1% of the occupied time (3.1%). The other criteria were all met for both cases.

Among the 13 cases with a “slightly too hot” evaluation in bedrooms, 4 did not exceed 1% of the time of occupancy above 26°C. Only case 23 presented extreme values: 12% of the time above 26°C, 1.2% over EN15251 comfort Category III, and 4 times above the *daily weighted exceedance* (We).

The 8 cases presenting a “too hot” appraisal all exceeded a percentage of occupied time above 26°C of 1%. Among these, 3 cases also did not meet the *daily weighted exceedance* criterion (We) and 2 exceeded 1% of the time of occupancy over EN15251 comfort Category III.

The results of the Jonckheere–Terpstra tests are presented in the rows at the bottom of

Data reported in bold italic correspond to failed criteria

. The only test that returned statistical significance was the one related to the percentage of occupied time with a temperature above 26°C. The effect size of $r = 0.43$ indicates a moderate increase in the encountered frequency with the perceived discomfort. Even though the tests were found not to be statistically significant, the magnitude of the effects related to small temperatures deviations ($>25^{\circ}\text{C}$ and $> \text{EN15251 category II}$) was estimated as moderate ($r > 0.3$), while only effects of small size were detected in living rooms ($r > 0.1$). These results confirm that lower temperatures are generally preferred in bedrooms compared to the living rooms [64], and that smaller temperature deviations lead to discomfort, probably due to the fact that adaptive opportunities are reduced during sleep [4].

This supports the use of the CIBSE *hours of exceedance* criterion based on a threshold of 26°C [47] to describe the occurrence of discomfort in bedrooms, although this criterion seems to be difficult to meet in practice (18 cases out of 23 showed temperatures above 26°C for more than 1% of the time of occupancy).

3.5. Thermal behaviour and buildings characteristics

Table 5 summarizes the characteristics of the buildings that did not comply with any of the CIBSE criteria (dwellings IDs 1, 7 and 23), or that presented the highest values for all the criteria in the bedroom (dwelling ID 3) and those of the building's IDs 2, 4, 16 and 17 that complied with all the criteria (CIBSE and PHI). As already mentioned, all the buildings were located in rural or semi-rural areas in relatively opened sites. The management of solar gains is therefore particularly crucial and the potential for heat dissipation by windows opening available.

The qualitative comparison of the characteristics showed that house type, number of occupants, heated floor area, construction type, window Solar Heat Gain Coefficient (SHGC), windows opening practice, as well as the location of the bedroom under the roof, are relatively similar in the two groups of buildings. Only small differences could be noticed for the buildings that complied with all the CIBSE criteria, since they had slightly higher heating needs and smaller glazing surfaces. Heating needs corresponded to a mean of 19.1 kWh/m² against 12.8 kWh/m² due, among other factors, to a higher mean U-value (0.3 vs 0.2 W/m².K) and a lower airtightness (n_{50} mean of 2.3 vs 1.6 1/h) of the thermal envelope. Glazing surfaces corresponded to a mean of 16% vs 20.7%, less often west-oriented (i.e., with sun exposure in the late afternoon).

Solar gains are mainly controlled by internal shading devices (manually-operated) in both groups. However, the absence of solar shading appears more frequent in the cases facing higher occurrences of overheating, especially for bedrooms. On the contrary, windows opening behaviour, as reported by the occupants did not seem to differ substantially. The main difference that can be noticed between the two groups is related to the presence of the occupants during the day. In fact, the buildings presenting overheating problems were usually those not occupied during the day. This difference – other than potentially influencing the physiological adaptation of the occupants if they are exposed to a mechanically-controlled environment during the day – could also affect the possibility to operate properly the solar shading devices and provide natural cooling by windows opening at the times needed. This last hypothesis could not be further investigated in our study, but it should probably be considered for future research on residential thermal comfort.

Table 5. Main characteristics of the buildings presenting the weakest (cases IDs 1, 3, 7 and 23) and strongest (cases IDs 2, 4,16 and 17) compliance with overheating criteria

Building IDs		IDs 1, 3, 7, 23	IDs 2, 4, 16, 17
		(weakest compliance with criteria)	(strongest compliance with criteria)
		mean [min-max] or n	mean [min-max] or n
House type		Detached : 2	Detached : 3
		Semi-detached :1	Semidetached :1
		Attached :1	
Type of construction		Masonry :3 ; Wooden Frame :1	Masonry :3 ; Wooden Frame :1
Number of occupants		4 [3-5]	3.3 [2-5]
Presence during the working hours		No : 4	Yes : 4
Heated floor area [m²]		217.3 [151.7- 330]	207.9 [119.7-275.3]
Window-to-floor surface ratio [%]		20.7 [15.2 -24.7]	16 [12.1-19.9]
Mean Uvalue (windows included) [W/m².K]		0.2 [0.2-0.4]	0.3 [0.2-0.4]
Airtightness (n50) [1/h]		1.6 [0.7-3.7]	2.3 [0.8-3.8]
Main window SHGC		0.5 [0.5-0.6]	0.6 [0.5-0.7]
Heating needs [kWh/m².K]		12.8 [5-23.8]	19.1 [8.8-29.4]
Living room	Orientation	SW :2 ; S :1 ; W :1	S :2 ; E :1 ; NE :1
	Solar shading type	In :3 ; No :1	In :3 ; Out :1 (Id : 4)
	Windows opening practice	Day and Night: 2	Day and Night: 2
		Day: 1	Never:2
		Never:1	
Bedroom	Under roof situation	Yes : 2 ; No :2	No :3 ; Yes :1
	Orientation	S: 1 ; SW:1 ; W:1 ; NW:1	S:1, SW:1, W:1, E:1
	Solar shading type	No :3 ; Out :1 (Id : 23)	In : 4
	Windows opening practice	Day: 3	Day and Night: 2
		Day and Night: 1	Day: 1 Never:1

Figure 4 presents the thermal summer conditions encountered in the living room of two lightweight buildings (cases IDs 17 and 23) that share similar building characteristics (cf. Table 1). The proper use of shading devices, combined with an adequate day and night ventilation by windows opening (as reported by the occupant) appears to be effective in limiting the risk of overheating situations (Figure 4 - left). On the opposite, opening the windows only during the day, combined with a probably inadequate operation of internal shadings - the occupants reported to be mostly absent during working hours - leads, in the south west oriented living room of building ID 23 (vs south for building ID 17), to extreme overheating situations (Figure 4 - right).

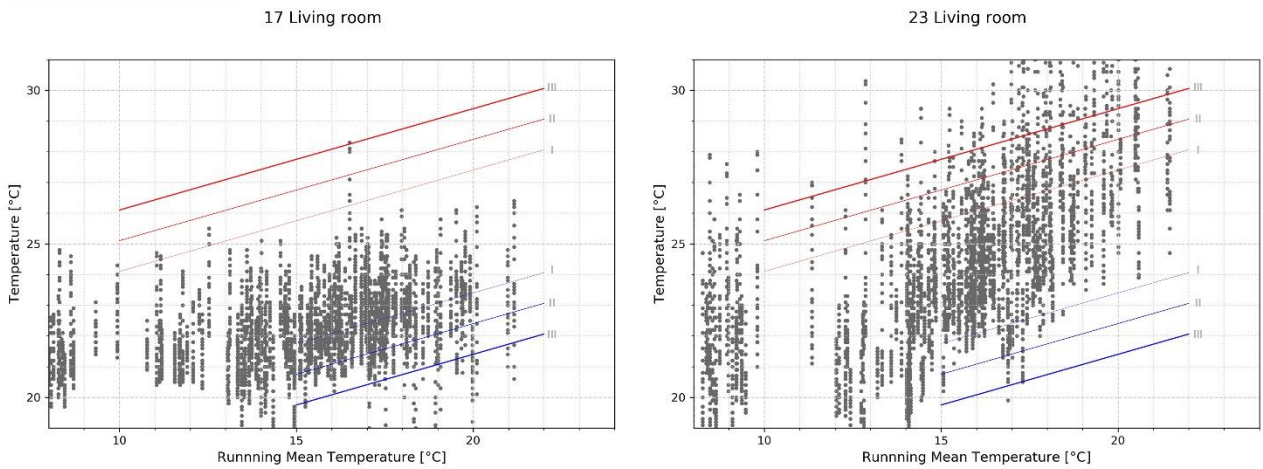


Figure 4. Measured hourly temperatures (y-axis) between May and September in the living rooms of building IDs 17 (left) and 23 (right) plotted against the running mean temperature (x-axes, Trm) of EN15251 adaptive standard (and indication of comfort categories I, II, III limits).

Even if further research is still needed, these preliminary results confirm the importance of properly considering the integration of specific design strategies [54] to prevent or mitigate risks of overheating (e.g., solar shading and natural cooling) even in a temperate climate, as well as the active role that should be played by the occupants in the operation of environmental controls [16].

4. CONCLUSIONS

This paper has presented the results of a post-occupancy evaluation measurement and survey campaign conducted in 23 nZEB houses in Wallonia (southern part of Belgium). To the authors' knowledge, this is the first medium-scale study of summer thermal comfort in nZEB houses that has been reported from this part of Europe. Analysis of the data collected in living rooms and in the master bedrooms was first conducted by applying criteria commonly used for the evaluation of indoor summer thermal conditions in free-running residential buildings. Rigorous statistical tests were then carried out to analyse the relationships between the achievement of different overheating criteria and the appraisal of indoor summer thermal comfort provided by the occupants. On such bases, the study provided a critical review of the capacity of current criteria to predict the satisfaction expressed by building occupants with their summer thermal comfort.

The results have emphasised the difficulty in maintaining comfortable thermal conditions in nZEB houses despite the temperate climate of Wallonia. Only 5 buildings met all the criteria suggested by CIBSE, mainly due to the high temperatures recorded in bedrooms. The analyses showed that the frequency of occurrence of small and large temperature deviations from the comfort zone should be quantified by room, in order to offer a complete understanding of summer thermal conditions and of the overall thermal behaviour of the buildings.

In living rooms, the long-term appraisal of summer thermal conditions appeared to be more related to the frequency of extreme temperatures. Conversely, the appraisal of summer thermal conditions in bedrooms seemed to be more influenced by smaller temperature deviations with respect to the living rooms, probably due to the fact that adaptive opportunities are reduced during sleep. Nevertheless, the overheating criteria adopted were found not to be able to properly predict the occurrence of perceived moderate discomfort, especially in living rooms. Larger studies, possibly also measuring and quantifying inter-individual differences of perception, are therefore needed to re-evaluate the boundaries and/or the tolerable frequencies of the adaptive criteria within the residential context. Although cases presenting higher risks of overheating were found to require slightly less heating, to present larger unshaded glazing surfaces, and to be more often west-oriented (hence requiring a better integration of bioclimatic strategies to mitigate overheating risks), the findings from this study also emphasise the importance of considering the behaviour of occupants (e.g., operation of shading systems and other environmental controls) in the reduction of overheating risks.

Further research aiming towards a better understanding of how environmental controls are operated by the occupants to maintain comfortable indoor summer thermal conditions appears necessary to tackle overheating issues in nZEB houses.

5. ACKNOWLEDGMENT

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