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

Dartevelle, Olivier; van Moeseke, Geoffrey; Mlecnik, Erwin; Altomonte, Sergio

DOI
10.1016/j.buildenv.2020.107531

Publication date
2021

Document Version
Final published version

Published in
Building and Environment

Building and Environment 190 (2021) 107531

Contents lists available at ScienceDirect

Building and Environment

journal homepage: http://www.elsevier.com/locate/buildenv

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

Olivier Dartevelle [a,*], Geoffrey van Moeseke [a], Erwin Mlecnik [b], Sergio Altomonte [a]

[a] Architecture et Climat, Université catholique de Louvain, Louvain-la-Neuve, Belgium

[b] Faculty of Architecture and the Built Environment, Delft University of Technology, Delft, the Netherlands

ARTICLE INFO

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.

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 [1], these having an increasingly more critical impact particularly in consideration of the higher sensitivity [2] of an ageing population [3]. Conversely, the evolution of building construction techniques (e.g., with higher thermal insulation, airtightness and enhancement of solar gains) driven by the evolution of energy performance standards [4–6] can also severely impinge on the summer thermal behaviour of buildings [7,8].

While in temperate countries such as the UK, the study of summer thermal indoor conditions in new buildings has acquired a consistent tradition [9–13], in Belgium – which shares a similar climate to the UK – and more particularly in Wallonia, this domain of research is still at its infancy. The *MEASURE* project [14], which conducted POE surveys in 149 Walloon residential 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 perception of discomfort, mainly in living rooms and bedrooms [15].

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 whole building energy simulation, they can provide guidelines for the optimization of strategies to mitigate overheating risks [16]. Conversely, when used for the analysis of monitoring data, they can offer benchmarks for the verification and comparison of indoor conditions [9]. The criteria recommended by CIBSE (Chartered Institution of Building Services Engineers) [17] and PHI (Passive House Institute) [18] are among the most commonly used for the study of summer thermal comfort in free-running residential buildings in temperate climates [10,11]. Nevertheless, their capacity to predict the satisfaction of occupants with their summer thermal comfort [19], 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.

* Corresponding author.
E-mail address: olivier.dartevelle@uclouvain.be (O. Dartevelle).

https://doi.org/10.1016/j.buildenv.2020.107531
Received 31 July 2020; Received in revised form 29 November 2020; Accepted 12 December 2020
Available online 18 December 2020

Building on the granular data collected in 23 single-family nZEB houses in Wallonia, this paper offers an overview of measured and perceived summer thermal conditions. This analysis provides robust evidence of the extent of overheating situations that can be encountered in these buildings in a temperate climate. Then, the relationship between perceived and measured summer thermal comfort, described through common criteria for overheating assessment, is statistically analysed. This evaluation is carried out distinctly in living rooms and in bedrooms so that differences and specific trends can be identified and discussed. On these bases, the paper presents a critical evaluation of the capacity of common overheating criteria to predict the satisfaction of occupants in a residential context. Finally, the factors and building characteristics that lead to the worst encountered overheating situations are discussed.

2. Method

Building characteristics and methods for data collection and analysis are illustrated in detail in the following paragraphs.

2.1. Buildings' sample

Twenty-three (23) nZEB houses were analysed for the purpose of this study. The majority of these dwellings were detached single-family houses (20 out of 23 cases). In Belgium, single-family houses represent the 79.7% of the housing stock [20], of which 30% are detached houses [21]. The houses included in our sample 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 [22]. They were all located in rural to semi-rural environments on relatively unobstructed sites, with little or no surrounding environmental shading.

These houses had been occupied for a minimum of 3 years before the beginning of this study. This selection criterion was established to avoid the potential bias that can appear during the first years of occupation of a building [23]. 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 study was submitted for approval to the Belgian Data Protection Authority. In this context, an informed consent form was obtained from all participants.

Requirements for nZEB houses in Wallonia rely on the definition provided in the European Directive 2010/31/EU on the energy performance of buildings [4], which primarily focuses on reducing heating demands. The volumetric and thermal characteristics of the envelope of the buildings analysed are described in Table 1. Heated floor areas, mean U-values, airtightness, yearly heating needs, and SHGC (Solar Heat Gain Coefficient) of windows were taken from the requirements of the Belgian EPBD (Energy Performance of Buildings Directive) calculation [24] (further description of the buildings' characteristics can be found in Ref. [25]).

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 was 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.

The size of the sample was defined by the practical need to offer an in-depth and accurate knowledge of the case studies. The relatively limited number of nZEB houses included in the analysis was, in fact, chosen to allow 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 to enable focused discussions with the occupants about, among other aspects, their habits and behaviours (e.g., presence during the day, windows opening). These data are reported in Table 1.

2.2. Measurements

Air temperatures were recorded every 10 min in the living rooms and in the main bedrooms of each house during an entire year (2016), resulting in approximately 52,560 data points for each room. Following recommendations from the literature [10], sensors were placed by the research team on top of existing furniture at a minimal height of 80 cm, away from windows (to avoid direct solar radiation) and from any other internal heat sources. Data were recorded using a dedicated wireless/4G router. The Belgian Building Research Institute (BBRI) conducted preliminary calibration tests of the measuring devices before the measurement campaign and verified compliance with the maximum errors declared by the manufacturer. These tests confirmed a maximum error of ±0.3 °C after calibration.

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 [28] 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):

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

As reported by the Royal Meteorological Institute of Belgium [29], 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 for most months of the year, particularly during the meteorological summer period, are generally consistent with seasonal norms, although a remarkably hot month of September was recorded (Fig. 1). Over the year, 97 days recorded maximum temperatures higher than 20 °C, 25 days exceeded 25 °C, and 6 days exceeded 30 °C.

2.3. Criteria for overheating assessment

Two groups of long-term summer comfort 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 [30]. Various limits, accepted frequencies, and periods of calculation can be found in the literature (see for example the work of [31]), 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 [32], while the Passive House Institute (PHI) brings this threshold to 10% of occupancy time [33]. The Chartered Institution of Building Services Engineers (CIBSE) in UK, in a previous version of its environmental Guide A [34], 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) [35]. 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 [8–10,13,26,27]. These criteria rely on a static characterisation of thermal comfort based on thermal neutrality [36]. The accuracy of such model in real buildings is, however, largely questioned [37].

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* Main windows orientation*	*Living room* Solar shading Type*	*Living room* Windows opening **	*Bedroom* Main windows orientation*	*Bedroom* Under roof location*	*Bedroom* Solar shading type*	*Bedroom* Windows opening **
	[–]	[–]	[–]	[–]	[–]	[%]	[W/m^2.K]	[1/h]	[–]	[kWh/m^2.y]	[–]	[–]	[–]	[–]	[–]	[–]	[–]
1	Attached	Masonry	5 *<12 y/o: 3*	No	330.0	15.2	0.24	1.25	0.51	14.8	W	In	Day and Night	W	No	No	Day and Night
2	Semi-attached	Masonry	4 *<12 y/o: 2*	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 *<12 y/o: 1*	No	151.7	19.0	0.15	0.68	0.54	5.0	S	In	Never	S	No	No	Day
4	Detached	Masonry	2 *(>65 y/o)*	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 *<12 y/o: 2*	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 *<12 y/o: 3*	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 *<24 y/o: 2*	No	201.1	24.0	0.19	0.74	0.5	7.6	SW	No	Day and Night	SW	Yes	No	Day
8	Detached	Wooden Frame	3 *<12 y/o: 1*	No	186.5	26.0	0.25	1.77	0.49	14.3	SW	Out	Never	SW	Yes	In	Never
9	Detached	Masonry	4 *<24 y/o: 2*	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 *<12 y/o: 2*	No	198.4	19.9	0.32	1.40	0.63	16.7	W	No	Never	W	No	Out	Day
12	Detached	Masonry	4 *<12 y/o: 2*	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 *<24 y/o: 4*	No	216.8	27.0	0.15	0.54	0.51	3.6	SW	Out	Day and Night	SW	No	Out	Day and Night
14	Detached	Wooden Frame	4 *<12 y/o: 2*	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	NW	In	Day and Night	NW	Yes	In	Day and Night
16	Detached	Masonry	5 <12 y/o: 3	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

(*continued on next page*)

Table 1 (*continued*)

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* Main windows orientation*	Solar shading Type*	Windows opening **	*Bedroom* Main windows orientation*	Under roof location*	Solar shading type*	Windows opening **
	[–]	[–]	[–]	[–]	[–]	[%]	[W/m².K]	[1/h]	[–]	[kWh/m².y]	[–]	[–]	[–]	[–]	[–]	[–]	[–]
18	Detached	Masonry	5 <12 y/o: 3	No	239.5	14.3	0.39	7.88	0.63	30.1	S	In	Never	SW	Yes	In	Never
19	Detached	Masonry	4 <12 y/o: 2	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 <12 y/o: 1	Yes	467.8	13.3	0.35	4.76	0.6	20.8	SW	In	Day	W	No	In	Day
22	Detached	Wooden Frame	4 <12 y/o: 2	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 <12 y/o: 2	No	186.59	24.7	0.40	3.69	0.63	23.8	SW	In	Day	NW	Yes	Out	Day

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

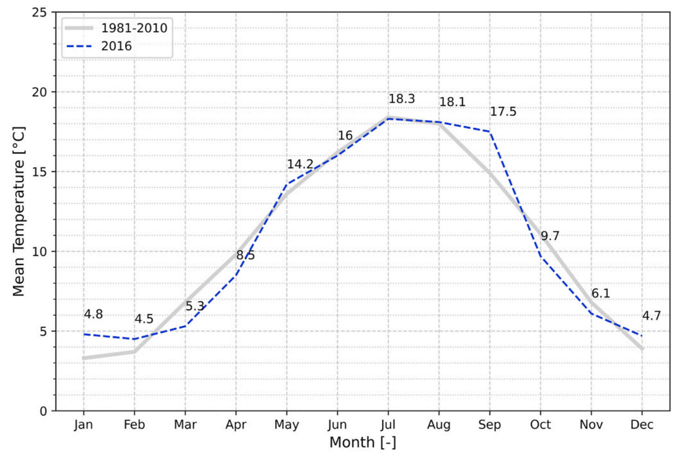

Fig. 1. Comparison of monthly mean temperatures of 2016 with the climate normal (1981–2010).

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 [38]. 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 [30]. This standard [28] 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 [17,39]. 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 [40,41].

In the most recent 8th edition of environmental Guide A [42], 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 [17] 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 particularly sensitive and fragile persons [43]. In residential buildings, as specified in its Technical Memoranda TM59 [44], 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 [17].

Some authors have argued, however, that the adaptive capacity is limited during the night [45] and that the quality of sleep decreases at temperatures above 24° Celsius [46]. For this reason, CIBSE adds, for the bedroom, a criterion based on an absolute threshold of 26 °C [34,44]. The general CIBSE approach is widely used for overheating analysis both in cases of monitoring studies and simulations [11,47–51].

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

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 5% of annual occupied hours over temperature of 25°C	PHI PHP
Hours of exceedance	28 °C living areas 26 °C bedrooms	1% of annual occupied hours over operative temperature of 28 °C (living areas) or 26 °C (bedrooms)	Guide A, CIBSE 2006 TM59, CIBSE 2017 (bedrooms only)
Hours of exceedance	(T_{op}- T_{max})[a]> 1K T_{op} - (*EN15251 Cat. II upp. limit*[b]) >1K T_{op} - (0.33 T_{rm} + 21.8 °C) >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[b]	TM52, CIBSE 2013 Guide A, CIBSE 2015 TM59, CIBSE 2017
Daily weighted exceedance	We = ∑(he) x WF *with WF* = min *(0; Top-Tmax)* *and he: corresponding time [h]*	Max 6 in any one day during occupied hours[c]	TM52, CIBSE 2013
Upper limit temperature	Tupp = Tmax + 4K	Absolute maximum value during occupied hours[c]	TM52, CIBSE 2013

[a] Rounded to the nearest unit.
[b] For spaces that are occupied by very sensitive and fragile persons upper limit of Category I is recommended.
[c] May fail to be met in dwellings (TM59, CIBSE 2017).

temperature (T_{op}), which can be seen as the manifestation of the combined effect of mean radiant temperature and air temperature in a space [42]. As in many other studies [10–13,26,27,49,52], 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.

Although this might represent a limitation, similar to other studies [27,49], it was assumed 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) [28].

According to their definition, the criteria need to be evaluated when occupants are present. Known periods of prolonged absence (e.g., vacations) were, thus, removed from the data in order to limit the bias that could be induced by periods of uncontrolled and non-evaluated thermal conditions (see section 2.4).

Room occupancy was found to considerably vary across days and houses. As a consequence, similar to many other studies [10,26,27], based on the discussions with the households and due to the absence of continuous high resolution spatio-temporal models of occupants' localisations, realistic occupancy assumptions had to be made. A general occupancy between 7am and 10pm in the living rooms, and between 10pm and 7am in the bedrooms, was assumed for the 7 cases that were occupied during working hours (cf. Table 1). Conversely, for the 16 houses that were not occupied during the day, occupancy of the living room was limited to 7am–9am and 5pm–10pm on business days. The implications of these assumptions might depend on the type (e.g., percentage based, maximum temperature, daily weighted exceedance) and the evaluation period for each criterion (year/summer) and they cannot be easily quantified with certainty. It would be interesting to conduct sensitivity analyses on real cases to weigh these implications, but these are beyond the scope of this study.

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 [14].

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 [53]. 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 Fig. 2, which was designed on the basis of the Bedford comfort scale [54]. 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 2.5).

Since people seldom report the same thermal experience, and considering that inter (and intra)-individual differences of perception would require a much larger sample to be quantified, these methodological choices (single family vote and votes (n = 23) reported on a scale with a limited number of points) were made to limit the influence of extreme individual evaluations. 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

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

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

[55]), 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 [56].

The relationships between the frequency of temperature deviations in bedrooms and in living rooms were analysed using the Spearman Rho test [57]. 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 [58,59]. 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 scale mentioned in section 2.4) could have occurred by chance. Inferences from the data were based on statistical and practical significance of the influences detected, and were derived from the estimation of the Pearson's r effects size [60].

For both the Spearman Rho and the Pearson's r effect sizes, the benchmarks proposed by Cohen [61] were used in this study: ≥0.1 = small effect, ≥0.3 = medium effect; ≥0.5 = large effect.

3. Results and discussion

3.1. Compliance with overheating criteria

Table 3 and Table 4 show, respectively, for the living rooms and the bedrooms, 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%)

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

		PHI	CIBSE 2006	EN15251	CIBSE TM52 2013		
ID	Occupants' thermal appraisal	% of time >25°C	% of time >28°C	% of time>Cat. II	% of time>Cat. III (>Tmax +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
[−]	[−]	[%]	[%]	[%]	[%]	[−]	[−]
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***
9	Too hot	***7.5***	0.5	0.1	0.0	0	0
23	Too hot	***22.3***	***7.2***	20.9	***14.4***	***40***	***68***
	Mean	8.9	0.9	2.1	1.1	2.7	3.2
	Mdn	6.4	0.4	0.4	0.0	0.0	0.0
	Sd	8.1	1.8	5.2	3.3	9.1	14.2
	Min	0.9	0.0	0.0	0.0	0	0
	Max	33.9	7.2	20.9	14.4	40	68
Jonckheere–Terpstra test:							
p-value		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 ≤ 0.001, **p ≤ 0.01, *p ≤ 0.05, n.s. = not significant (p ≥ 0.05); r < 0.10w = negligible; 0.10 = r < 0.30 = small; 0.30 = r < 0.50 = moderate; r ≥ 0.50 = large.
Data reported in bold italic correspond to failed criteria.

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

		PHI	CIBSE 2006, 2017	EN15251	CIBSE TM52 2013		
ID	Occupants' thermal appraisal	% of time >25°C	% of time >26°C	% of time>Cat. II	% of time>Cat. III (>Tmax +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
	Mean	8.0	4.0	1.7	0.3	0.8	0
	Mdn	6.4	2.6	0.1	0.0	0.0	0.0
	Sd	7.5	5.1	4.0	0.7	2.0	0
	Min	0.7	0.0	0.0	0.0	0	0
	Max	31.7	20.5	17.5	2.9	7	0
Jonckheere–Terpstra test							
p-value		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 ≤ 0.001, **p ≤ 0.01, *p ≤ 0.05, n.s. = not significant (p ≥ 0.05); r < 0.10 = negligible; 0.10 = r < 0.30 = small; 0.30 = r < 0.50 = moderate; r ≥ 0.50 = large. Data reported in bold italic correspond to failed criteria.

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 Tmax + 1, daily weighted exceedance* (*We)* and *upper limit temperature (Tupp)*, and case ID 22 regarding *We*). In the bedrooms, 4 cases do not fulfil at least one of the CIBSE adaptive criteria (*Tmax + 1* is not met for cases IDs 3, 7 and 23; *We* for cases IDs 3, 7, 18 and 23; and *Tupp* is never reached).

Case ID 3 is noteworthy 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) 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 [13,50], which suggests that nZEB houses in temperate climates might be particularly at risk of overheating.

3.2. Appraisal of indoor thermal conditions

Fig. 3 shows the results of the appraisal of indoor thermal conditions as provided by the occupants. The appraisal is organised 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 appear, thus, to present the most variable conditions between winter and summer. In only 2 cases (IDs 5 and 15), bedroom summer thermal conditions were appraised by participants as “comfortable”.

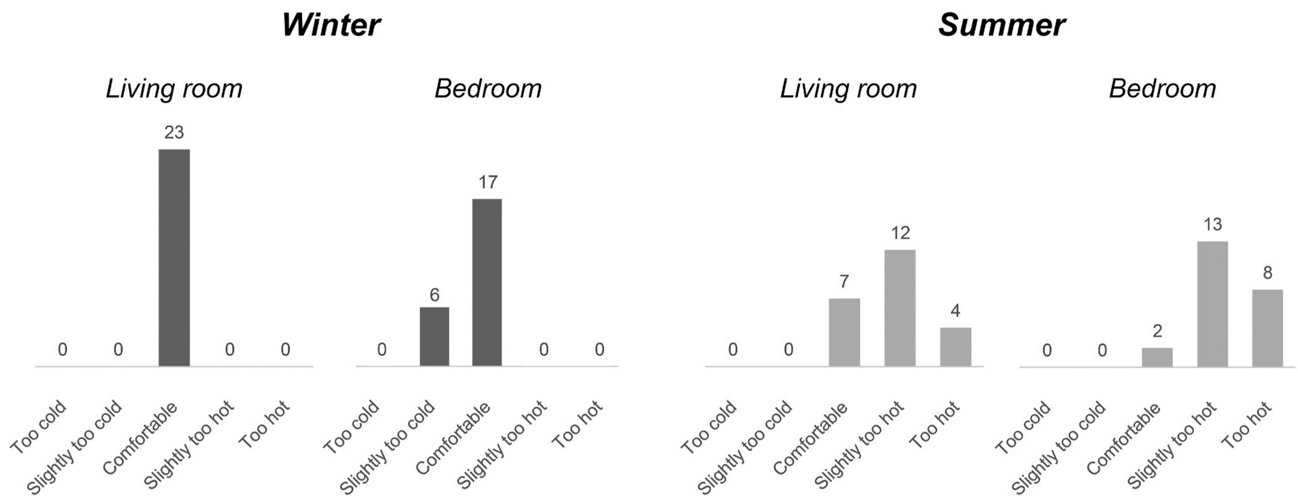

Fig. 3. Appraisal of indoor thermal conditions provided by the occupants according to the season and the room.

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 [23]. 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 5 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 (or EN15251 Cat. II and III) as done in previous studies [10,26]). The combination of criteria suggested by CIBSE TM52 [17] appears globally in line with this finding.

Alternatively, cumulative indexes (for example in Kelvin hours (K.h)) could be used by room to quantify the intensity (in Kelvin) and the

Table 5
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	0.552
		p-value	<0.01	<0.05	<0.05	<0.01
	% of time > 28°C	Spearman Rho	0.253	0.362	0.389	0.229
		p-value	n.s.	n.s.	n.s.	n.s.
	% of time >EN15251Cat. II	Spearman Rho	0.440	0.453	0.508	0.367
		p-value	<0.05	<0.05	<0.05	n.s.
	% of time >EN15251Cat. III	Spearman Rho	0.265	0.214	0.273	0.226
		p-value	n.s.	n.s.	n.s.	n.s.

			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	0.552
		p-value	<0.01**	<0.05*	<0.05*	<0.01**
	% of time >28 °C	Spearman Rho	0.253	0.362	0.389	0.229
		p-value	n.s.	n.s.	n.s.	n.s.
	% of time>EN15251Cat. II	Spearman Rho	0.440	0.453	0.508	0.367
		p-value	<0.05*	<0.05*	<0.05*	n.s.
	% of time>EN15251Cat. III	Spearman Rho	0.265	0.214	0.273	0.226
		p-value	n.s.	n.s.	n.s.	n.s.

***p ≤ 0.001, **p ≤ 0.01, *p ≤ 0.05, n.s. = not significant (p ≥ 0.05).
Rho<0.10 = negligible; 0.10≤ Rho <0.30 = small; 0.30≤ Rho <0.50 = moderate; Rho ≥0.50 = large.

duration of the temperature deviation (in hours), as suggested by EN15251 [28] in order to simplify the use of indicators.

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

3.4.1. Living rooms

As presented in Table 3, 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 Tmax + 1 and upper limit temperature Tupp*). Among the 12 cases considered as "slightly too hot", only case ID 1 exceeded the adaptive CIBSE criteria (*hours of exceedance Tmax + 1, daily weighted exceedance We* and *upper limit temperature Tupp*) but in a more moderate way when compared to cases IDs 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 (We = 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. The only test for which statistical significance was detected is related to the *adaptive upper limit temperature Tupp* criterion (a criterion that may fail to be met in residential buildings [44]). 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 long-term summer thermal conditions in living rooms. Li et al. have recently found similar results in air-conditioned office buildings [19].

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 criterion *percentage of the time of occupancy above 25°C exceeding 5%*. However, among these 14 buildings, five were reported as being "comfortable", this suggesting thermal satisfaction, or a possible adaptation from the part of the occupants, which is not captured by static criteria [38].

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 [17] are based on the difference between T_{op} and T_{max} (here, represented by the upper limit of EN15251 comfort Category II). This difference (rounded value) has to reach 1-degree K 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 [43]. 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 [41].

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.

3.4.2. Bedrooms

As presented in Table 4, only two 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, four 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 four times above the *daily weighted exceedance* (We).

The eight cases presenting a "too hot" appraisal all exceeded a percentage of occupied time above 26 °C of 1%. Among these, three cases also did not meet the *daily weighted exceedance* criterion (We), and two 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 Table 4. 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 °C and > 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 [62], and that smaller temperature deviations lead to perception of discomfort, probably due to the fact that adaptive opportunities are reduced during sleep [45].

This supports the use of the CIBSE *hours of exceedance* criterion based on a threshold of 26 °C [44] 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 building characteristics

Table 6 summarizes the characteristics of the buildings that did not comply with any of the CIBSE criteria (cases IDs 1, 7 and 23), or that presented the highest values for all the criteria in the bedroom (case ID 3). The table also presents the characteristics of buildings 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 unobstructed sites. The management of solar gains was, therefore, particularly crucial, and the potential for heat dissipation by window opening was largely available.

Due to the small size of these sub-samples, the comparison of their characteristics was uniquely based on qualitative criteria. This analysis 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

Table 6
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 1, 3, 7, 23 (weakest compliance with criteria)	Building IDs 2, 4, 16, 17 (strongest compliance with criteria)
		n or mean [*min-max*]	n or mean [*min-max*]
House type		Detached: 2 Semi-detached:1 Attached:1	Detached: 3 Semidetached: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 [m^2]		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 U-value (windows included) [$W/m^2.K$]		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 [$kWh/m^2.K$]		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: 1 Never:1	Day and Night: 2 Never:2
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: 1	Day and Night: 2 Day: 1 Never:1

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/m^2 against 12.8 kWh/m^2 due, among other factors, to a higher mean U-value (0.3 vs. 0.2 W/m^2. 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 were mainly controlled by internal shading devices (manually-operated) in both groups. When solar shading was not available, especially in bedrooms, higher occurrences of overheating were recorded. Windows' opening behaviour, as reported by the occupants, did not 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 were 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.

Fig. 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 (Fig. 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 (Fig. 4 - right).

Even if further research is still needed, these preliminary results confirm the importance of properly considering the integration of specific design strategies [52] 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 [11].

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 study of summer thermal comfort in nZEB houses that has been reported from this part of Europe. Analysis of the data collected in living

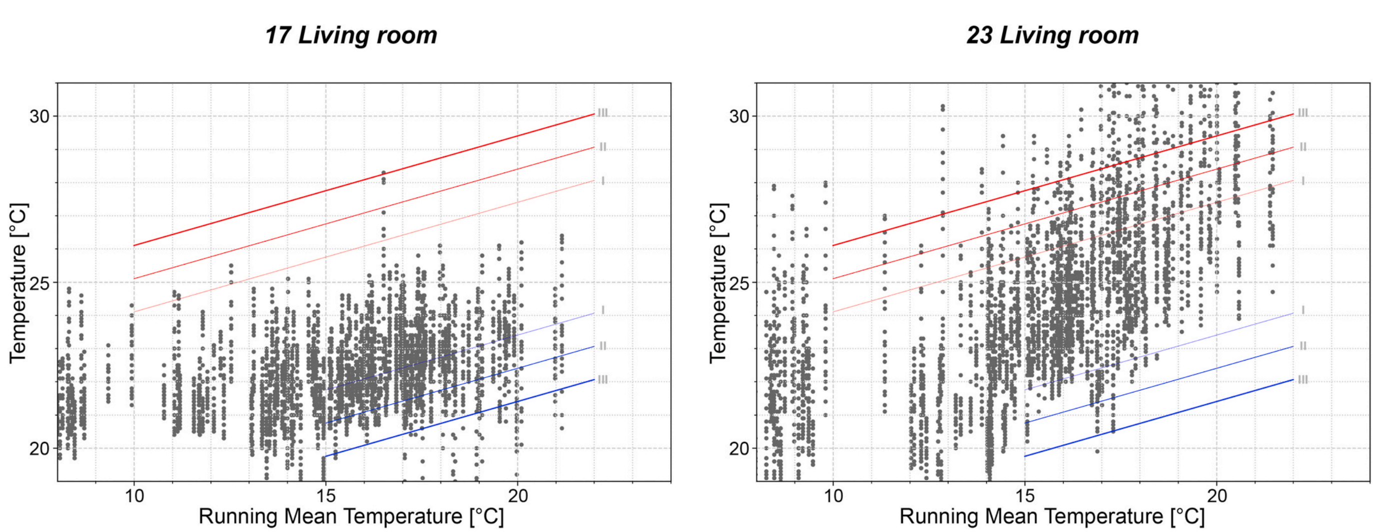

Fig. 4. Measured hourly temperatures (y-axis) between May and September in the living rooms of building IDs 17 (left) and 23 (right) plotted against the running mean temperature (x-axes, Trm) of EN15251 adaptive standard (and indication of comfort categories I, II, III limits).

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 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 conditions 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 five 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 adopted overheating criteria 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.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The post-occupancy measurement campaign was carried out in partnership with the Belgian Building Research Institute (BBRI) with the financial support of the Walloon Region within the frame of the MEASURE project (real performance and occupant satisfaction measures in high energy performance residential buildings).

A special thanks to Dr. ir. M.J. Tenpierik for the preliminary discussion that gave a special input to the accomplishment of this study.

References

[1] IPCC, in: R.K. Pachauri, L.A. Meyer (Eds.), Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 2014, p. 151p.
[2] World Health Organization, Health and global environmental change. Heat-waves: risks and responses, Series 2 (2004).
[3] European Commission, The 2018 Ageing Report: Economic & Budgetary Projections for the 28 EU Member States (2016-2070), 2018. Institutional paper 079.
[4] European Parliament, Directive 2010/31/UE of the European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings, 2010.
[5] European Parliament, Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the Energy Performance of Buildings, 2002.
[6] European Parliament, Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 Amending Directive 2010/31/EU on the Energy Performance of Buildings and Directive 2012/27/EU on Energy Efficiency, 2018.
[7] A. Dengel, M. Swainson, in: N. Foundation (Ed.), Overheating in New Homes. A Review of the Evidence, NHBC Foundation, Milton Keynes, 2012.
[8] R.S. McLeod, M. Swainson, Chronic overheating in low carbon urban developments in a temperate climate, Renew. Sustain. Energy Rev. 74 (2017) 201–220.
[9] A. Beizaee, K.J. Lomas, S.K. Firth, National survey of summertime temperatures and overheating risk in English homes, Build. Environ. 65 (2013) 1–17.
[10] K.J. Lomas, T. Kane, Summertime temperatures and thermal comfort in UK homes, Build. Res. Inf. 41 (3) (2013) 259–280.
[11] S.M. Tabatabaei Sameni, M. Gaterell, A. Montazami, A. Ahmed, Overheating investigation in UK social housing flats built to the Passivhaus standard, Build. Environ. 92 (2015) 222–235.
[12] A. Pathan, A. Mavrogianni, A. Summerfield, T. Oreszczyn, M. Davies, Monitoring summer indoor overheating in the London housing stock, Energy Build. 141 (2017) 361–378.
[13] R.V. Jones, S. Goodhew, P. de Wilde, Measured indoor temperatures, thermal comfort and overheating risk: post-occupancy evaluation of low energy houses in the UK, Energy Procedia 88 (2016) 714–720.
[14] O. Dartevelle, V. Vanwelde, MEsures de performAnces réelles et de Satisfaction des occUpants dans les bâtiments Résidentiels à hautes performances Energétiques : rapport de synthèse sur le climat intérieur, 2018, p. 80.
[15] O. Dartevelle, S. Obyn, V. Vanwelde, Measure of Occupants' Satisfaction in High Energy Performance Residential Buildings : Results from the Action Construire Avec l'Energie in Belgium., PLEA2016 - Cities, Buildings, People : towards Regenerative Environments, 2016.
[16] M. Hamdy, S. Carlucci, P.-J. Hoes, J.L.M. Hensen, The impact of climate change on the overheating risk in dwellings—a Dutch case study, Build. Environ. 122 (2017) 307–323.
[17] T.M.52 Cibse, The Limits of Thermal Comfort: Avoiding Overheating in European Buildings, 2013.
[18] P.H. Institue, Passive House Requirements, 2015. https://passivehouse.com/02_informations/02_passive-house-requirements/02_passive-house-requirements.htm.
[19] P. Li, T. Parkinson, S. Schiavon, T.M. Froese, R. de Dear, A. Rysanek, S. Staub-French, Improved long-term thermal comfort indices for continuous monitoring, Energy Build. 224 (2020).
[20] M. Anfrie, S. Cassilde, O. Gobert, M. Kryvobokov, S. Pradella, Chiffres clés du logement en Wallonie – Troisième édition, Centre d'Etudes en Habitat Durable, 2017, p. 261.
[21] E. Climact, BPIE, Stratégie wallonne de rénovation énergétique à long terme du bâtiment, 2017.
[22] M.C. Peel, B.L. Finlayson, T.A. McMahon, Updated world map of the Köppen-Geiger climate classification, Hydrol. Earth Syst. Sci. 11 (5) (2007) 1633–1644.
[23] E. Mlecnik, T. Schütze, S.J.T. Jansen, G. de Vries, H.J. Visscher, A. van Hal, End-user experiences in nearly zero-energy houses, Energy Build. 49 (2012) 471–478.
[24] Gouvernement wallon, Arrêté du Gouvernement wallon déterminant la méthode de calcul et les exigences, les agréments et les sanctions applicables en matière de performance énergétique et de climat intérieur des bâtiments, 2008.
[25] J. Deltour, V. Vanwelde, O. Dartevelle, Jade Deltour, Véronique Vanwelde, Olivier Dartevelle, MEsures de performAnces réelles et de Satisfaction des occUpants dans les bâtiments Résidentiels à hautes performances Energétiques : rapport de synthèse sur les performances énergétiques réelles, 2018, p. 100.
[26] T.O. Adekunle, M. Nikolopoulou, Thermal comfort, summertime temperatures and overheating in prefabricated timber housing, Build. Environ. 103 (2016) 21–35.
[27] M.J. Fletcher, D.K. Johnston, D.W. Glew, J.M. Parker, An empirical evaluation of temporal overheating in an assisted living Passivhaus dwelling in the UK, Build. Environ. 121 (2017) 106–118.
[28] E.N.15251 NBN, Critères pour l'environnement intérieur et évaluation des performances énergétiques des bâtiments couvrant la qualité d'air intérieur, la thermique, l'éclairage et l'acoustique, NBN, Brussels, 2007.
[29] Royal Meteorological Institute of Belgium, Bilan Climatologique Annuel 2016, 2017.
[30] F. Nicol, M. Humphreys, Derivation of the adaptive equations for thermal comfort in free-running buildings in European standard EN15251, Build. Environ. 45 (1) (2010) 11–17.
[31] S. Carlucci, L. Pagliano, A review of indices for the long-term evaluation of the general thermal comfort conditions in buildings, Energy Build. 53 (2012) 194–205.
[32] Plate-forme Maison Passive, Les critères du passif, 2018. https://www.maisonpassive.be/?Les-criteres-du-passif.
[33] Passive House Institute, Criteria for the Passive House, EnerPHit and PHI Low Energy Building Standard, 2016.
[34] CIBSE, Guide A - Environmental design, 2006.
[35] Passive House Institute, Passive House Planning Package, 9, 2015.
[36] P.O. Fanger, Thermal Comfort, Robert E. Krieger Publishing Company, Malabar, FL, USA, 1982.
[37] T. Cheung, S. Schiavon, T. Parkinson, P. Li, G. Brager, Analysis of the accuracy on PMV – PPD model using the ASHRAE global thermal comfort database II, Build. Environ. 153 (2019) 205–217.

[38] R. de Dear, G.S. Brager, Developing an adaptive model of thermal comfort and preference, in: A. Transactions (Ed.), ASHRAE Winter Meeting., San Francisco, CA, USA, 1998.
[39] R. de Dear, J. Xiong, J. Kim, B. Cao, A review of adaptive thermal comfort research since 1998, Energy Build. 214 (2020).
[40] N.A. Oseland, Predicted and reported thermal sensation in climate chambers, offices and homes, Energy Build. 23 (2) (1995) 105–115.
[41] R. de Dear, J. Kim, T. Parkinson, Residential adaptive comfort in a humid subtropical climate—sydney Australia, Energy Build. 158 (2018) 1296–1305.
[42] CIBSE, Guide A - Environmental design, 2015.
[43] B.W. Olesen, The philosophy behind EN15251: indoor environmental criteria for design and calculation of energy performance of buildings, Energy Build. 39 (7) (2007) 740–749.
[44] T.M.59 Cibse, Design Methodology for the Assessment of Overheating Risk in Homes, 2017.
[45] L. Peeters, R. de Dear, J. Hensen, W. D'haeseleer, Thermal comfort in residential buildings: comfort values and scales for building energy simulation, Appl. Energy 86 (5) (2009) 772–780.
[46] M. Humphreys, The influence of season and ambient temperature on human clothing behaviour, in: P.O. Fanger, O. Valbjorn (Eds.), Indoor Climate (Copenhagen: Danish Building Research), 1979.
[47] L. Pomfret, A. Hashemi, Thermal comfort in zero energy buildings, Energy Procedia 134 (2017) 825–834.
[48] S. Yannas, J. Rodríguez-Álvarez, Domestic overheating in a temperate climate: feedback from london residential schemes, Sustainable Cities and Society 59 (2020).
[49] J.C. Gamero-Salinas, A. Monge-Barrio, A. Sánchez-Ostiz, Overheating risk assessment of different dwellings during the hottest season of a warm tropical climate, Build. Environ. 171 (2020).
[50] B. Ozarisoy, H. Elsharkawy, Assessing overheating risk and thermal comfort in state-of-the-art prototype houses that combat exacerbated climate change in UK, Energy Build. 187 (2019) 201–217.
[51] V. Tink, S. Porritt, D. Allinson, D. Loveday, Measuring and mitigating overheating risk in solid wall dwellings retrofitted with internal wall insulation, Build. Environ. 141 (2018) 247–261.
[52] J. Mlakar, J. Štrancar, Overheating in residential passive house: solution strategies revealed and confirmed through data analysis and simulations, Energy Build. 43 (6) (2011) 1443–1451.
[53] ASHRAE, ANSI/ASHRAE Standard 55-2017, Thermal Environmental Conditions for Human Occupancy, 2017.
[54] T. Bedford, The warmth factor in comfort at work. A physiological study of heating and ventilation, Industrial Health Research Board Report Medical Research Council 76 (1936).
[55] N.V. Smirnov, Table for estimating the goodness of fit of empirical distributions, Ann. Math. Stat. 19 (2) (1948) 279–281.
[56] A. Field, Discovering Statistics Using SPSS, 2013.
[57] C. Spearman, Correlation calculated with faulty data, Br. J. Psychol. 3 (1910) 271–295.
[58] A.R. Jonckheere, A distribution-free k-sample test against ordered alternatives, Biometrika 41 (1/2) (1954).
[59] T.J. Terpstra, The asymptotic normality and consistency of kendall's test against trend, when ties are present in one ranking, Indagat. Math. 14 (3) (1952) 327–333.
[60] R. Rosenthal, Meta-Analytic Procedures for Social Research, second ed., Sage, Newbury Park,CA, 1991.
[61] J. Cohen, Quantitative methods in psychology : a power primer, Psychol. Bull. 112 (1) (1992) 155–159.
[62] M. Berge, H.M. Mathisen, Perceived and measured indoor climate conditions in high-performance residential buildings, Energy Build. 127 (2016) 1057–1073.