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► To cite this version:

María José Rueda López, Bassam Moujalled, Gaëlle Guyot, Benjamin Golly, Michel Ondarts, et al.. Analysis and comparison of thermal comfort indicators based on a long-term campaign in low energy residences. *Journal of Building Engineering*, 2023, 65, pp.105707. 10.1016/j.job.2022.105707 . hal-04409771

HAL Id: hal-04409771

<https://hal.science/hal-04409771v1>

Submitted on 10 Feb 2025

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Analysis and comparison of thermal comfort indicators based on a long-term campaign in low energy residences

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Abstract

There is a large number of thermal comfort indicators in the literature. However, their description is generally ambiguous since there is no single and clear way to calculate them. This article evaluates thermal comfort using steady state and adaptive approaches according to 9 temperature-based indicators, 8 RH-based indicators and 1 proposed temperature-RH-based indicator. All of them are calculated using 3-4 years of measurements in the living room and the parental bedroom of 3 new and occupied nearly-zero energy houses in France, with and without occupancy scenario, during 3 seasons (winter, summer and interseason). All the measurements come from low-cost probes sampling every minute, except the outdoor temperature of one house, which comes from the nearest meteorological station. The threshold values selected correspond to current standards and the occupancy scenario is based on the habits of the inhabitants of these specific houses. Results show that the difference between the data distribution using 1-hour and 10-minutes as time steps for the same season and year is 0-1% in the three houses. This suggests that 1-hour time step is enough for the calculation of temperature-based and RH-based comfort indicators in low energy houses, even using low-cost sensors. All indicators tested are sensitive to the occupancy scenario and season. The absence of an occupancy scenario in the calculation of the “degree-hour” using the EN 16798 lower limits leads to an overestimation of up to 93 % in these houses. In the case of the “percentage of time outside the RH range [25 % ; 60 %]”, the difference range between results with and without scenario is [-57 % ; 52 %] depending on the house and season considered.

Keywords

Comfort indicators, temperature, relative humidity, nearly zero energy houses

1. Introduction

The perception of comfort is quite variable from one individual to another (Mishra and Ramgopal 2013). However, regardless of individual characteristics, people tend to rate thermal conditions as the most

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important factor in achieving comfort, with greater importance than visual, acoustic and air quality factors (Frontczak and Wargocki 2011).

Thermal comfort is defined as “that condition of mind that expresses satisfaction with the thermal environment” (ANSI/ASHRAE 2017; NF EN ISO 7730 2006, 77). Interest in human thermal comfort in built and occupied spaces has increased exponentially in recent years and consequently also the number of comfort indicators or indices that attempt to characterize it (Rupp, Vásquez, and Lamberts 2015; Carlucci and Pagliano 2012; Carlucci 2013). Rupp et al. reviewed 466 articles published in the last years that examine the various sub-areas of research related to this topic (Rupp, Vásquez, and Lamberts 2015). Similarly, Carlucci and Pagliano found more than seventy comfort indicators proposed over time between 1905 and 2010, most of them were published after 1970 (Carlucci and Pagliano 2012). Moreover, the number of studies related to the measurement of thermal comfort in real and occupied buildings is increasing (Gauthier et al. 2020; Li et al. 2020; Jowkar, Dear, and Brusey 2020; CEREMA and ADEME 2018).

According to the MacPherson classification (Macpherson 1962), thermal environment indicators could be grouped in three categories: 1) indicators based on the calculation of heat exchange between the body and its environment, 2) indicators based on physiological strain, and 3) indicators based on the measurement of physical parameters (no measure of the physiological effect produced on individuals is provided). Although it is well known that the results obtained with the indicators of the first class tend to describe the thermal environment with greater precision (combination of the second and third classes), its calculation requires a great amount of information related to the thermal sensations of the occupants, which is not always available. Two examples of this first class of indicators are the Predicted Mean Vote (PMV) and the Percentage People Dissatisfied (PPD) developed by Fanger (Fanger 1970; NF EN ISO 7730 2006), which takes into account metabolic rate, clothing insulation, air temperature, mean radiant temperature, air velocity and air humidity. Dynamic models, such as the Fiala model, predict human thermal responses based on local variations of surface convection, directional radiation exchange, evaporation and moisture collection at the skin, and clothing (Fiala, Lomas, and Stohrer 1999). The literature review of Yao et al. (Yao et al. 2022) provides an overview of seven adaptive heat balance models.

We seek to evaluate thermal comfort in Nearly Zero Energy Houses (NZEH) occupied by families over a long period of time (long-term thermal comfort monitoring). Thus, for this study, we focus on indicators that can be calculated from physical parameters that can be easily measured in situ and continuously in buildings occupied over a long period. Even if indicators based on the heat balance of the human body (e.g. PMV/PPD or Fiala model) are more complete, they are not suited in our case, because they require the measurement of certain parameters (air velocity, clothing and metabolism of the occupants) which are difficult to obtain continuously over a long period. It is important to explicit the kind of building and occupation because the expected level of thermal comfort varies according to the building typology (office, classroom, house, etc.) (Dear et al. 2020). The definition of the term “Nearly Zero Energy Building (NZEB)”, which encompasses the NZEHs, varies from one author to another (Wang et al. 2021). This study considers a NZEB as a building that has a very high energy performance (European Union 2010).

The database used in this study comes from the COMEPOS project² (INES 2021). During this project, a long-term measurement campaign (between 3 and 4 years) was conducted in three real and occupied

² <https://www.ines-solaire.org/news/massifier-la-construction-de-maisons-a-energie-positive/>

NZEHs in France. The comfort evaluation was based on long-term measurements of air temperature and relative humidity (RH) made with low-cost sensors.

Nowadays, low-cost connected sensors are frequently used in buildings to measure indoor air temperature and RH but there is a lack of reliable methods to evaluate indoor thermal comfort based on these measurements. Indeed, there are numerous temperature-based and RH-based comfort indicators in the literature. However, their description is often ambiguous since not all of them have reference values, a concrete period, a time step, and a specific place and instrumentation rules for taking the measurements. Even rarer is finding indicators that considers the occupation period (occupancy scenarios). Some of these ambiguities have already been pointed by Khovalyg et al. (Khovalyg et al. 2020) in a critical review of the requirements for indoor thermal environment across international standards.

Concerning the measurement period, ASHRAE standard 55 (ANSI/ASHRAE 2017) specifies that they shall span two hours or more and represent a sample of the total occupied hours in the period selected for evaluation or shall take place during periods directly determined to be the critical hours of anticipated occupancy. In addition, this standard establishes that the measuring instrumentation shall meet a measurement range and an accuracy of [10 °C ; 40 °C] and ± 0.2 °C for air temperature and [25 % ; 95 %] and ± 5 % for RH.

Due to the differences in the calculation of the indicators (methods and threshold values) and in the way the parameters are measured (period, time step and instrumentation rules), it is extremely complicated to compare the results of different authors. The innovation of this study is to calculate each indicator from the same database corresponding to long-term measurements of air temperature and RH in real inhabited houses using low-cost sensors. The results are compared to show which indicators rank houses similarly and which are complementary. To achieve this goal, this paper focuses on:

- 1) Test the relevance of using 1 hour as a time step for the calculation of the comfort indicators using low-cost sensors.
- 2) Highlight the magnitude of the variation in the comfort indicators results with and without the use of an occupancy scenario.
- 3) Describe the difference between results of the comfort indicators calculated for different real and occupied NZEH.
- 4) Propose measures to standardize the calculation of the comfort indicators.

2. Materials and methods

2.1. Case studies: new and occupied nearly-zero energy houses

The measurements were conducted in three new and occupied NZEH located in the Alps and Paris regions in France during 3-4 years. Table 1 and Figure 1 present the characteristics and plans of the houses. The operation of the ventilation system of the houses is described in more detail by Rueda López et al. (Rueda López et al. 2021).

Table 1. Characteristics of the study houses and measurement periods. Adapted from (Rueda López et al. 2021).

	House 1	House 2	House 3
Climate zone *	Cold (H1c)	Cold (H1a)	
Location	Alps region	Paris region	
End of construction year	2016	2017	2017
Total area (m²)	123	106	147
Heat transfer coefficient (W/(m²·K))	$U_{\text{ext_wall}}$	0.20	0.16
	$U_{\text{crawlspace}}$	0.19	0.20
	U_{roof}	0.12	0.07
	U_{window}	1.40	1.40 - 2.01
Glazed windows	Double		
Solar protection	Wood and aluminum shutters		
Heating system	Radiant floor heating	Inertia radiators	
Cooling system	None	Air conditioner installed in summer 2019 at the request of a pregnant occupant	None
Inhabitants	2 adults and 1 child	2 adults and 1 child (2018) 2 adults and 2 children (2020)	2 adults and 3 children
Observations	Bedroom windows half-open at night	An adult is not present every day because of his work A child was born in 2020	An adult works at night outside the house
Measurement period	1 June 2017 – 31 May 2021	29 September 2017 – 16 June 2020	24 November 2017 – 3 December 2020

* Climate zone according to the French thermal standard RT2012 (Ministère de la transition écologique 2021). H1 corresponds to the coldest zone of France (northeast) composed by 3 regions (a, b and c).

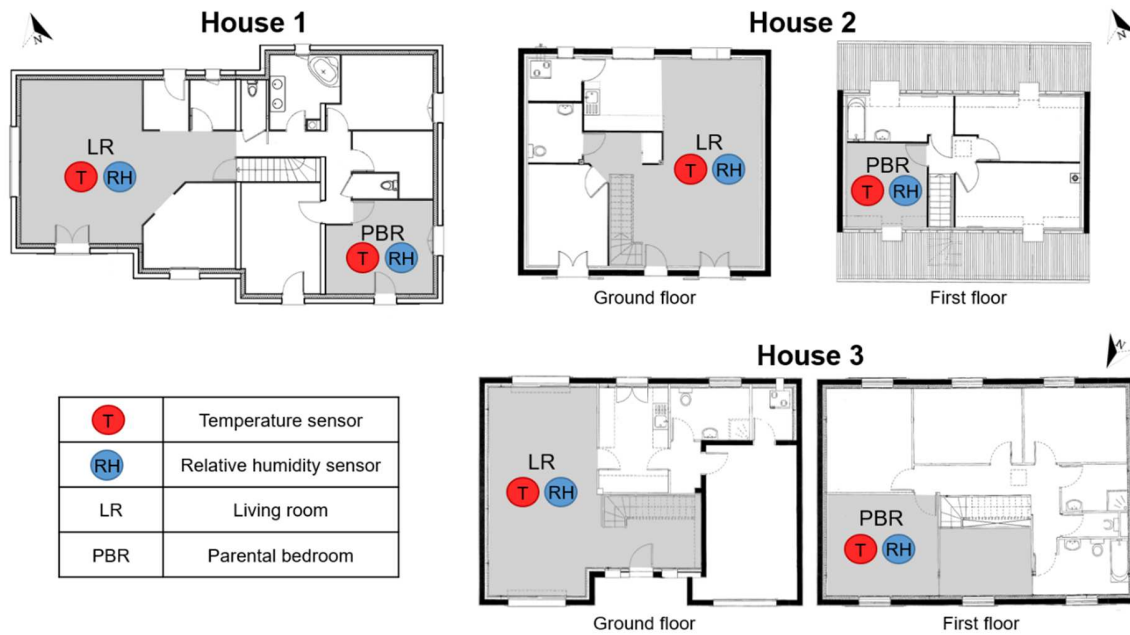


Figure 1. Plans of the study houses and sensor locations. Areas in gray corresponds to the monitored rooms. Adapted from (Rueda López et al. 2021).

The living room (LR) and parental bedroom (PBR) of the three houses are equipped with an E4000 probe (Nanosense n.d.) for the measurement of the temperature and the RH. The measuring range and accuracy of the probe are $[0\text{ }^{\circ}\text{C}; 50\text{ }^{\circ}\text{C}]$ and $\pm 0.3\text{ }^{\circ}\text{C}$ for the temperature sensor, and $[10\text{ }%; 90\text{ }%]$ and $\pm 3\text{ }%$ for the RH sensor (Rueda López et al. 2021).

The exterior temperatures analyzed in this paper comes from the nearest weather station: from a meteorological station located 17 km from House 1 and from an STE2000 probe (Delta Dore 2021) outside House 2 and House 3. The STE2000 probe has a measuring range of $[-20\text{ }^{\circ}\text{C}; 50\text{ }^{\circ}\text{C}]$. The time step of the on-site measurements (E4000 and STE2000 probes) is 1 minute and it is 1 hour for the off-site measurements (meteorological station near to House 1). The probes collect data and send data to a hub (aggregator) which sends a csv file every 24 hours.

2.2. Data quality validation

In order to remove parasitic measures that can affect the results, we treated the data according to the steps shown in Figure 2.

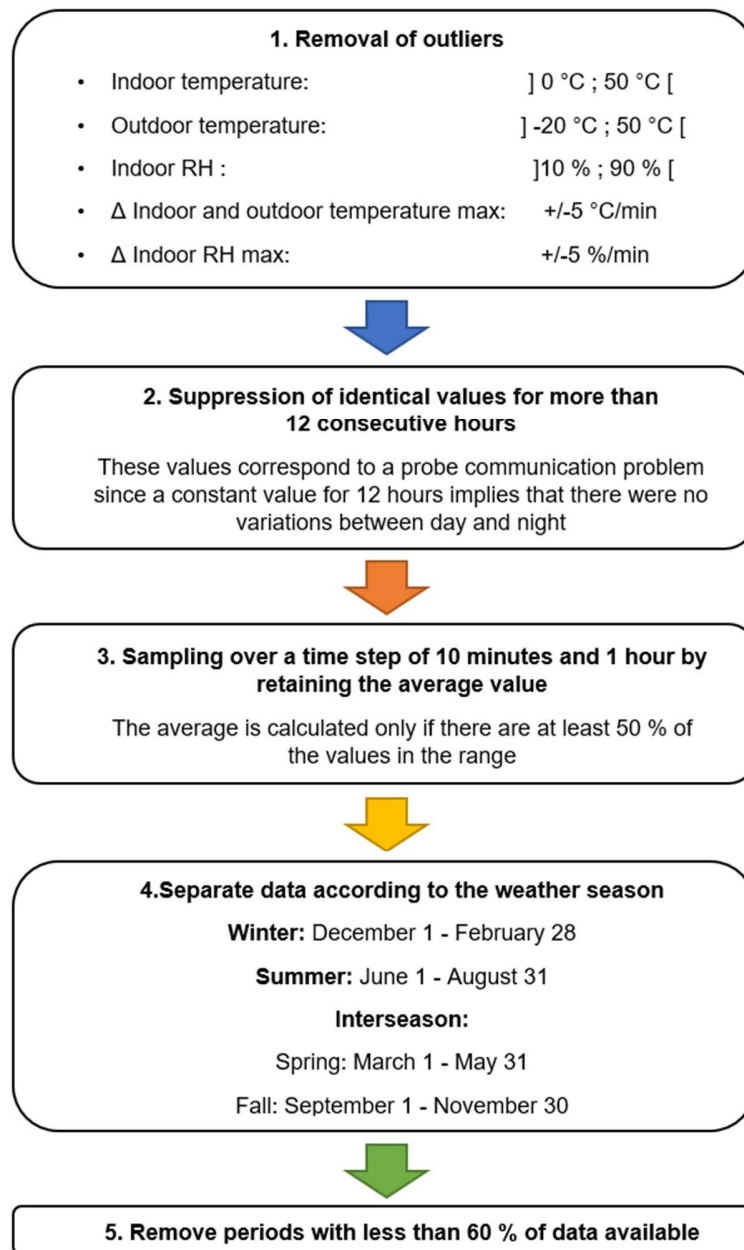


Figure 2. Treatment steps for temperature and RH measurements.

Since the calculation of RH requires the measurement of the temperature, the quantity of indoor temperature data and indoor RH data by season are equals. However, some steps to clean the data are specially adapted to the parameters (temperature or RH), thus the percentage of data available seldom differs between both parameters for a same season.

Figure 3 presents the percentage of data available per season for both parameters, which are in the range [62 % ; 100 %] in all houses in all seasons.

HOUSE	PARAMETER	ROOM	2017		2017-2018	2018			2018-2019	2019			2019-2020		2020		2020-2021	2021	
			SUMMER	FALL	WINTER	SPRING	SUMMER	FALL	WINTER	SPRING	SUMMER	FALL	WINTER	SPRING	SUMMER	FALL	WINTER	SPRING	
HOUSE 1	T	LR																	
		PBR																	
	HR	LR																	
		PBR																	
HOUSE 2	T	LR																	
		PBR																	
	HR	LR																	
		PBR																	
HOUSE 3	T	LR																	
		PBR																	
	HR	LR																	
		PBR																	

	NO DATA
	NO DATA - MALFUNCTION OF THE CAPTOR
	DATA AVAILABLE BY SEASON > 60 %
	DATA AVAILABLE BY SEASON < 60 % (DATA REMOVED)

Figure 3. Percentage of data available by house, parameter, room and season.

2.3. Comfort indicators calculation based on temperature and RH measurements

We present the indicators and threshold values considered in this study according to the parameter on which they are based: temperature (Table 2), RH (Table 3) or both.

Table 2. Temperature-based indicators.

Indicator	Units	Definition	Equation*	Reference
Maximum T_o in summer	°C	Max value of the summer data	---	(INES 2021)
Mean of T_a or T_o	°C	Mean value of the data	---	(Li et al. 2020)
Variance of T_a or T_o	°C ²	The variance measures the degree of dispersion of the data from their mean. The higher the variance, the more scattered the data. The variance is the square of the standard deviation (STD). Thus, the units of the variance are the same as those of the parameter but squared.	$Variance_T = \frac{\sum_{i=1}^n (T_{a,i} - \bar{T}_a)^2}{n-1} \text{ or } \frac{\sum_{i=1}^n (T_{o,i} - \bar{T}_o)^2}{n-1}$	Eq. 1 (Li et al. 2020)
Number of hours over 28 °C indoors in summer	---	Sum of hours that T_o exceed the thermal discomfort threshold of 28 °C. The thermal discomfort is acceptable under 50 hours (upper limit of the comfort zone), permanent above 200 hours, and very marked above 500 hours (CEREMA and ADEME 2018). The 28 °C threshold was calculated according to the EN15251 norm (NF EN 15251 2007) for another COMEPOS house in the H1a climate zone, near to House 2 and House 3 (Gondian 2019).	$Hours_{T>28^\circ C} = \sum (t_{T_o>28^\circ C})$	Eq. 2 (CEREMA and ADEME 2018; INES 2021)
Discomfort volume above 28 °C in summer	°C.h	Sum of the quantity of degrees that exceeds the limit of 28 °C multiplied by the time corresponding to this event.	$DV_{T>28^\circ C} = \sum (T_{T_o>28^\circ C}(t) - 28^\circ C) \cdot t$	Eq. 3 (CEREMA and ADEME 2018; INES 2021)
Percentage of time outside a T_o range	%	Percentage of time in which the thermal requirements corresponding to the interior temperature are not met.	$\%TOTR = \frac{\text{number of hours } T_o \text{ outside range}}{\text{total number of hours}} \cdot 100$	Eq. 4 (NF EN 16798-2 2014; Li et al. 2020)
Daily range outlier	%	Number of days that T_a or T_o daily range (maximum temperature – minimum temperature) exceeded a threshold, divided by the total number of days, and expressed in percentage. A 2 °C threshold was proposed by Li et al. (Li et al. 2020) based in a study of long-term thermal comfort indices in air-conditioned office buildings. The temperature limits of standards are not required in the calculation.	$DRO = \frac{\text{number of days } T_a \text{ or } T_o \text{ daily range } > 2^\circ C}{\text{total number of days}} \cdot 100$	Eq. 5 (Li et al. 2020)
Combined index	%	This index includes the amount of time that T_a or T_o is outside a range, and the daily variance in temperature exceeding 2 °C. Both components have the same weight in the equation and the result is given on a scale from 1 to 100.	$CIndex = \left(\frac{\text{number of hours } T_a \text{ or } T_o \text{ outside range}}{\text{total number of hours}} + \frac{\text{number of days } T_a \text{ or } T_o \text{ daily range } > 2^\circ C}{\text{total number of days}} \right) \cdot \frac{100}{2}$	Eq. 6 (Li et al. 2020)
Degree-hour	°C.h	Product sum of the weighting factors, in function of T_o , T_o limit and T_o optimal, and the exposure time. The weighting factor calculation varies depending on the standard concerned: ISO 7730 (Eq. 8) or EN 16798 (Eq. 9). For individual houses, the RE2020 indicates that under 350 °C.h comfort is assured, from 1250 °C.h the discomfort is excessive, and between the two values discomfort is likely (compliance with the requirement but fixed penalty).	$DH = \sum wf \cdot t$	Eq. 7 (Li et al. 2020; NF EN 16798-2 2014; NF EN ISO 7730 2006; Journal Officiel de la République Française 2021; Cabassud and Guldner 2021)
			$wf_{ISO} = 1 + \frac{ T_o - T_o \text{ limit} }{ T_o \text{ optimal} - T_o \text{ limit} } \text{ if } T_o \geq T_o \text{ limit upper or } T_o \leq T_o \text{ limit lower}$	Eq. 8
			$wf_{EN} = T_o - T_o \text{ limit} \text{ if } T_o \geq T_o \text{ limit upper or } T_o \leq T_o \text{ limit lower}$	Eq. 9

* n: total number of hours ; T_a : air temperature ; T_o : operative temperature ; \bar{T}_a and \bar{T}_o : sample mean temperatures

ASHRAE specifies that the operative temperature (T_o) could be calculated as the mean value of the air temperature (T_a) and the mean radiant temperature (\bar{T}_r) when the air speed is small (<0.2 m/s) (ANSI/ASHRAE 2017), which is the case of the study houses. Nevertheless, the database of the COMEPOS project only provide T_a values, no \bar{T}_r measures have been taken so there is no information about the T_o in these houses. This situation does not necessarily imply that we should put aside the comfort T_o -based indicators such as the degree-hour or the discomfort volume. In fact, further research made with 48 office buildings of the ASHRAE Global Thermal Comfort Database conclude that the measurement of T_a is sufficient to estimate \bar{T}_r under typical office conditions, the median absolute difference between T_a and \bar{T}_r was 0.4 °C (Dawe et al. 2020). A similar comparison study made in four rooms of a building in Berlin using integral radiation measurements and three types of globe thermometers shows that the difference between T_a and \bar{T}_r is negligible under moderate outdoor conditions (Walikewitz et al. 2015). In addition, a study comparing the results of comfort indicators using both T_a and T_o measurements from air-conditioned office buildings in Sydney find that half of the indicators better predict long-term satisfaction with T_a than with T_o , the difference between T_a and T_o was smaller than 0.5 °C for most rooms (Li et al. 2020). These studies reinforce the simplification that T_o is similar to T_a under indoor conditions, especially when there are not \bar{T}_r measures. Moreover, the fact that the houses are well insulated means that it is unlikely to have problems with cold or hot walls.

Table 3. RH-based indicators.

Indicator	Units	Definition	Reference
Maximum duration above a certain limit	h	---	(NF EN 15665 2009)
Maximum duration below a certain limit	h	---	(NF EN 15665 2009)
Number of hours above a certain limit	---	Number of hours with RH > 40 % in bedrooms and with RH > 45 % in other rooms.	(NF EN 15665 2009; Nielsen and Ambrose 1995)
		Number of hours with RH > 75 %. Maximum threshold of 600 hours in the kitchen, 1000 hours in the bathroom and 100 hours in the other rooms during the heating season.	(NF EN 15665 2009; CCFAT 2015)
Number of hours below a certain limit	---	Number of hours with RH < 30 %. Maximum threshold of 800 hours during the heating season (Mansson 2001).	(NF EN 15665 2009; Mansson 2001)
Number of times the level has been above a certain limit for more than a certain period	---	---	(NF EN 15665 2009)
Number of times the level has been below a certain limit for more than a certain period	---	---	(NF EN 15665 2009)
Percentage of time outside a RH range	%	Percentage of time with RH > 70 % to identify risk of condensation.	(Guyot 2018)
		Percentage of time with RH]30 % ; 70 %[.	(Van Den Bossche et al. 2007)

2.4. New indicators

Inspired by the “degree-hour”, we propose to test a new indicator to identify periods of discomfort based on RH measurements: the “percentage RH-hour”. This indicator is calculated according to Equations 10 and 11, and as its name announces, its units are %·h.

$$\% RH - hour = \sum wf \cdot t \quad (Eq. 10)$$

$$wf = |RH - RH_{limit}| \text{ if } RH \geq RH_{upper\ limit} \text{ or } RH \leq RH_{lower\ limit} \quad (Eq. 11)$$

Since the T_o and RH parameters are tightly intertwined, it seems logical to connect them in one comfort indicator. However, we have found none indicator of this type for indoor environments in the literature. Indeed, the “discomfort index” or “temperature–humidity index (THI)” proposed by Thom E.C. links both parameters (Thom 1959; Encyclopedia Britannica 1998), but it was created for outdoor environments (the same person's expectations of comfort are not the same inside as outside). Therefore, we propose an indoor temperature-RH-based indicator: the percentage of time when T_o and RH are simultaneously in the ranges of values recommended by the standards. That is, merging the “percentage of time outside a T_o range” indicator with the “percentage of time outside a RH range” indicator.

2.5. Threshold values

Table 4 summarizes the T_o and RH recommendations of ANSES (ANSES 2016), ASHRAE (ANSI/ASHRAE 2017), EN 16798 (NF EN 16798-1 2019) and ISO 7730 (NF EN ISO 7730 2006). It is important to notice that the four standards are correlated with the comfort measurement but they have its own purpose:

- ANSES recommends ranges of T_o and RH (Table 4), to prevent the development of fungal contamination in buildings.
- ASHRAE proposes thermal environmental conditions for human occupancy based on a steady state approach (3 methods) and in an adaptive approach for naturally conditioned spaces during summer (1 method). T_o ranges from the first approach varies according to parameters such as the air velocity, humidity ratio and occupants’ metabolic rate and clotting insulation. T_o ranges defined by equations 12 and 13 corresponds to the adaptive approach and allows acceptable thermal environments (80 % of acceptability) in only occupant-controlled naturally conditioned spaces. There are no RH limits established by this standard, only humidity ratio under specific conditions.
- EN 16798 recommends T_o ranges for residential buildings energy calculations. T_o -winter ranges are acceptable for buildings equipped with or without mechanical cooling systems. However, T_o -summer ranges are acceptable only in buildings with cooling systems. Equations 14-21 allow the calculation of T_o ranges for buildings without cooling systems during summer and interseason. RH ranges are suggested design criteria for spaces where humidity is determined by human occupancy. There are four classes to rank the level of expectation: I for high, II for normal, III for acceptable or moderate and IV for low.
- ISO 7730 aims to determinate and interpret thermal comfort using PMV and PPD indices. T_o ranges correspond to example design criteria to guarantee the comfort in buildings where occupants’ metabolic activity is 70 W/m^2 (sedentary activity) and assuming a clotting insulation of 0.5 clo during summer and 1.0 clo during winter. There are three classes to describe the thermal

environment: A for high, B for normal and C for acceptable. This standard does not propose RH ranges, arguing that at moderate temperatures (< 26 °C) and moderate activity levels (< 2 met), the influence of RH on body thermal comfort is limited.

Table 4. Operative temperatures (T_o) and relative humidity (RH) for residential buildings recommend by ANSES, ASHRAE, EN 16798 and ISO 7730.

Standard	Winter T_o		Summer T_o		RH
	With mechanical cooling system	Without mechanical cooling system	With mechanical cooling system	Without mechanical cooling system	With or without mechanical cooling system
ANSES	[18 °C ; 22 °C]		[18 ; 22 °C]		[40 % ; 60 %]
ASHRAE *	---	Eq. 12-13	---	Eq. 12-13	---
EN 16798 class I	[21 °C ; 25 °C]		[23.5 °C ; 25.5 °C]	Eq. 14,15,20,21	[30 % ; 50 %]
EN 16798 class II	[20 °C ; 25 °C]		[23 °C ; 26 °C]	Eq. 16,17,20,21	[25 % ; 60 %]
EN 16798 class III	[18 °C ; 25 °C]		[22 °C ; 27 °C]	Eq. 18-21	[20 % ; 70 %]
EN 16798 class IV	[17 °C ; 25 °C]		[21 °C ; 28 °C]	---	---
ISO 7730 class A	[21 °C ; 23 °C] $T_o \text{ optimal} = 22 \text{ °C}$		[23.5 °C ; 25.5 °C] $T_o \text{ optimal} = 24.5 \text{ °C}$	---	---
ISO 7730 class B	[20 °C ; 24 °C] $T_o \text{ optimal} = 22 \text{ °C}$		[23 °C ; 26 °C] $T_o \text{ optimal} = 24.5 \text{ °C}$	---	
ISO 7730 class C	[19 °C ; 25 °C] $T_o \text{ optimal} = 22 \text{ °C}$		[22 °C ; 27 °C] $T_o \text{ optimal} = 24.5 \text{ °C}$	---	

* Refer to ASHRAE standard 55 methods (ANSI/ASHRAE 2017) to calculate thermal comfort requirements in all occupied spaces by a steady state approach.

$$T_o \text{ ASHRAE upper limit} = 0.31\overline{T_{pma(out)}} + 21.3 \quad (\text{Eq. 12})$$

$$T_o \text{ ASHRAE lower limit} = 0.31\overline{T_{pma(out)}} + 14.3 \quad (\text{Eq. 13})$$

$$T_o \text{ EN upper limit class I} = 0.33T_{rm \text{ EN}} + 18.8 + 2 \quad (\text{Eq. 14})$$

$$T_o \text{ EN lower limit class I} = 0.33T_{rm \text{ EN}} + 18.8 - 3 \quad (\text{Eq. 15})$$

$$T_o \text{ EN upper limit class II} = 0.33T_{rm \text{ EN}} + 18.8 + 3 \quad (\text{Eq. 16})$$

$$T_o \text{ EN lower limit class II} = 0.33T_{rm \text{ EN}} + 18.8 - 4 \quad (\text{Eq. 17})$$

$$T_o \text{ EN upper limit class III} = 0.33T_{rm \text{ EN}} + 18.8 + 4 \quad (\text{Eq. 18})$$

$$T_o \text{ EN lower limit class III} = 0.33T_{rm \text{ EN}} + 18.8 - 5 \quad (\text{Eq. 19})$$

$$T_o \text{ EN optimal} = 0.33T_{rm \text{ EN}} + 18.8 \quad (\text{Eq. 20})$$

$$T_{rm \text{ EN}} = 0.2(T_{d-1} + 0.8T_{d-2} + 0.64T_{d-3}) \quad (\text{Eq. 21})$$

T_{d-1} : Daily mean outdoor air temperature for the previous day (°C)

T_{d-i} : Daily mean outdoor air temperature for the i – th previous day (°C)

$\overline{T_{pma(out)}}$: Prevailing mean outdoor air temperature (°C), calculated as the arithmetic mean of 7 to 30 sequential mean daily outdoor air temperatures prior to the considered day

T_{rm} : Outdoor running mean temperature for the considered day (°C)

For the temperature-based indicators that do not have specific thresholds established such as the “combined index” or the “degree-hour” (T_o thresholds and ranges required), we propose to use the values from the ISO 7730 class B and EN 16798 class II, corresponding to a normal thermal environment expected in new buildings. In fact, ISO 7730 class B and EN 16798 class II are equivalents since the second refers to the thermal comfort indices PMV and PPD of the first. We consider that the 1 °C difference between the two classes ranges in winter is due to a transcription error, that is why we only used the ISO 7730 class B range in winter in this study. For summer and interseason, only EN 16798 proposes a temperature range for places without mechanical cooling system (adaptive approach), thus we only refer to this norm. For the RH-based indicators from EN15665 (RH thresholds required), we propose to use the values from EN 16798 class II (no RH values recommended for the ISO 7730 classes) and to keep 70 % of RH as a reference value to identify risk of condensation.

As shown in Table 1, House 2 is the only house of the set with a mechanical cooling system. This system was installed in summer 2019 at the request of the pregnant occupant who complained of thermal discomfort during the summer. Indeed, summer 2019 in France had two heat waves of 6 days each according to the official service of meteorology and climatology in France (Météo-France 2020). That means that the reference values of this specific house change from summer 2019: adaptive comfort approach before 2019 and steady state approach after.

EN 16798-2 (NF EN 16798-2 2014) recommends 3-6 % of occupied hours outside the limits of the class as an acceptable deviation. That means that a building meets the criteria of a specific class if the measured parameter, which represents 95 % of the occupied space, do not exceed this percentage. Agreeing with this recommendation, the present study considers 6 % of occupied time outside the limits of the class as the maximal acceptable deviation.

2.6. Occupancy scenarios

One of the objectives of the comfort indicators in dwellings is to reflect the feeling of the inhabitants. Since the inhabitants of a house usually settle in different rooms during the day according to their activities (e.g. living-room during the day and bedroom at night), it is important to consider an occupancy scenario in the calculation of comfort indicators. That means, focus in certain rooms during specific hours to avoid the underestimation or overestimation of the indicators. A recent study carried out in the three houses on CO₂-based indoor air quality indicators (Rueda López et al. 2021) proposes an occupancy scenario representative of the inhabitants’ habits (Table 5). All the indicators presented before have been calculated using this scenario and another one including all hours.

Table 5 Occupancy scenarios for the calculation of temperature-based and RH-based indicators. Weekdays and weekend included. Adapted from (Rueda López et al. 2021).

No scenario	Scenario
All hours included	Living room: 07h00 to 08h30 12h00 to 14h00 19h00 to 21h00 Bedroom: 21h00 to 06h20

2.7. Analysis method of comfort indicators

Since the indicators listed before are not all linked to each other and have different limit values to be compared, it is necessary to analyze them separately. The method to analyze the results consist in:

1. Evaluate the impact of the time step by analyzing the distribution (boxplots) of the measurements taken every 10 minutes and every hour. If the distribution with both time steps is similar, we continue the study exclusively with the results at the time step of 1 hour.
2. Group the indicators into families according to how they are calculated.
3. Group the indicators results by house and by season, then calculate the average of the results obtained of each indicator in the LR and the PBR and obtain the confidence interval. This allows simplifying the analysis and at the same time represent the results of the seasons during the 3-4 years of measurement.
4. Calculate the difference range between results with and without occupancy scenario, taking the results without scenario as a reference.
5. Compare the results with the limit values if they are available.
6. Characterize the comfort level of the houses (acceptable or not).
7. Compare the results of the indicators of the three houses during the same season to identify if they rank the houses in the same way. That is, normalize the results of each house with respect to the maximum and minimum values recorded during the season and plot them on a radar.
8. Make recommendations on the comfort indicators if possible.

In order to compare the results of the different indicators with each other, and thus identify if the indicators rank the houses in the same way, we normalize the mean values of each indicator. Only the results obtained with the use of an occupation scenario are included in this stage of the study since these tend to better describe the conditions to which the inhabitants are exposed. The normalization is made with respect to the maximum and minimum mean values recorded during the season (winter or summer) in the three houses (Eq. 22). This means that all normalized values are in the range [0 ; 1], with 0 being the most comfortable and 1 being the least comfortable.

$$x_{norm} = \frac{x - x_{min}}{x_{max} - x_{min}} \quad (Eq. 22)$$

Summing up, this article evaluates thermal comfort according to 9 temperature-based indicators, 8 RH-based indicators and 1 temperature-RH-based indicator. All of them evaluated in 3 new and occupied NZEHs, with and without occupancy scenario, during 3 seasons (winter, summer and interseason) using 3-4 years of measurements.

2.8. Study limitations

The following points highlight the limits of this study, which should be considered in the analysis of results:

- Parameters: As noted above, the assessment of thermal comfort based solely on air temperature and RH is less accurate than other indicators such as the PMV and PPD and the Fiala model.
- Threshold values: These values were selected based on current standards. However, they may not fully reflect the thermal needs of the inhabitants.

- Occupancy scenario: The proposed occupancy scenario is a simplification of the occupancy schedules of the three houses. In fact, this scenario is consistent with the occupancy schedules recorded in 567 dwellings between 2003 and 2005 according to the French Health Surveillance Institute (InVS) (Zeghnoun, Dor, and Grégoire 2010). However, families do not always respect these schedules, which leads to inaccuracy in the results of the indicators.
- Number of samples: This study is based on measurements taken in two rooms (living room and parental bedroom) of three houses during 3-4 years.
- Low-cost sensors: The percentage of available data per season, year and room is not the same in the three houses due to sensor failures.

3. Results

3.1. Data distribution and impact of the time step

Figure 4A presents the data distribution of the indoor air temperature and RH by season and by year in the LR and PBR of the three houses, and Figure 4B presents the outdoor temperature distribution of the three houses by season, both using 1-hour time step. The distribution was calculated using the boxplot function of the Seaborn Python library. The box horizontal sides are the first and third quartile (50 % of data is located in this range), the horizontal line inside the box is the median, the black point is the mean, and the length of whiskers is 1.5 times the interquartile difference.

Since the difference in the distribution using 1-hour and 10-minutes as time steps is small enough to be considered negligible, we only present the 1-hour time step results. The difference between mean values using both time steps for the same season and year is 0-1 % in the three houses, the same trend is observed for the first, second and third quartile. The difference between STD using both time steps is 0-2 % for the three houses, except for some occasions when it reaches up to 10 % in House 1 (the data of this house are less dispersed so small variations generate relatively high differences). In fact, 1-hour time step is commonly used to characterize hygrothermal conditions in low energy houses because the quality insulation materials of this kind of houses avoid large hygrothermal variations in a short time.

Despite the fact that the three houses were conceived with the same construction materials to be houses with low energy consumption, the distribution of indoor air temperature and RH varies considerably from one house to another during the same period of the year for the same room. For example, the first and third quartile of the temperatures registered in the LR during the winter are [21 °C ; 24 °C] in House 1, [20 °C ; 21 °C] in House 2, and [19 °C ; 22 °C] in House 3. This situation may be linked to the difference between the outside temperatures of the houses. Indeed, all of them are located in areas with similar climates (H1 corresponding to the coldest zone of France). However, the outdoor temperature distributions shown in Figure 4B are different in each house for the same season and year. There are even differences in outside temperature between House 2 and House 3, which are approximately 50 km away from each other.

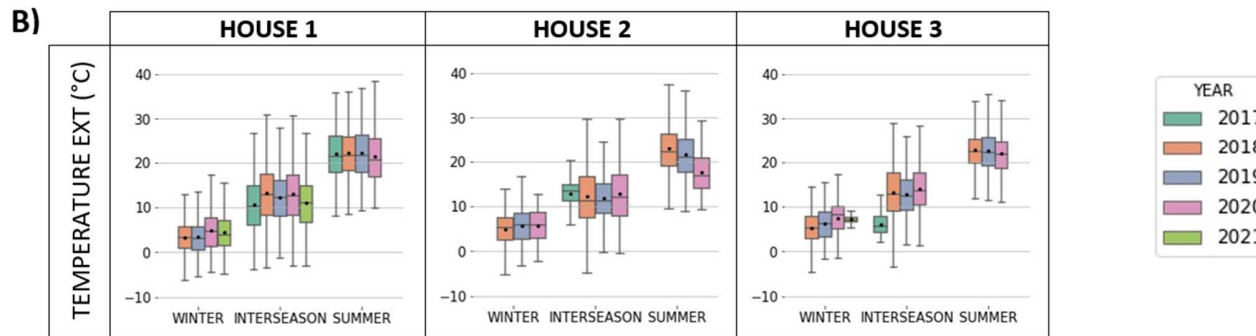
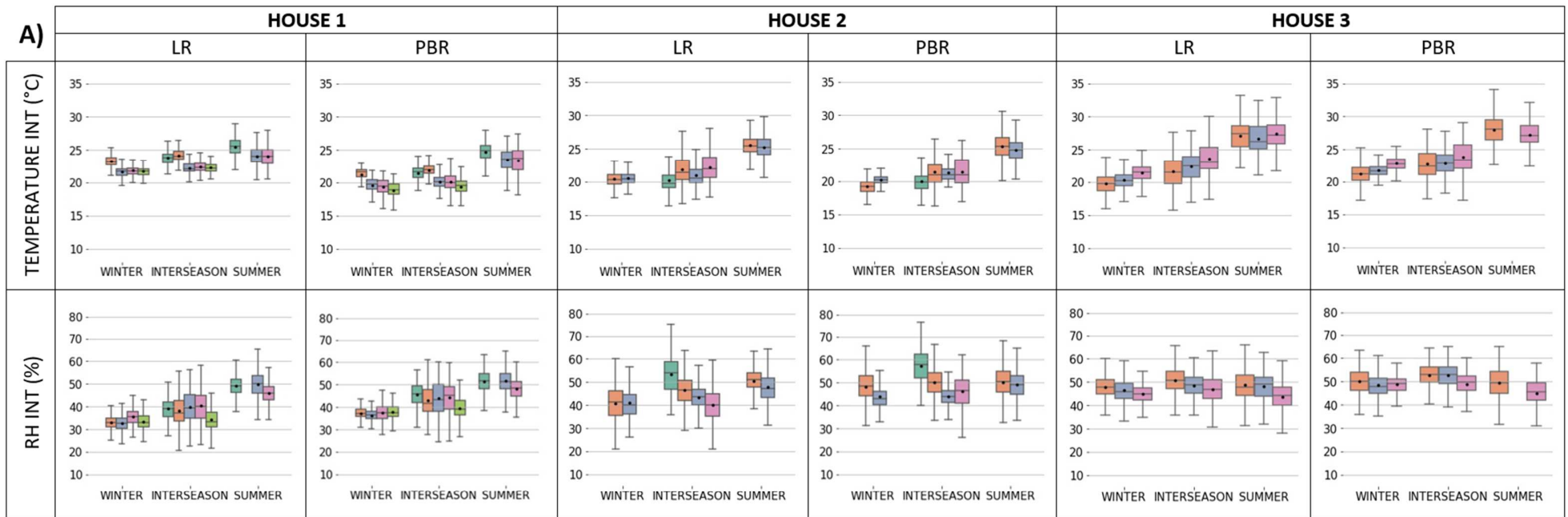


Figure 4. A) Indoor air temperature and RH distribution by season and by year in the LR (living room) and PBR (parental bedroom) of the three houses using 1-hour time step. B) Outdoor air temperature distribution by season and by year of the three houses using 1-hour time step. The mean values are represented as black points.

3.2. Indoor temperature-based indicators

We calculated the indicators per room (LR or PBR) per year and per season for each house. The results are presented in terms of the mean value of each indicator. The mean values of the considered indicators in the three houses by season, with and without occupancy scenario, can be consulted in the following appendices: temperature-based indicators at Table A1, RH-based indicators at Table A2, and the temperature-RH-based indicator at Table A3.

3.2.1. Maximum, mean and variance

Figure 5 presents the maximum, mean and variance of indoor temperature in the three houses, with and without an occupancy scenario. Each bar indicates the mean value of the indicators results during a season considering the temperature in the LRs and PBRs over 3-4 years of measurements. The black lines on the bars correspond to the 95 % confidence intervals. This means that all seasons are represented in the figure.

Regardless the season and the occupancy scenario, the maximum temperature and variance are lower in House 1 than in House 2 and House 3. However, the trend is not always the same with the mean. House 2 has a lower mean temperature in winter and interseason with and without occupancy scenario than House 1 and House 3 (0.2-1.4 °C fewer).

The maximal temperature in winter is near to the higher value of the comfort range (24 °C) in all houses. Regarding the mean temperature with and without occupancy scenario, the three houses are within the ISO 7730 class B winter comfort range ([20 °C ; 24 °C]). The figure does not allow to determine if the comfort ranges are respected during the summer and the interseason since the comfort range in these seasons varies from day to day (adaptive approach). The maximal variance in all houses in all seasons is inferior or near to 4 °C², it means a STD less than 2 °C, which is the same value found by Li et al. (Li et al. 2020) for air-conditioned office buildings.

To quantify the differences between scenarios, we show throughout the article the minimal and maximal differences between the averages of the three houses in a range [min ; max]. The difference range between results with and without occupancy scenario is [-6.2 % ; -0.1 %] for the maximum, [-0.7 % ; 1.5 %] for the mean and [-51.6 % ; 7.1 %] for the variance. Only in the case of the maximum temperature, the results without occupancy scenario are higher than those with occupancy scenario in all seasons. This can be explained for summer and interseason considering that people try to improve their home environment as soon as they get home by opening windows or turning on fans, which means that maximum temperature is usually reached when no one is present. In winter, the maximal temperature with and without occupancy scenario is extremely similar (less than 0.5 % of difference), probably because the heating is usually regulated regardless the occupancy.

The impact of the use of an occupancy scenario is low for the maximum and mean indicators since the differences between the results with and without occupancy scenario are less than ± 2 %, except for the maximal temperature in summer in House 2 where the difference is 6 %. In the case of the variance, the impact of the occupancy scenario differs from one house to another (e.g. the difference in variance between scenarios in winter is higher in House 1 than in the other houses) and between seasons (e.g. the difference in variance between scenarios in House 1 is higher in winter than in the other seasons).

The maximum, mean and variance in Houses 2 and 3 have a similar profile throughout the seasons since they are similar in location and construction technique. The variations, which are more clearly observed in

the variance profiles, can be explained by occupation habits that vary from one family to another. Hence the importance of taking occupancy into account in the characterization of thermal comfort.

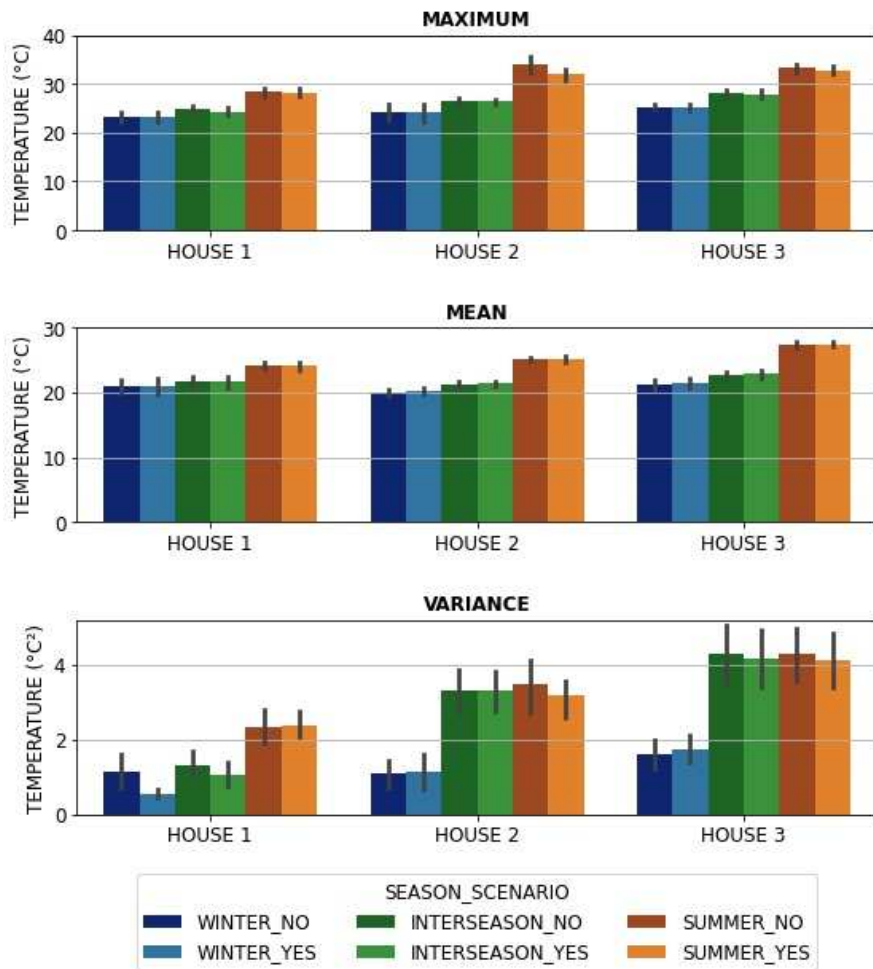


Figure 5. Maximum, mean and variance of the indoor temperature in the 3 houses (living rooms and parental bedrooms) during 3-4 years, with and without an occupancy scenario, with a 1-hour time step.

3.2.2. Number of hours and discomfort volume over 28 °C in summer

Figure 6 presents the number of hours over 28 °C and the discomfort volume over 28 °C in summer in the three houses. Both indicators are closely linked since the second requires the calculation of the first. We observe the same tendency of results in both indicators with and without occupancy scenario.

The use of an occupancy scenario strongly affects the number of hours over 28 °C and the discomfort volume over 28 °C. In fact, the results with occupancy scenario are [28 % ; 75 %] lower than those without occupancy scenario. Accepting that a temperature over 28 °C indicates thermal discomfort and it is acceptable under 50 hours, the thermal discomfort in House 1 is acceptable regardless the use of the occupancy scenario. However, the thermal discomfort in House 2 is only acceptable using the occupancy

scenario. In House 3, the thermal discomfort is permanent (over 200 hours) with the occupancy scenario, and very marked (over 500 hours) without the occupancy scenario. There are no thresholds to describe the results of the discomfort volume indicator.

Despite the similarities in the construction, climate zone and outdoor temperature distribution in summer (Figure 4B) of House 2 and House 3, the profile of both houses differs considerably in both indicators. Two explanations are: 1) the orientation and size of the windows and 2) the behavior of the occupants towards the use of solar protection and the opening of windows. In fact, the window in the parental bedroom of House 2 is facing south while the window in House 3 is facing north, which causes the solar heat to enter differently and the use of sun protection changes. Another explanation is the fact that an air conditioner was installed in House 2 in summer 2019, which implies that from that moment the inhabitants have greater control of the temperature inside their house. However, the confidence intervals reveal that the number of hours above 28 °C in the summer of 2018 was not that different from the summer of 2019 in House 2 (only two summer measurements in House 2).

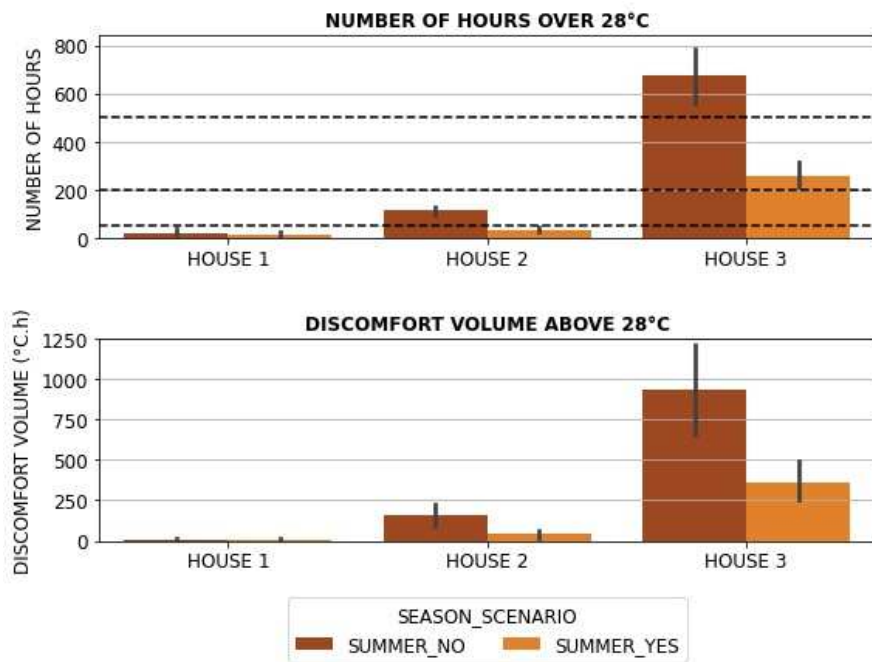


Figure 6. Number of hours and discomfort volume over 28°C in summer in the 3 houses (living rooms and parental bedrooms) during 3-4 years, with and without an occupancy scenario, with a 1-hour time step. Broken lines indicate discomfort thresholds: acceptable under 50 hours, permanent over 200 hours, and very marked over 500 hours.

3.2.3. Percentage of time outside a temperature-range

The percentage of time outside the temperature range in the three houses is presented in Figure 7. The temperature reference range is constant in winter ([20 °C ; 24 °C]) and adaptive in summer (it depends on the outdoor temperatures). Only summer 2019 in House 2 is compared to a constant reference range ([23 °C ; 26 °C]) due to the installation of the air conditioner.

All the bars, which represent the average of the results per season in the LR and PBR, show values much higher than the recommendation of maximum 6 % outside the range (NF EN 16798-2 2014), which means that the three houses are usually outside the ISO 7730 class B and EN 16798 class II. However, the confidence intervals show that there are some years in which the seasons respect the reference range, especially during the interseason in House 1 and House 2.

Concerning the occupancy scenario, the results with occupancy scenario are not necessarily lower than the results without one. In fact, the difference range between results with and without occupancy scenario is [-15 % ; 19 %] in winter, [-2 % ; 9 %] in interseason, and [-22 % ; -6 %] in summer. This indicates that the use of an occupancy scenario during the summer leads to obtain results closer to the comfort range, but this phenomenon is not always replicated in winter and interseason.

The percentages of discomfort time in winter are high for houses equipped with a heating system. However, there are no records indicating a failure of these systems or complaints from the inhabitants. One possible explanation is that the winter reference range does not reflect the thermal needs of the inhabitants. Another explanation is that the inhabitants turn on the heating in specific rooms only while they are occupied. In fact, the temperature of the three houses in winter is usually closer to the lower limit (20 °C) than to the upper limit (Figure 4). These factors make us rethink how well a standard scenario reflects real occupancy and emphasize the need to have information about the habits of the occupants.

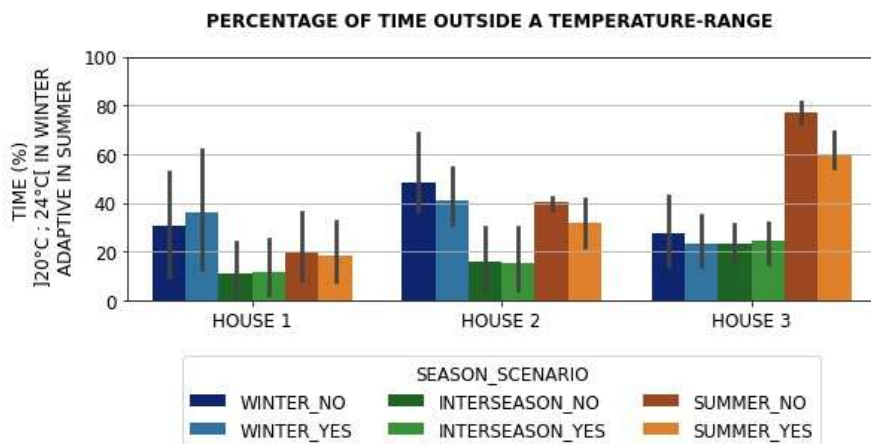


Figure 7. Percentage of time outside a temperature-range in the 3 houses (living rooms and parental bedrooms) during 3-4 years, with and without an occupancy scenario, with a 1-hour time step. Temperature-ranges are calculated with an adaptive approach in summer and interseason.

3.2.4. Daily range outlier (DRO)

The results using the DRO indicator in the three houses are presented in Figure 8. A high percentage implies that the daily temperature ranges exceed the threshold of 2 °C for a large part of the measurement period, and therefore implies a period of discomfort. Although the threshold of 2 °C was proposed for air-conditioned office buildings, it seems to be correct for NZEH without cooling system since the maximal STD founded in the three houses is near or less than 2 °C as seen in the “variance of temperature”

indicator. It is important to point out that this indicator does not provide enough information to qualify comfort, but its analysis is necessary to understand the results of the “combined index” indicator.

The results with occupancy scenario are [-69 % ; -27 %] lower than those without occupancy scenario. That means that the lack of use of an occupancy scenario leads to an overestimation of the period of discomfort. It also means that the 2 °C threshold is too restrictive if an occupancy scenario is not used.

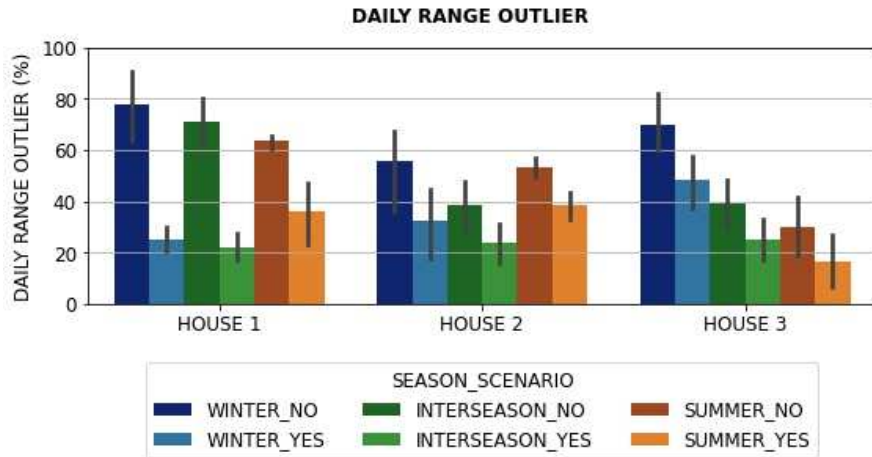


Figure 8. Daily range outlier in the 3 houses (living rooms and parental bedrooms) during 3-4 years, with and without an occupancy scenario, with a 1-hour time step.

3.2.5. Combined index

The combined index is based on two indicators: the “percentage of time outside a range” and the “DRO” (taking up a 2 °C threshold). The higher the percentage, the more uncomfortable is the room. Figure 9 presents the results of this indicator in the three houses.

All seasons in the three houses, with and without occupancy scenario, exceed the recommendation of a 6 % maximum deviation. The results with occupancy scenario are lower than the results without one. The difference range between results with and without occupancy scenario is [-43 % ; -25 %] in winter, [-59 % ; -21 %] in interseason, and [-34 % ; -24 %] in summer.

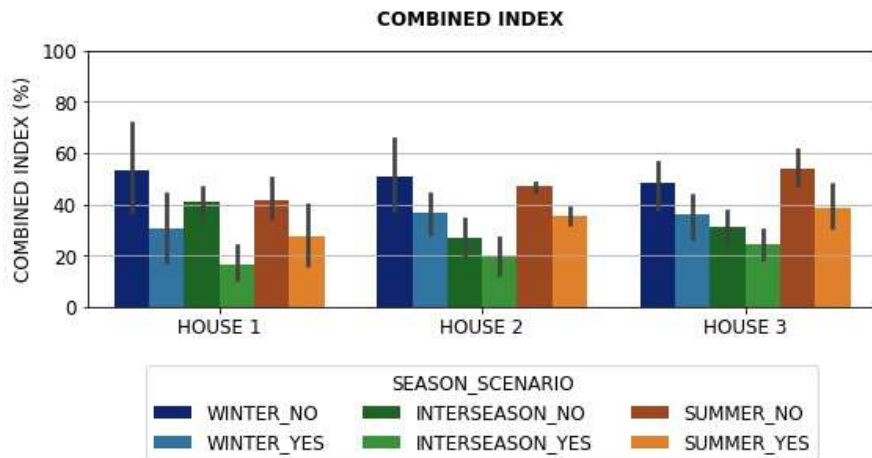


Figure 9. Combined index in the 3 houses (living rooms and parental bedrooms) during 3-4 years, with and without an occupancy scenario, with a 1-hour time step.

3.2.6. Degree-hour

As explained before, the calculation of the “degree-hour” is different depending on the standard and the limits chosen (lower or upper). In all cases, the higher the value, the more uncomfortable is the room. Figure 10 presents the average degree-hours over the different years using the lower and upper values from the EN 16798 standard.

Results with occupancy scenario are lower than those without one, except in summer in House 1 and House 3 where the result is zero with and without occupancy scenario using the lower limits. We observe a significant difference between results with and without occupancy scenario reaching up to -93 % with EN 16798 lower limits, and [-69 % ; -30 %] with upper EN 16798 limits.

Regarding the threshold of 350 °C.h, the winter results using the EN 16798 upper limits are well below the threshold in a range of [9 °C.h ; 44 °C.h] without occupancy scenario and in a range of [5 °C.h ; 31 °C.h] with occupancy scenario. Interseason values are higher than winter values in all houses but only exceed the threshold in House 3 without occupancy scenario (543 °C.h). In summer, the highest values are displayed, being House 3 the most resentful with values of up to 3.6 times the limit with occupancy scenario and up to 9.4 times the limit without occupancy scenario. The discomfort in summer in House 3 can be described as excessive since it exceeds 1250 °C.h.

Using the EN 16798 lower limits, we see that the profile of results is the inverse of the profile using the upper values: the highest values are displayed in winter and they decrease in interseason and summer. In addition, we observed larger ranges of confidence intervals using the lower limits. The threshold of 350 °C.h is exceeded in the three houses in winter without occupancy scenario (more than 2 times higher than the threshold in House 1 and House 2) but it is not exceeded in any house using an occupancy scenario.

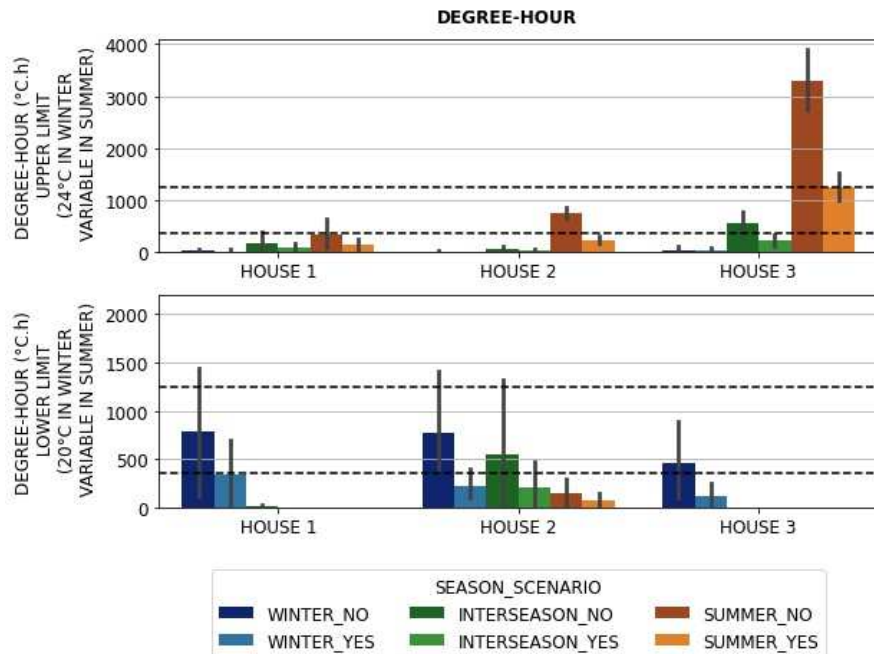


Figure 10. Degree-hour in the 3 houses (living rooms and parental bedrooms) during 3-4 years, with and without an occupancy scenario, with a 1-hour time step. Temperature-ranges are calculated with an adaptive approach in summer and interseason. Broken lines indicate discomfort thresholds: acceptable below 350°C.h and excessive above 1250°C.h.

This is a good example of how the choice of reference values impact the calculation and results of an indicator. In this specific set of houses, all of them have a heating system that can be manipulated by the inhabitant, but only House 2 has a cooling system. It means that the inhabitants have more control of the inside temperatures in winter than in summer. Since the inhabitants tend to overheat their houses during the winter, it is normal that the use of the EN 16798 upper winter limit in the “degree-hour” calculation impacts less than the use of the EN 16798 lower winter limit. In other words, it is preferable to use the lower limit to characterize cold discomfort in winter. In the case of summer, the little control of the inhabitants over the temperature of their house, coupled with the lack of information on their aeration habits and the fact that the comfort range depends on the outside temperature, makes it more difficult to explain how the reference values influence the result of the indicator. However, the fact of having higher results in summer using the upper limits is logical considering that it is more common for the summer temperature to be above the upper limit than to be below the lower limit.

3.3. RH based indicators

3.3.1. Maximum duration above or below a RH limit

Figure 11 presents the results of the “maximum duration above or below a RH limit”, calculated with the maximum and minimum values of the EN 16798 class II range: 60 % and 25 % respectively. Considering that a very high and a very low RH during long periods produces a feeling of discomfort, the maximum duration above and below a limit indicates the longest periods under uncomfortable conditions. The range of the maximum duration above 60 % of RH is [0 h ; 31 h] without occupancy scenario and [0 h ; 8 h]

with occupancy scenario. Concerning the discomfort due to low RH, the range of the maximum duration below 25 % of RH is [0 h ; 5 h] without occupancy scenario and [0 h ; 2 h] with occupancy scenario. The use of the occupancy scenario reduces the results [-85 % ; -45 %], except in House 2 in summer using the 25 % of RH limit where the result without occupancy scenario is 1.8 h and with scenario is 0 h.

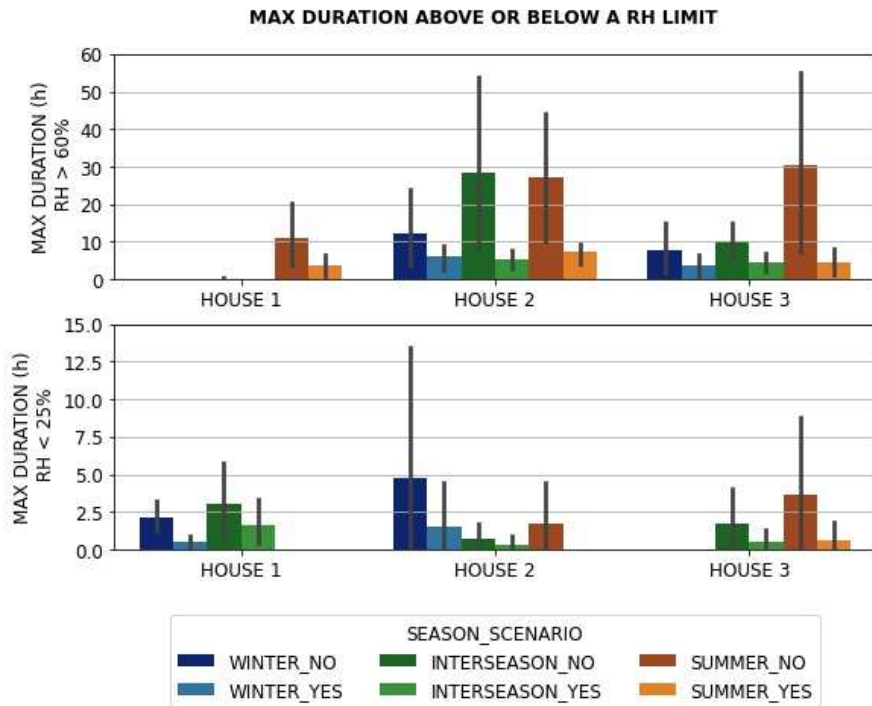


Figure 11. Maximum duration above or below a RH limit in the 3 houses (living rooms and parental bedrooms) during 3-4 years, with and without an occupancy scenario, with a 1-hour time step.

There are no reference values to compare the results, but in general, the accumulation of hours per season in the three houses seems acceptable, considering that winter and summer each cover three months of the year and the interseason covers 6 months of the year. In the most critical case, which is the summer in House 3 without occupancy scenario, the number of hours is the equivalent of 1.3 days. However, this indicator does not allow to know if other relatively long periods of high or low RH occurred during the same season.

3.3.2. Number of hours above or below a RH-limit

The number of hours above or below a RH-limit allow to have a notion of the quantity of time when the discomfort produced by a high or low level of humidity is present. Figure 12 shows the results of this indicator using the maximum and minimum values of the EN 16798 class II range: 60 % and 25 % respectively.

The range of the number of hours above 60 % of RH is [0 h ; 125 h] without occupancy scenario and [0 h ; 60 h] with occupancy scenario. The range of the number of hours below 25 % of RH is [0 h ; 17 h] without occupancy scenario and [0 h ; 5 h] with occupancy scenario. The results with occupancy scenario are [-84 % ; -26 %] lower than those without occupancy scenario. Similarly to the “maximum duration below 25 % of RH” results, House 2 in summer using the 25 % of RH limit presents 1.8 h without occupancy scenario and 0 h with scenario, which means that in this specific case, the maximal duration in discomfort is the equivalent to the number of hours of discomfort.

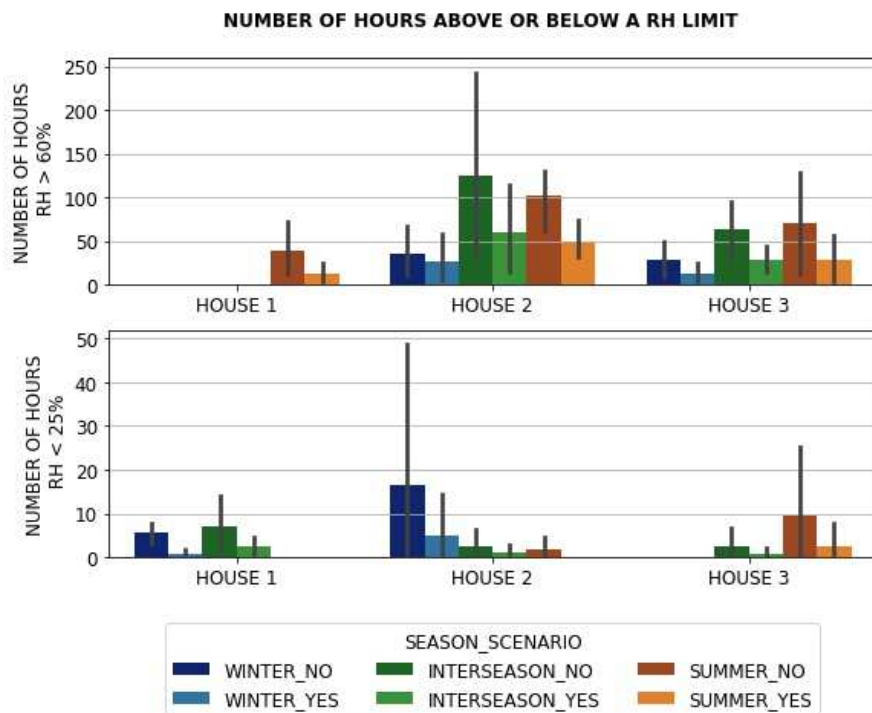


Figure 12. Number of hours above or below a RH limit in the 3 houses (living rooms and parental bedrooms) during 3-4 years, with and without an occupancy scenario, with a 1-hour time step.

This indicator does not provide reference values to compare the results and it does not allow knowing if the hours of discomfort were continuous or intermittent. In House 2 without occupancy scenario, which is the house and scenario with greater number of hours above 60 % of RH in all seasons, the number of hours above the limit was 35 h in winter, 125 h in interseason, and 102 h in summer. This large number of hours of discomfort may suggest that House 2 is uncomfortable during long periods of the season. However, the results of the “maximum duration above 60 % of RH” show that the hours of discomfort were intermittent since the maximum duration in House 2 without scenario was 12 h in winter, 29 h in interseason, and 27 h in summer. In other words, the period of discomfort was divided into several periods of shorter duration.

3.3.3. Percentage of time outside a RH-range

Figure 13 presents the results of the indicators linked to a percentage of time outside a RH-range (the graphs have different scales). The percentage of time that RH is outside the range of [25 % ; 60 %] (EN 16798 limits) was not found in the literature revised but it gives important information to understand the impact of the RH in the indicator proposed to link the temperature and the RH (percentage of time in a temperature-range and a RH-range simultaneously).

Assuming that all measures outside the range represent periods of discomfort, a high percentage implies a great amount of time of discomfort during the season. Regardless the use of an occupancy scenario, House 1 and House 3 are completely comfortable during all seasons with 0 % of RH above 70 % and less than 6 % of time outside the RH range of [25 % ; 60 %]. House 2 is not far from the other houses with 1 % maximum of RH above 70 %, and up to 10 % of time outside the RH range of [25 % ; 60 %] with and without occupancy scenario in all seasons.

The difference range between results with and without scenario is [-57 % ; 52 %] for the “percentage of time outside the RH range [25 % ; 60 %]”. In the case of the “percentage of time with RH over 70 %”, results with occupancy scenario are up to twice as high as those without it.

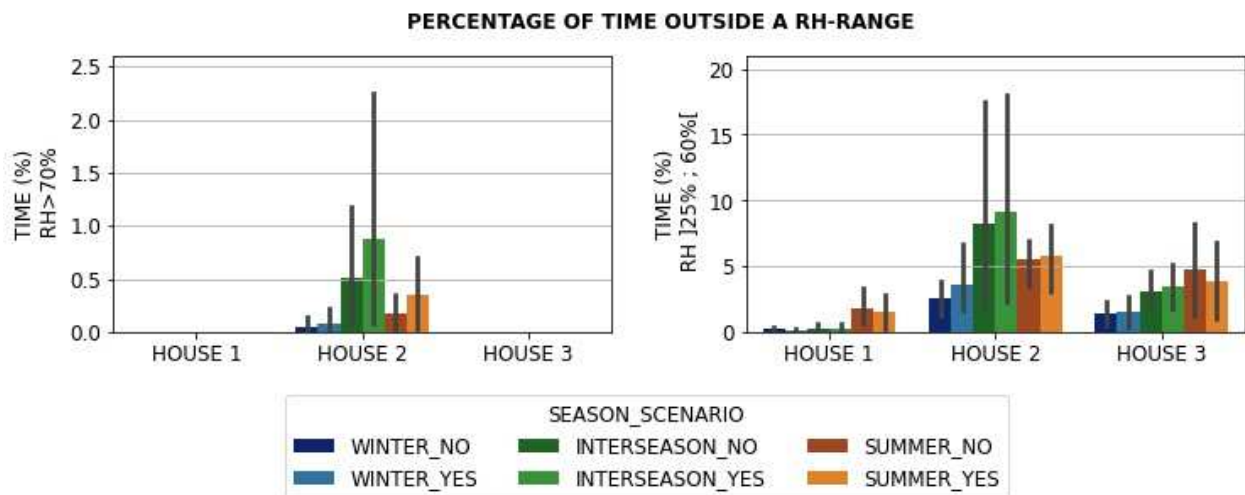


Figure 13. Percentage of time outside a RH-range in the 3 houses (living rooms and parental bedrooms) during 3-4 years, with and without an occupancy scenario, with a 1-hour time step.

3.3.4. Percentage RH-hour

We adapted the “degree-hour” indicator, which is calculated differently depending on the standard, to RH measures using the lower and upper limits of the EN 16798 class II: 25 % and 60 % of RH respectively. The results are presented in Figure 14. As in the “degree-hour”, a high value of “percentage RH-hour” indicates a long period of discomfort.

The results with an occupancy scenario are systematically lower than the results without one, [33 % ; 84 %] lower with the 25 % of RH lower limit, and [22 % ; 79 %] lower with the 60 % of RH upper limit.

It is important to notice that the highest level of discomfort does not occur in the same season in the three houses. According to the “percentage RH-hour” using 25 % of RH as reference, the highest level of discomfort occurs in interseason in House 1, in winter in House 2 and in summer in House 3. In the case of the “percentage RH-hour” using 60 % of RH as reference, the highest level of discomfort occurs in summer in House 1 and House 3, and in interseason in House 2.

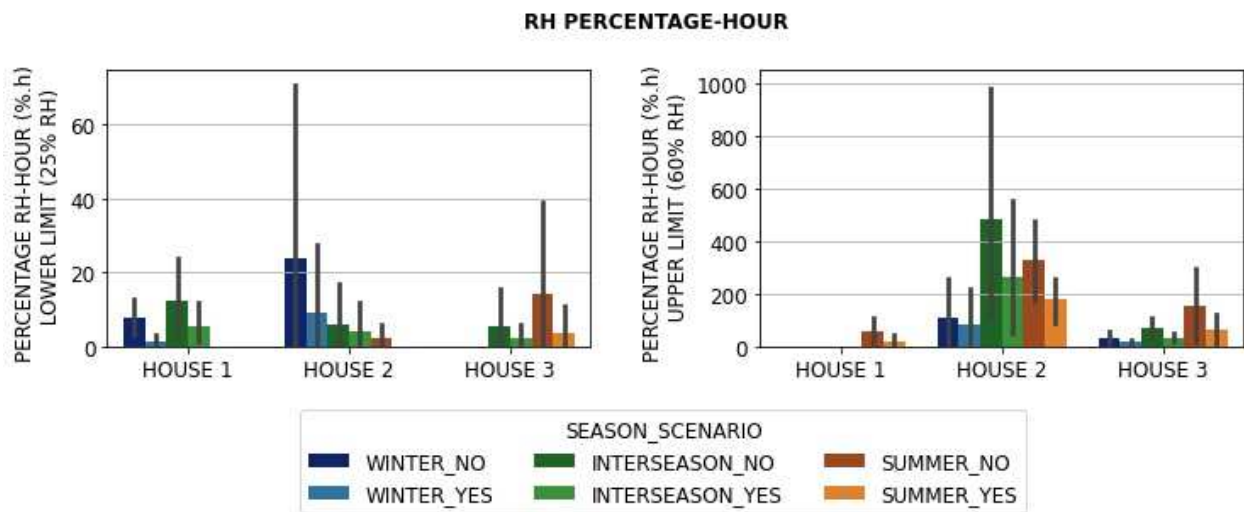


Figure 14. RH percentage-hour in the 3 houses (living rooms and parental bedrooms) during 3-4 years, with and without an occupancy scenario, with a 1-hour time step.

3.4. Indoor temperature – RH – indicator

Figure 15 shows the percentage of time that the rooms are in the comfort range of the EN 16798 class II, that is in the temperature range and RH range simultaneously. A high percentage indicate that the house was comfortable for most of the season.

The impact of the temperature-range and the RH-range is detailed in previous figures: percentage of time outside a temperature range (Figure 7) and percentage of time RH]25 % ; 60 %[(Figure 13). In all three houses, the temperature tends to exceed the threshold range more frequently than the RH. In fact, depending on the house and season, with and without occupancy scenario, the percentage of time outside a temperature-range is 2 to 20 times higher than the percentage of time outside a RH-range. The exceptions are winter and interseason in House 1 where the percentage of time outside a temperature-range with and without occupancy scenario is more than 20 times higher.

Assuming that the maximal deviation of 6 % recommended by the EN 16798-2 standard is valid for this indicator, none of the houses can be considered completely comfortable according to the EN 16798 class II using this indicator with or without an occupancy scenario (the use of an occupancy scenario does not always lead to an increase in the percentage of time in the comfort range). It is unlikely that new houses

built with quality materials and designed to be thermally comfortable without large energy costs have low percentages of time within the comfort ranges, especially in periods of occupation. The fact that the results of the “percentage of time in the RH-range” are globally in the comfort range, especially in Houses 1 and 3, implies that the problem is mainly related to the temperature indicators that give high percentages of discomfort.

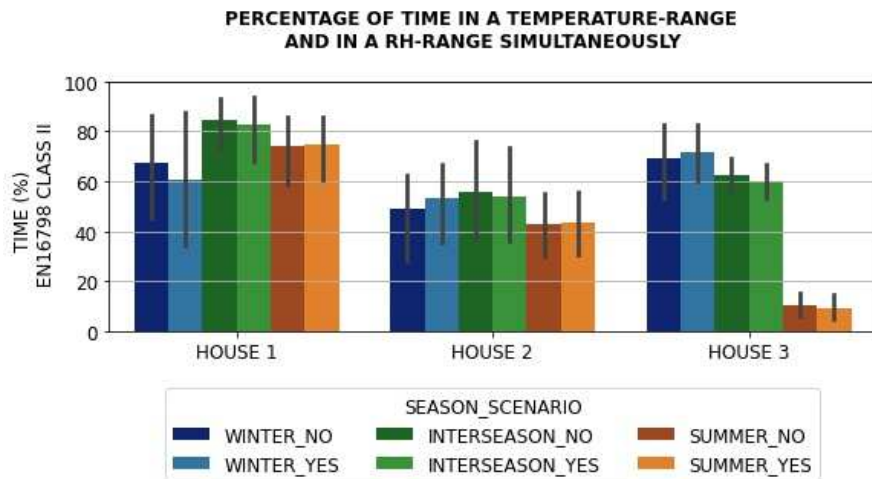


Figure 15. Percentage of time in a temperature-range and in a RH-range simultaneously, in the 3 houses (living rooms and parental bedrooms) during 3-4 years, with and without an occupancy scenario, with a 1-hour time step.

4. Discussion

There is a large number of comfort indicators based on the exclusive measurement of temperature or RH indoors. These can be grouped into families: some indicators are calculated based in the same parameter (temperature or RH), in a similar way (e.g. the “percentage of time outside a temperature range” and the “percentage of time outside a RH range”), using the same reference values to calculate different metrics (e.g. the “number of hours over 28 °C indoors in summer” and the “discomfort volume above 28 °C in summer”), etc. However, we did not find records of comfort indicators in closed spaces that combine temperature and RH. We proposed the “percentage of time in a temperature-range and in a RH-range simultaneously” indicator. Unfortunately, this indicator should be improved before being used in future tests. In fact, it is necessary to fix threshold values to compare the results.

Given that the comfort indicators are intended to quantify the comfort felt by the inhabitants, it is not necessary to make exhaustive measurements in each room of the house, it is enough to measure in the most frequented rooms such as the bedrooms or the living room. In the case of houses with good insulation, the living space usually has a relatively homogeneous temperature and RH, that is, ensuring comfort in the most frequented rooms can ensure an acceptable level of comfort in the rest of the living space.

The little variation in the distribution of temperature and RH at a time step of 1 hour and 10 minutes shows that a value per hour is sufficient for the calculation of comfort indicators based on temperature and RH. However, in the case of using low cost sensors, it is advisable to carry out more than one measurement per hour and treat the data to obtain a representative value for each hour.

Given that the use of an occupancy scenario leads to evaluate exclusively the periods in which the inhabitants are exposed to the thermal conditions of a room, the comfort indicators calculated with an occupancy scenario better describe the comfort resented by the inhabitants. Inversely, the indicators calculated without an occupancy scenario tend to overestimate or underestimate the real comfort resented by the inhabitants. The indicators that without an occupancy scenario tend to overestimate the discomfort are: the “maximal temperature”, the “number of hours over 28 °C indoors in summer”, the “discomfort volume above 28 °C in summer”, the “daily range outlier”, the “combined index”, the “degree-hour”, the “maximum duration above or below a RH-limit”, the “number of hours above or below a RH-limit” and the “percentage RH-hour”. The rest of the indicators show seasons where the results with an occupancy scenario are higher than those without one. Only the “percentage of time with RH over 70 %” show a constant tendency to underestimate the results without occupancy scenario.

The sensitivity of the comfort indicators to the occupancy scenario exposed during this study shows not only the importance of their use but also of the choice of a scenario that reflects the real occupancy. The ideal is to build the occupancy scenario during the measurement campaign based on data from presence sensors, CO₂ concentration sensors, questionnaires, etc. And as a last resort, use a standard scenario that is close to the reality of the occupants.

Despite the fact that all the indicators presented have the objective of qualifying the degree of comfort of a room, most of them cannot be directly compared with each other since they evaluate different points (dispersion of data, quantity of hours outside a range, etc.). In view of this constraint, we propose to investigate whether the indicators manage to classify the three houses in the same order. Figure 16 presents the normalized values (calculated as explained in section 2.7) in four radars according to the parameter on which the indicators are based (temperature or RH) and the season. Only the results obtained with the use of an occupation scenario are included in this stage of the study since these tend to better describe the conditions to which the inhabitants are exposed. Besides, the preceding figures reveal that all the indicators are sensitive to the occupancy scenarios. A regular polygon means that the results of the indicators are consistent with each other for a given house, which is only the case of House 2 using the RH-based indicators in winter (Figure 16C). The fact that the ranking of houses varies according to the indicators implies that both temperature-based indicators and RH-based indicators have a certain degree of sensitivity. E.g. Focusing on the temperature-based indicators (Figure 16 A and B), the “maximum” and the “variance” indicate that regardless the season, House 1 is the most comfortable house and House 3 is the least comfortable house. However, according to the “daily range outlier” in summer, the most and less comfortable houses are House 3 and House 2, respectively. Indeed, some indicators are more sensitive than others, showing different rankings depending on the season. This is the case of the “percentage of time outside a range”, which indicates that the least comfortable house is House 2 in winter and House 3 in summer.

In general terms, the houses are classified in the following order according to temperature-based indicators: House 1 is the best, followed by House 2 and House 3. For the RH-based indicators, the ranking is slightly different: House 1 is still the best, followed by House 3 and House 2.

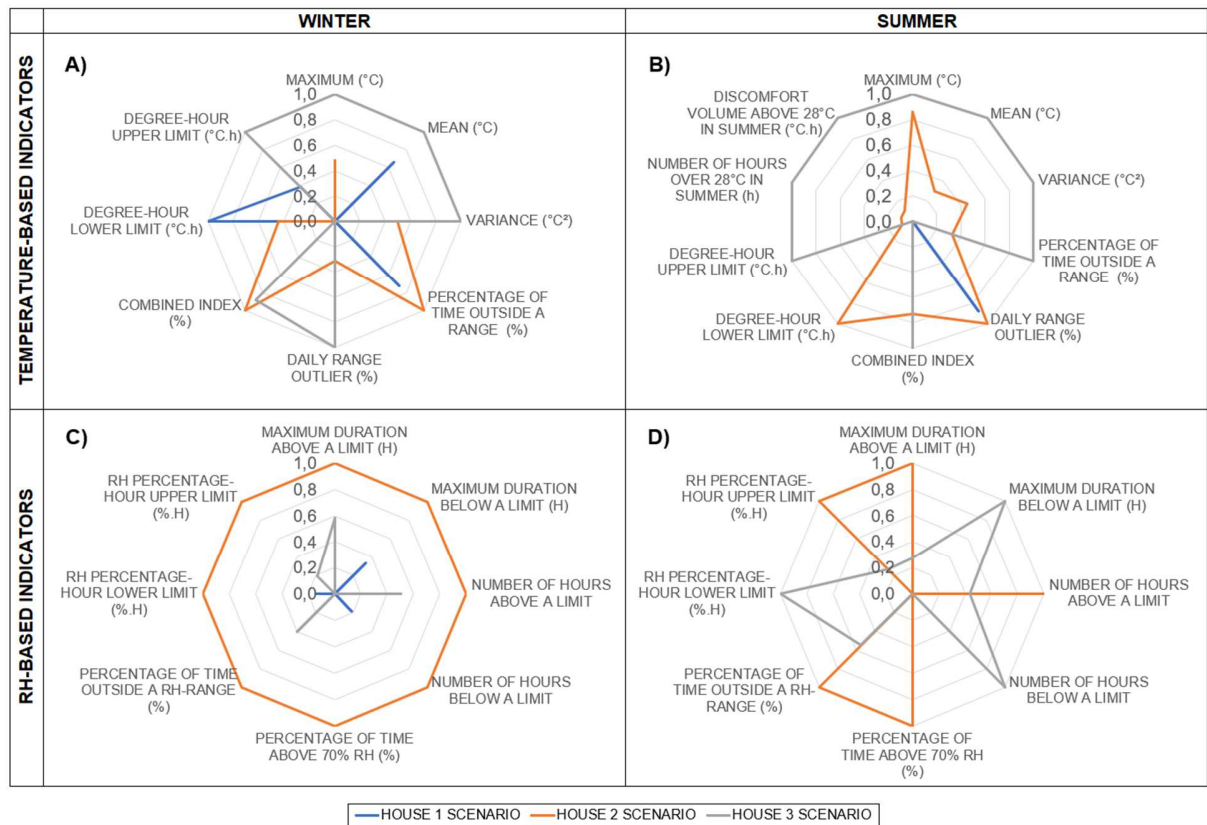


Figure 16. Comparison of results of temperature-based indicators and RH-based indicators with occupancy scenario, by season and by house.

The information provided by each comfort indicator is presented in Figure 17 for the temperature-based indicators and in Figure 18 for the RH-based indicators. Some indicators provide concise information in a direct way (e.g. the “maximum temperature” and the “mean temperature”) while others provide information in a direct and indirect way (e.g. the “degree-hour”). No indicator provides information (direct or indirect) of all the points evaluated. In fact, no temperature-based indicator provides the maximal duration (number of hours) under uncomfortable thermal conditions and no RH-based indicator provides information about the maximum, mean and dispersion of values.

It is not necessary to calculate each of the indicators to have a global idea of the degree of comfort in a room. The choice of indicators depends on the information required, an example is the "maximum temperature" which specifies the highest degree of discomfort that can be reached but is not useful to know the usual temperatures in the room. In turn, the indicator that provides the most information is not necessarily the best, since by encompassing so much information, it does not allow to identify the cause of the discomfort.

It is difficult to understand the thermal conditions of a room based on these indicators separately. However, their information can be complementary and can provide more accurate information when presented in parallel:

- The “maximal”, “mean” and “variance” that give a general picture of the data distribution (elements commonly represented together in form of boxplot).
- Assuming that the discomfort is automatically felt above 28 °C, the “number of hours over 28 °C indoors in summer” and the “discomfort volume above 28 °C in summer”. The first quantify the time under uncomfortable conditions and the second provides information about by how many degrees this limit was exceeded (the discomfort is not the same when the limit is exceeded by one degree as when it is exceeded by ten degrees).
- The “percentage of time outside a temperature-range” that quantify the discomfort period, and the “variance” that quantify the dispersion of the data. Both indicators are fused in the “combined index”.
- The “number of hours above or below a RH-limit” that quantifies the discomfort period, and the “maximum duration above or below a RH-limit” that presents the longest period under these circumstances.
- The “percentage of time outside a temperature range”, and the “percentage of time outside a RH-range”. Both indicators are fused in the “percentage of time in a temperature-range and in a RH-range simultaneously”. This last indicator gives a picture of the percentage of time that a room is under the optimal temperature and RH conditions if the comfort ranges of both parameters are correctly selected.

Temperature-based indicator	Provided information								
	Maximum temperature	Mean temperature	Dispersion of temperatures	Number of °C out of range	Time outside range				
					Yes/No	Number of hours	Number of times	Percentage	Maximum duration
Maximum temperature	Direct								
Mean temperature		Direct							
Variance of temperatures			Direct						
Number of hours over 28 °C in summer				Indirect	Direct	Direct			
Discomfort volume above 28 °C in summer				Indirect	Direct	Direct			
Percentage of time outside a range							Direct		
Daily range outlier			Indirect		Direct	Direct			
Combined index			Indirect		Direct	Direct		Indirect	
Degree-hour				Indirect	Direct	Direct			

Type of information		
Direct	Indirect	Not available

Figure 17. Information provided by each temperature-based indicator.

RH-based indicator	Provided information								
	Maximum RH	Mean RH	Dispersion of RH	% of RH out of range	Time outside range				
					Yes/No	Number of hours	Number of times	Percentage	Maximum duration
Maximum duration above or below a certain limit					Dark Blue				Dark Blue
Number of hours above or below a certain limit					Dark Blue	Dark Blue			
Number of times the level has been above or below a certain limit for more than a certain period					Dark Blue		Dark Blue		
Percentage of time outside a RH range					Dark Blue	Light Blue		Dark Blue	
RH percentage-hour				Light Blue	Dark Blue	Light Blue			

Type of information		
Dark Blue	Light Blue	White
Direct	Indirect	Not available

Figure 18. Information provided by each RH-based indicator.

Indeed, in parallel analysis of indicators is only valid when the indicators are all calculated based on the same limits (e.g. ISO 7730 and EN 16798 limits). In fact, the same indicator calculated with the same database but different limits can generate different results. An example of this situation is the “degree-hour” calculated with the lower and the upper values of the EN 16798 class II ranges: summer was the most uncomfortable season in all houses using the upper values while winter was the most uncomfortable season in all houses using the lower values. We can therefore propose the most penalizing situations with the upper threshold in summer and the lower threshold in winter. Moreover, the interpretation of results should be guided by reference values, e.g. from what percentage outside the range we can determine that the comfort in a room is insufficient. However, less than half of the indicators propose reference values and when they do, these are usually a single value that allows a binary result. That is, the room is comfortable if the reference value is not exceeded, otherwise the room is uncomfortable. Unfortunately, this binary treatment leads to results that may not reflect the reality of an environment. The use of ranges to decompose the results is a possible solution, such is the case of the “number of hours over 28 °C indoors in summer” where the result is divided into categories (the thermal discomfort is acceptable under 50 hours, permanent above 200 hours, and very marked above 500 hours). This type of presentation of results also allows the calculation of the percentage of time in each category and results in a greater understanding of the environment.

In order to contribute to the creation of a robust benchmark of thermal comfort indicators and based on the type of information provided by each indicator and on the results of its application in the three houses of study, we propose the calculation of the following indicators in parallel:

- the “number of hours over 28°C in summer”, which quantifies the amount of time of discomfort due to high temperatures in summer
- the “percentage of time outside a temperature range” which quantifies the amount of time of discomfort during other seasons, including discomfort due to low temperatures

- the “degree-hour”, which couples the number of degrees out of range with the time out of range by proposing ranges of reference values to classify the comfort level
- the “percentage of time outside a RH range” which quantifies the duration of discomfort caused by very low or very high humidity level

As already explained, comparison between studies is difficult due to variations in the calculation of the indicators and in the measurement protocols. However, it is worth comparing our proposal of indicators with the conclusions of the Li et al. study from which several of the indicators discussed in this study were taken (Li et al. 2020). They assessed several thermal comfort indicators and their correlation with the long-term thermal satisfaction of building occupants using the database of a long-term campaign in four air-conditioned office buildings in Sydney. They have also fixed the temperature ranges according to the ISO 7730 and EN 16798 standards for the calculation of the “percentage of time outside a temperature range” and the “degree-hour”. The “number of hours over 28°C in summer” and the “percentage of time outside a RH range” were not calculated. This study concludes that the best-performing indicators are the “percentage of time outside a temperature range” and the “combined index” using the ISO 7730 Class B temperature range and the “daily range outlier” setting the temperature range at the 80th percentile of the data. These last two indicators were not retained in the proposed benchmark due to the lack of reference values to compare the results and classify the houses. However, we consider that they are interesting and have the potential to correctly assess thermal comfort in dwellings.

Conclusions

There is a large number of temperature-based and RH-based comfort indicators in the literature. However, their description is generally ambiguous since there is no single and clear way to calculate them. In fact, several of these indicators require establishing threshold values such as optimal temperatures and RH percentages, but they do not provide specific values. For the indicators that do not provide these threshold values, it is recommended to use those of standards such as the ISO 7730 or EN 16798, or those from national regulations when they exist. However, the choice of the threshold values should not be taken lightly because they can considerably affect the indicator result and characterize a house as uncomfortable when in reality it is not. We recommend providing a means of reporting occupants' feelings such as interviews or questionnaires to be filled out by occupants during the measurement period.

In addition to having a unique way of calculating, a clear and concise indicator must have an associated reference value and an acceptable deviation that allows the result to be compared. Even propose reference ranges that allow the results to be associated with some category (good, tolerable, bad) and thus more easily observe the changes over time (e.g. calculation of the percentage of time in each category). How, when and where to measure are also key points in the calculation of comfort indicators.

In this study, we calculated several indoor thermal comfort indicators based exclusively on temperature and RH measurements in the living room and the parental bedroom of three low-energy houses using low-cost sensors sampling each minute during 3-4 years. To simplify the calculation, we consider T_a to be equivalent to T_o with an indoor air speed of less than 0.2 m/s and use the threshold values from the ISO 7730 class B and EN 16798 class II for the indicators that do not explicitly define the thresholds. The maximal accepted deviation of occupied time outside the limits of the class is 6%. A representative scenario of housing occupancy schedules was proposed. Each one of the indicators was calculated with and without the occupancy scenario.

The study has proved that a time step of 1 hour provides information of sufficient quality for the calculation of comfort indicators linked to temperature and RH in low-energy houses, even using low-cost sensors. It is not advisable to calculate the comfort indicators with the data of the full day in each corner of the house because the full day data can overestimate or underestimate the discomfort suffered by the inhabitants and because none of the rooms in a house need to be comfortable all the time. In fact, all the indicators tested in this study are sensitive to the occupation scenarios. It is preferable to focus in the most frequented rooms such as the living-room and bedrooms, during the occupancy hours. If this information is not available, it is important to consider a standard occupancy scenario close to the real activities of the inhabitants.

None of the indicators tested in this study provide sufficient information to characterize by itself and in a conclusive way the level of comfort of a house. However, the parallel analysis of certain indicators can provide more accurate information, especially in case of combining two parameters in a single indicator. An example of this kind of indicators is the “percentage of time in a temperature-range and in a RH-range simultaneously”. Their results suggest that although the three houses were built to be comfortable and energetically performing, the level of comfort is low during occupancy periods in all of them. Given the quality of construction of these houses and the fact that their inhabitants did not expressed such an extreme level of discomfort, it is most likely that the indicator does not reflect the reality. In fact, the “percentage of time outside a RH-range” do not suggest such discomfort levels during occupancy periods. And even using the correct comfort ranges of temperature and RH, it is very difficult to recognize the cause of discomfort without reviewing the influence of each parameter on the indicator. Therefore, it is highly recommended to use more than one indicator and carry out a parallel analysis, and in case of analyzing combined indicators, include the indicators that compose it.

The comparison of the results of the different indicators calculated using the same database lead us to propose to study in parallel the following indicators in order to obtain a better visibility of the thermal comfort in low energy houses: the “number of hours over 28°C in summer”, the “percentage of time outside a temperature range”, the “degree-hour” and the “percentage of time outside a RH range”.

Some on-going perspectives are the calculation of the comfort indicators with data from a short measuring campaign with low-quality and high-quality sensors during the heating season. This time, the occupation scenario will be created based on the real activities registered by the inhabitants and the results of the indicators will be compared with the degree of comfort indicated by the inhabitants.

Acknowledgements

The authors thank the Consejo Nacional de Ciencia y Tecnología (CONACYT) and the Consejo Potosino de Ciencia y Tecnología (COPOCYT) for the financial support, and the COMEPOS project for the data provided.

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Appendices

Table A1. Temperature-based comfort indicators: Mean values in the three houses by season, with and without occupancy scenario.

Temperature-based indicator	Reference value(s) for calculation	Season	House 1		House 2		House 3	
			No Scenario	Scenario	No scenario	Scenario	No scenario	Scenario
Maximum (°C)		Winter	23.3	23.2	24.3	24.2	25.2	25.2
		Interseason	24.7	24.3	26.6	26.4	28.0	27.9
		Summer	28.4	28.2	34.2	32.0	33.2	32.7
Mean (°C)		Winter	20.9	21.1	20.1	20.3	21.2	21.5
		Interseason	21.6	21.6	21.3	21.4	22.7	22.8
		Summer	24.2	24.1	25.2	25.1	27.3	27.4
Variance (°C ²)		Winter	1.2	0.6	1.1	1.2	1.6	1.8
		Interseason	1.3	1.0	3.3	3.3	4.3	4.2
		Summer	2.3	2.4	3.5	3.2	4.3	4.1
Number of hours over 28 °C in summer (h)	28 °C	Summer	15.0	9.5	113.0	32.5	673.8	256.8
Discomfort volume above 28 °C in summer (°C.h)	28 °C	Summer	5.4	3.9	159.1	40.2	932.3	357.0
Percentage of time outside a range (%)	[20 °C ; 24 °C] in winter and adaptive range in summer and interseason	Winter	30.4	36.1	48.7	40.8	27.6	23.5
		Interseason	10.9	11.8	15.7	15.5	23.2	24.5
		Summer	19.7	18.6	40.4	32.1	77.3	60.2
Daily range outlier (%)	2 °C threshold	Winter	77.6	25.2	55.8	32.5	70.1	48.5
		Interseason	71.0	21.8	38.6	23.9	39.1	25.0
		Summer	63.6	36.2	53.5	38.9	30.0	16.7
Combined index (%)	[20 °C ; 24 °C] in winter and adaptive range in summer and interseason, and 2 °C threshold for all seasons	Winter	53.5	30.6	50.9	36.7	48.2	36.0
		Interseason	41.0	16.8	27.1	19.7	31.2	24.8
		Summer	41.7	27.4	47.0	35.5	53.7	38.5
Degree-hour (°C.h)	20 °C in winter and variable in summer and interseason	Winter	788.1	348.8	768.2	220.2	454.4	119.1
		Interseason	13.2	0.9	550.4	203.3	1.3	0.4
		Summer	0.0	0.0	147.2	67.3	0.0	0.0
	24 °C in winter and variable in summer and interseason	Winter	23.8	15.0	9.0	5.4	43.5	30.6
		Interseason	164.4	73.3	65.4	26.2	543.2	226.3
		Summer	325.2	131.6	754.6	230.8	3303.8	1258.5

Table A2. RH-based comfort indicators: Mean values in the three houses by season, with and without occupancy scenario.

RH-based indicator	Reference value(s) for calculation	Season	House 1		House 2		House 3	
			No Scenario	Scenario	No Scenario	Scenario	No Scenario	Scenario
Maximum duration RH > 60 % (h)		Winter	0.0	0.0	12.3	6.0	7.8	3.5
		Interseason	0.2	0.1	28.5	5.3	10.0	4.5
		Summer	11.0	3.5	27.0	7.5	30.6	4.6
Maximum duration RH < 25 % (h)		Winter	2.1	0.5	4.8	1.5	0.0	0.0
		Interseason	3.0	1.6	0.7	0.3	1.7	0.5
		Summer	0.0	0.0	1.8	0.0	3.6	0.6
Number of hours RH > 60 % (h)		Winter	0.0	0.0	35.0	25.8	28.8	13.0
		Interseason	0.2	0.1	124.6	59.8	62.7	28.3
		Summer	39.3	13.2	102.3	49.3	70.2	29.0
Number of hours RH < 25 % (h)		Winter	5.5	0.9	16.5	4.8	0.0	0.0
		Interseason	7.0	2.4	2.4	0.9	2.6	0.8
		Summer	0.0	0.0	1.8	0.0	9.4	2.6
Percentage of time out of a RH range (%)	RH > 70 %	Winter	0.0	0.0	0.1	0.1	0.0	0.0
		Interseason	0.0	0.0	0.5	0.9	0.0	0.0
		Summer	0.0	0.0	0.2	0.4	0.0	0.0
	[25 % ; 60 %] of RH	Winter	0.3	0.1	2.6	3.6	1.4	1.5
		Interseason	0.3	0.3	8.3	9.2	3.1	3.5
		Summer	1.8	1.6	5.5	5.8	4.8	3.9
RH percentage-hour (%.h)	25 % of RH	Winter	7.7	1.2	23.9	9.1	0.0	0.0
		Interseason	12.2	5.5	5.9	4.0	5.5	2.1
		Summer	0.0	0.0	2.5	0.0	14.2	3.7
	60 % of RH	Winter	0.0	0.0	109.7	85.5	32.7	16.0
		Interseason	0.1	0.0	484.8	266.7	69.8	33.5
		Summer	57.4	21.5	328.8	179.2	155.3	63.2

Table A3. Temperature-RH-based comfort indicators: Mean values in the three houses by season, with and without occupancy scenario.

Temperature-RH-based indicator	Reference value(s) for calculation	Season	House 1		House 2		House 3	
			No Scenario	Scenario	No Scenario	Scenario	No Scenario	Scenario
Percentage of time in a temperature-range and in a RH-range simultaneously (%)	Temperature [20 °C ; 24 °C] and RH [25 % ; 60 %] Variable temperature range and RH [25 % ; 60 %]	Winter	67.6	61.0	49.1	53.4	69.4	71.7
		Interseason	84.6	82.8	55.5	54.1	62.6	60.0
		Summer	74.1	74.8	42.8	43.4	10.6	9.5

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