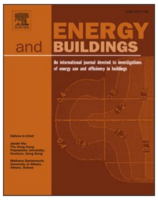
Energy & Buildings 303 (2024) 113804

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enb



Multi-criteria decision support framework for climate change-sensitive thermal comfort evaluation in European buildings

Deepak Amaripadath [a,b,*], Ronnen Levinson [c], Rajan Rawal [d], Shady Attia [e]

[a] School of Geographical Sciences and Urban Planning, Arizona State University, Tempe, AZ, USA
[b] Urban Climate Research Center, Arizona State University, Tempe, AZ, USA
[c] Heat Island Group, Lawrence Berkeley National Laboratory, Berkeley, CA, USA
[d] Centre for Advanced Research in Building Science and Energy, CEPT University, Ahmedabad, India
[e] Sustainable Building Design Lab, Department of UEE, Faculty of Applied Sciences, University of Liege, 4000 Liege, Belgium

ARTICLE INFO

Keywords:
Timber dwelling
Built environment
Comfort models
Overheating
Heat waves

ABSTRACT

This paper proposes a novel multi-criteria decision support framework for climate change-sensitive evaluation of building thermal comfort performance in European buildings. The proposed framework considers various comfort categories based on building use and condition, comfort models based on building operation, sensitivity to climate change, key performance indicators, and their thresholds. The proposed framework is then implemented using a passive house-certified high-performance timber dwelling near Brussels as a case study. The thermal comfort in the free-running reference timber dwelling is assessed using a whole-building energy performance simulation model with a static threshold of 26 °C for the bedrooms and an adaptive threshold for the other occupied zones. The analysis found an increase in indoor overheating degree by 1.7 °C and ambient warmness degree by 6.5 °C during heat waves from the current scenario to the end of the century scenario. However, the reference timber dwelling effectively suppressed the impacts of climate change with varying degrees of success towards the end of the century. The proposed framework is intended to support decision-makers in effectively evaluating performance during the early stages of building design. The study highlights the need for further research on building performance assessment techniques and guidelines in a changing climate.

1. Introduction

Climate change is one of the most significant issues of the 21st century, creating social, environmental, and economic concerns [1]. The average global air temperature has significantly risen over the past century [2]. Global warming and changes in temperature variability exacerbate extreme heat events like heat waves [1], and according to epidemiological studies from [3], mortality increases above a heat threshold of approximately 24.7 °C of the maximum daily temperature. The elderly, children and those with pre-existing medical conditions are particularly vulnerable to changes in heat wave attributes, which may increase mortality, particularly in these demographics, as shown in [4,5]. One of the major impacts of these extreme heat events is overheating in buildings, which is expected to worsen in changing climate scenarios [6]. Building thermal comfort during heat waves is significant since people spend most of their time at home, making them susceptible to overheating exposure[7], and indoor overheating during sleep is identified as a major threat to public health[8,9]. Since the intense heat wave of 2003 in Europe, which resulted in roughly 70,000 additional deaths, the overheating issue gained prominence and attracted vital public attention and research efforts, particularly in European countries [10,11]. More recently, 3,271 additional deaths were attributed to the heat waves that swept through England and Wales in the summer of 2022 [12].

Abbreviations: ASHRAE, American Society of Heating, Refrigerating and Air-Conditioning Engineers; AWD, Ambient Warmness Degree; CBE, Center for Built Environment; CCOhR, Climate Change Overheating Resistivity; CIBSE, Chartered Institution of Building Services Engineers; EBC, Energy in Buildings and Communities; EPBD, Energy Performance of Buildings Directive; HVAC, Heating, Ventilation, and Air Conditioning; IEA, International Energy Agency; IOD, Indoor Overheating Degree; ISO, International Organization for Standardization; KPI, Key Performance Indicator; MAR, Modele Atmospherique Regional; PMV, Predicted Mean Vote; PPD, Predicted Percentage of Dissatisfied; SET, Standard Effective Temperature; TMY, Typical Meteorological Year; TRNSYS, Transient System Simulation Tool; XMY, eXtreme Meteorological Year.

* Corresponding author at: School of Geographical Sciences and Urban Planning, Arizona State University, Tempe, AZ, USA.
E-mail address: deepak.amaripadath@asu.edu (D. Amaripadath).

https://doi.org/10.1016/j.enbuild.2023.113804
Received 10 October 2023; Received in revised form 21 November 2023; Accepted 26 November 2023

Table 1
List KPIs and recommended thresholds in the proposed framework.

No.	Performance indicators	Recommended thresholds	Standard/Literature
1	Indoor overheating degree [°C]	Moderate impact, IOD ≤ 0.5 °C Strong impact, 0.5 °C < IOD < 2 °C Extreme impact, IOD ≥ 2 °C	Flores-Larsen et al. [29]
2	Climate change overheating resistivity [°C]	Resistive, if CCOhR > 1 Not resistive, if CCOhR < 1	Rahif et al. [30]
3	Hours of exceedance [%]	26 °C, 6 % annually, 25 % monthly, and 50 % weekly for occupied hours.	ISO 17772–1 – Energy performance of buildings [28] EN 16798–1 – Energy performance of buildings [36]
		> 25 °C, 5 % annually for all hours.	Passive House [41]
		≥ 27 °C for a Category II, mechanically cooled building at 3 % annually for occupied hours.	CIBSE Guide A – Environmental design [42]
4	Standard effective temperature [°C]	30 °C during a heat wave in a free-running building. For LEED passive survivability, unmet SET degree-hours must be less than 120 for a 7-day heat wave event.	Sheng et al. [31] ASHRAE 55 – Thermal environmental conditions for human occupancy [38] Ji et al. [40]

During heat waves, indoor overheating is more probable in buildings with insufficient solar shading and ventilation, among other factors [6]. Overheating is caused by allowing access to external heat gains and retaining internal heat gains, and it is expected that urbanization and climate change to worsen it [13]. Stringent building energy code requirements emphasizing greater airtightness and higher thermal insulation have partially contributed to overheating [14,15]. Additionally, buildings with no active cooling systems, intermittent access to power, or with frequent power outages are prone to overheating issues [16]. Even though there are many comfort indices for indoor environments, no universally accepted design support framework is available for indoor thermal comfort evaluation in Europe that can be used for various comfort categories and models [14].

The numerical evaluation from Pyrgou et al. [17] shows the importance of the building's features, such as thermal insulation level and heating, ventilation, and air Cconditioning (HVAC) systems, to prepare for local microclimate events and to be more heat-wave resilient. This study used the local microclimate in Perugia in Central Italy - from 2013 to identify the nature of the heat wave event and its effects on the thermal-energy performance of buildings. In line with these results from Pyrgou et al. [17], studies from Porritt et al. [18] reduced air temperature in 19th-century terraced dwellings to below the Chartered Institution of Building Services Engineers (CIBSE) Guide A – Environmental design thermal comfort thresholds for all occupied hours by using a comprehensive range of passive measures during heat waves. A simulation approach was used here to analyze the impact of various single and clustered measures using multi-zone dynamic thermal simulation combined with a nodal airflow model. A similar method is used in Ramakrishnan et al. [19], where renovation using phase change materials and night ventilation as building features enhanced the summer thermal comfort. The study recommended incorporating phase change materials into building fabrics during the renovation to help lower the risks of extreme heatwaves in free-running buildings. These measures involving night ventilation lowered the heat xposure risks by 7.8 % from 1370 to 1201 h for the entire summer of 2160 h.

The analysis from Zinzi et al. [20] used numerical thermal analyses using the Transient System Simulation Tool (TRNSYS). The study evaluated the building's performance with several interventions, including thermal insulation, mechanical cooling systems, thermal free-floating conditions, and various night ventilation techniques. Contrary to the results from Ramakrishnan et al. [19], the persistence of high temperatures rendered night ventilation fairly ineffective during heat waves Zinzi et al. [20] and significantly impacted thermal comfort in free-running buildings. The studies from Sakka et al. [21] analyzed the evolution of indoor temperature with outdoor climate and building thermal capacitance. The findings proposed solar protection and dissipation strategies for low-income dwellings, where high indoor temperatures of up to 40 °C were recorded. To prevent overheating during heat waves, studies by Zeng et al. [22] suggested pre-cooling the buildings during off-peak hours. Pre-cooling reduced overheating and overall unmet degree-hours by roughly 60 % compared to the baseline during heat waves. High-capacity cooling systems can also help reach the pre-cooling setpoint faster and produce better outcomes. Willand et al. [23] focused on the concerns that current energy-saving measures prioritizing thermal comfort during winter may result in overheating and heat stress during summer. The study found that unless actively cooled, dwellings that comply with energy efficiency regulations were warmer in Australia.

The missing aspects identified from the review of the existing literature are: Firstly, most existing studies rely on a unique assumption of comfort model and building type and do not address climate change sensitivity. Climate change-sensitive studies should quantify future climate change impacts while considering the current scenario on the building performance. The framework proposed in this study recommends climate change overheating degrees for this purpose. Secondly, there is a lack of support frameworks to help decision-makers effectively evaluate thermal comfort considering different building categories and operation modes considering the existing studies from Table 1. Therefore, despite the availability of extensive literature, the current state-of-the-art lacks a robust framework based on universally accepted best practices. The relevance of the current study is based on several factors. Firstly, the framework will inform decision-making and prompt problem-solving for the building's thermal comfort. Secondly, the study evaluated a high-performance timber dwelling. This is significant since the market share of timber houses is consistently increasing throughout Europe to meet the region's increasingly stringent energy efficiency standards as per [24]. Thirdly, even though timber structures have low emissions and high energy efficiency, it has a large thermal resistance that will exacerbate the overheating risks during summer [25]. Fourthly, the reference dwelling typology used in the study is significant since it is estimated that the European market for multi-story timber buildings will grow at 8 % per year, and it is anticipated to grow from €5 billion at its current value to at least €10 billion annually by 2030 as per [26]. According to projections from [27], the increased demand for housing, decarbonization, and urbanization will result in a 170 % rise in worldwide wood consumption over the next 30 years.

Based on these observations, the main objective of the study is to implement the proposed framework on a free-running high-performance timber dwelling for heat waves from 2001 to 2020 (2010s_Current), 2041 to 2060 (2050s_Midfuture), and 2081 to 2100 (2090s_Future). The thermal comfort in the reference dwelling is evaluated using relevant climate change-sensitive and multizonal key performance indicators (KPI). The main novelty of the study is that it proposes a comprehensive framework to enhance the decision-making process while evaluating the building's thermal comfort by considering criteria like the comfort category, comfort model, and climate change sensitivity. This framework is built on internationally recognized standards like International Organization for Standardization (ISO) 17772-1 – Energy performance of buildings [28] and state-of-the-art literature from [6,29–31], enabling a universal comparison of comfort models, KPIs, and thresholds that may be used irrespective of the climate. The framework also covers residential and commercial buildings, whether new, retrofits, or old, and is not restricted to any architectural or operating type. Furthermore,

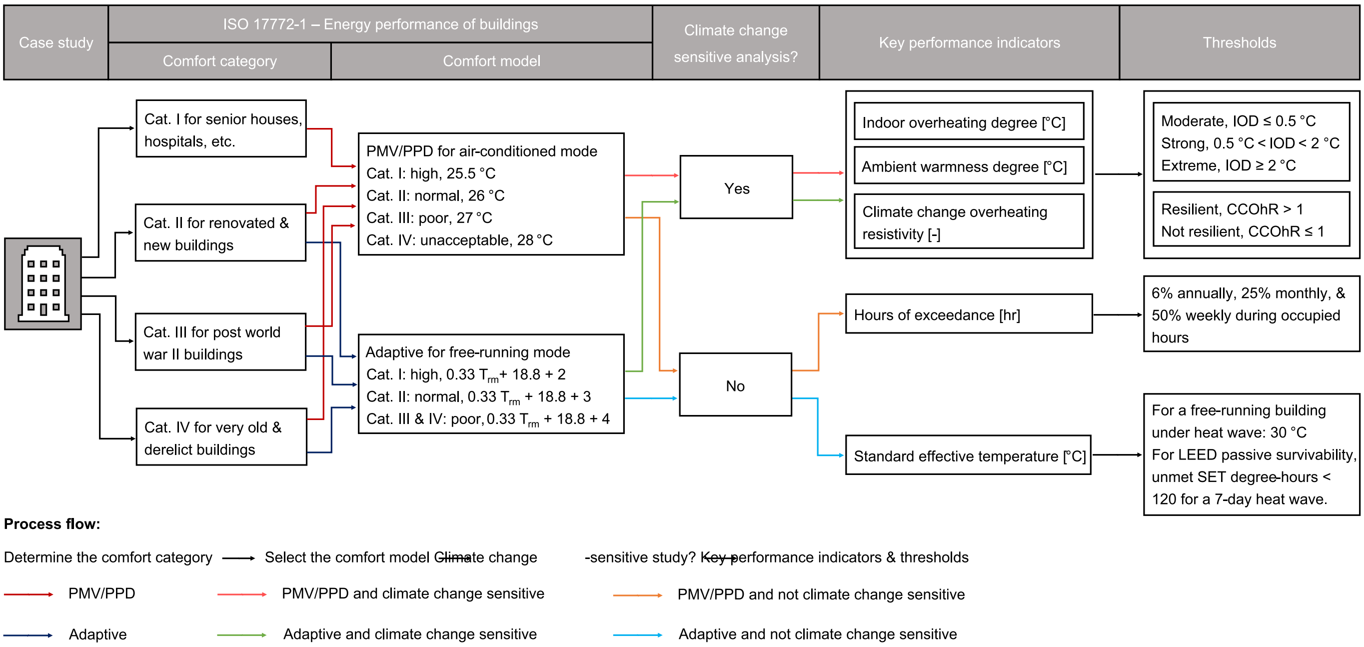


Fig. 1. Proposed multi-criteria decision support framework with comfort categories, models, and thresholds alongside the KPIs and thresholds for building thermal comfort evaluation during heat waves.

a multizonal, time-integrated, and climate change-sensitive method is incorporated to evaluate overheating risks for future climate scenarios.

2. Methodology

This study developed and implemented a multi-criteria decision support framework to evaluate building thermal comfort during heat waves using a high-performance timber building case study. The scope of the proposed framework is focused on European buildings. The reference building is in Kettenis, Belgium, in mixed humid climates (4A), per American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 169 – Climatic data for building design standards [32].

2.1. *Multi-criteria decision support system*

The first part of the study introduces the proposed multi-criteria decision support system that integrates existing comfort standard ISO 17772–1 – Energy performance of buildings with the KPIs and thresholds from the existing literature. Building-specific characteristics and comfort thresholds are included here based on the building category and operation. In the second part of the framework, the KPIs are applied based on whether the study is climate change-sensitive or not, and the respective thresholds are implemented. The framework was developed by reviewing the international standards, existing literature, and focus-group discussions. The proposed framework is shown in Fig. 1.

The implementation of the framework involves four main steps: (i) specify the comfort category, (ii) identify the building operation mode and comfort model, (iii) specify if climate change-sensitive or not, and 4) identify the relevant KPIs and their thresholds. The comfort categories

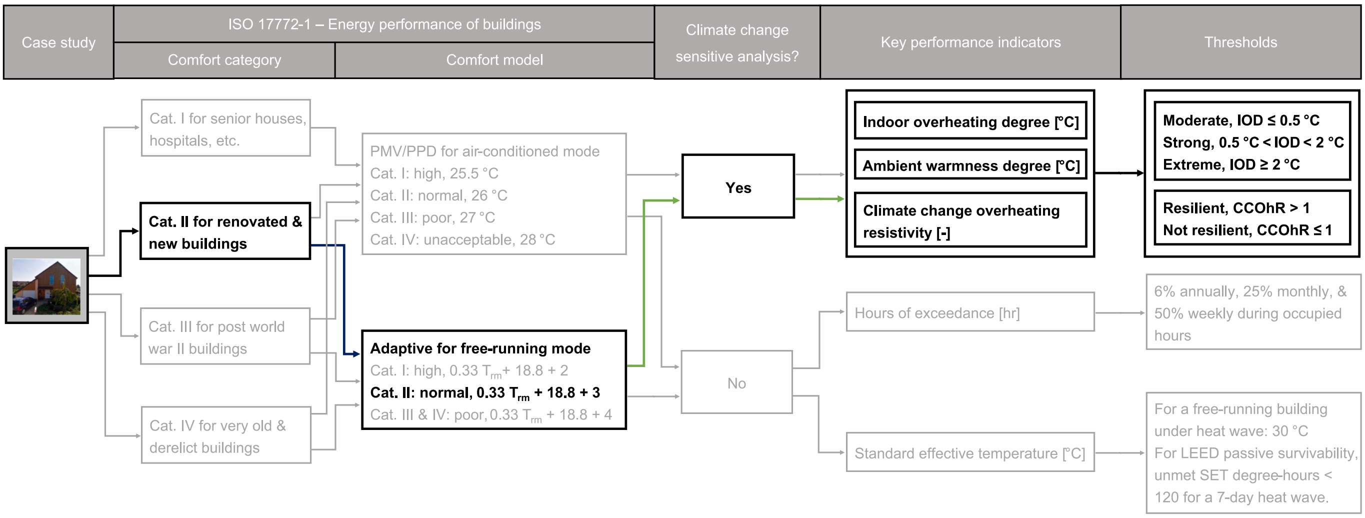


Fig. 2. Implementation of the multi-criteria decision support framework for building thermal comfort evaluation on a high-performance timber dwelling as a representative case study during heat waves from current and future scenarios.

are based on building use and conditions, whereas comfort models are defined based on building operation modes.

Step 1: Specify the comfort category.

This framework is applicable for thermal comfort evaluations of all comfort categories defined by ISO 17772-1 – Energy performance of buildings [28]. Category I refers to buildings that require high levels of comfort, such as senior housing and hospitals. Category II includes newly constructed and renovated buildings with normal comfort levels. Post-World War II buildings with poor comfort levels are classified as Category III. Old and derelict buildings with unacceptable comfort levels are classified as Category IV.

Step 2: Identify building operation and comfort model.

The comfort model is selected based on the building operation mode. A static or predicted mean vote (PMV)/predicted percentage of dissatisfied (PPD) comfort model with fixed operative temperature limits is used if the building is air-conditioned. If the building is free-running, an adaptive comfort model with varying operative temperature limits calculated with outdoor temperature is used [28]. The operative temperature limits for static and adaptive comfort models with different categories are shown in Fig. 2.

Step 3: Specify if climate change-sensitive or not.

Building performance is primarily influenced by the building's characteristics and the climate [33]. Either of these two variables will impact the outcomes of the building performance analysis. Predicting the impact of climate change on future building performance involves using climate change-sensitive KPIs. On the other hand, the building performance without considering climate change's direct impact can be analyzed using other KPIs.

Step 4: Determine relevant KPIs and thresholds.

The KPIs used to analyze the thermal comfort per the framework is below. These KPIs were selected based on the IEA EBC Annex 80 dynamic simulation guidelines [34]. The existing thresholds of the KPIs from existing standards and literature based on analytical and simulation-based studies are listed in Table 1. However, these thresholds are prepared in the scope of European buildings in line with recommendations from IEA Annex 80 – Resilient cooling of buildings. Therefore, while applying it globally, the threshold should be adapted for the calculations in the frameworks concerning various climatic contexts and building codes.

2.1.1. *Indoor overheating degree*

To estimate indoor overheating, a multizonal and time-integrated index called the Indoor Overheating Degree (IOD) [6] and implemented in [35] was used. IOD [°C] values are calculated using Eq. (1).

$$\mathrm{IOhD} = \frac{\sum_{z=1}^{Z}\sum_{i=1}^{\mathrm{N_{occ}}(z)}\left[\left(\mathrm{T}_{\mathrm{in},z,i} - \mathrm{T}_{\mathrm{comf,upper},z,i}\right)^{+} \times \mathrm{t}_{i,z}\right]}{\sum_{z=1}^{Z}\sum_{i=1}^{\mathrm{N_{occ}}(z)}\mathrm{t}_{i,z}} \tag{1}$$

where Z is the total number of conditioned building zones, i is the number of occupied hours, $N_{occ}(z)$ is occupied hours in zone z, $T_{in,z,i}$ is the indoor operative temperature at zone *z* during hour *i* in °C, $T_{comf,upper,z,i}$ is maximum comfort threshold at zone z during hour i in °C, and $t_{i,z}$ is the time step, which is an hour in this case. $T_{comf,upper,z,i}$ values for static models can be derived from standards like ISO 17772–1 – Energy performance of buildings [28] and EN 16798–1 – Energy performance of buildings [36]. For the adaptive model, the equation for calculating the upper limit of the adaptive model from ISO 17772–1 – Energy performance of buildings, based on the outdoor running mean temperature, is given in Eq. (2). T_{rm} is the outdoor running mean temperature [°C] calculated from the mean daily air temperature [28].

$$\mathrm{T}_{\mathrm{comf,upper},z,i} = 0.33\,\mathrm{T}_{\mathrm{rm}} + 18.8 + 3 \tag{2}$$

2.1.2. *Ambient warmness degree*

Ambient warmness degree (AWD) from [6] and implemented in [37] measures the severity of outdoor conditions using the average of cooling degree days (CDD) using outdoor dry-bulb temperature ($T_{out,a,i}$) for a base temperature (T_b) of 18 °C [30] by the total building occupied hours, which is shown in Eq. (3). h_i is the timestep used in the measurements.

$$AWD = \frac{\sum_{i=1}^{N}\left[\left(T_{out,a,i} - T_b\right)^{+} \times h_i\right]}{\sum_{i=1}^{N}h_i} \tag{3}$$

2.1.3. *Climate change overheating resistivity*

Climate change resistivity towards building overheating is indicated by the climate change overheating resistivity (CCOhR) indicator [30]. CCOhR [-] is calculated using Eq. (4).

$$\frac{1}{\mathrm{CCOhR}} = \frac{\sum_{Sc=1}^{Sc=M}\left(\mathrm{IOhD_{Sc}} - \overline{\mathrm{IOhD}}\right) \times \left(\mathrm{AWD_{Sc}} - \overline{\mathrm{AWD}}\right)}{\sum_{Sc=1}^{Sc=M}\left(\mathrm{AWD_{Sc}} - \overline{\mathrm{AWD}}\right)^{2}} \tag{4}$$

where Sc is the weather-scenario counter, and M is the total number of weather scenarios. CCOhR values greater than 1 indicate that the reference dwelling can withstand climate change induced outdoor thermal stress during intense heat waves. CCOhR values are calculated for intense heat waves in current, mid-future, and future scenarios.

2.1.4. *Hours of exceedance*

The equation for calculating the Hours of exceedance (HE) for the static and adaptive models is shown in Eq. (5) as described in [13]. Depending on the building operation mode, static or adaptive limits can be used to calculate the percentage of hours of exceedance [%] during the occupied hours.

$$\mathrm{HE_{op}} = \sum_{i=1}^{N_{occ}(z)}\mathrm{H_{disc}} \tag{5}$$

$\mathrm{H_{disc}} = 1$; if $\mathrm{T}_{\mathrm{op},i} > \mathrm{T}_{\mathrm{comf,upper},z,i}$, $\mathrm{H_{disc}} = 0$; if $\mathrm{T}_{\mathrm{op},i} \leq \mathrm{T}_{\mathrm{comf,upper},z,i}$.where, H_{disc} is the number of discomfort hours [hr] and $T_{op,i}$ is the indoor operative temperature [°C].

2.1.5. *Standard effective temperature*

Standard effective temperature (SET) from [38] evaluates human response to heat stress in buildings [31]. Standard effective temperature can be calculated using clima tool from the Center for Built Environment (CBE) [39]. To determine the unmet SET degree-hours, SET thresholds of 30 °C for free-running buildings are recommended in [34]. However, to obtain SET values comparable to the actual environmental parameters, the skin temperature, skin wettedness, and skin heat loss should be corrected as per [40]. As per this modified SET definition, the standard environment has a radiation temperature that is approximately equal to the air temperature, a relative humidity of 50 %, a metabolic rate that is similar to the actual environment, standard clothing insulation, and standard air velocity that varies according to the metabolic rate. The main findings from [40] offered calculation methods for the modified standard environment parameters. These modifications on the SET were mainly focused on the length of the calculations and the adaptive modes of operation.

2.2. *Application to a case study*

The implementation steps for the proposed framework using the reference high-performance timber dwelling are shown in Fig. 2. The reference dwelling is a Category II dwelling that uses an adaptive comfort model for free-running dwellings. The case study is a climate change-sensitive study and uses KPIs like IOD, AWD, and CCOhR, along with their thresholds.

2.2.1. *Reference high-performance timber dwelling*

In the second part of the study, the proposed framework is tested using a high-performance timber dwelling as a representative case study. The reference dwelling is in Kettenis near Brussels, Belgium, at 50.6473 °N, 6.0469 °E. It is a nearly zero-energy dwelling constructed in 2008 and participated in the Project Construire avec Energie from the

Reference building

Simulation model

Ground floor

First floor

Fig. 3. Illustration of the real building, simulation model, and floor plans of the reference timber dwelling.

Walloon regional government as per [43]. The project complies with the Belgian Passive House standards [44], making it a nearly zero-energy dwelling. De Meester de Betzenbroeck also performed a thorough energy assessment and building characterization for the reference dwelling [45]. It is a timber construction with a timber truss framework. It has two floors, with the ground floor housing the kitchen, living room, and dining area and the first floor housing the bedrooms and bathroom. The reference dwelling has a floor area of 174 m^2 with an unconditioned garage attached. The dwelling has an infiltration rate of 0.5 ACH. Four people are living in this dwelling. The real building, simulation model, and floor plans are shown in Fig. 3. The building simulation model was developed using DesignBuilder v6.1, the graphical user interface for the EnergyPlus v9.1 simulation engine. The building baseline simulation model and more details for the high-performance timber dwelling used in this study can be accessed from [46].

The house is well-insulated and has a wood pellet heating system. No air-conditioning is implemented, and it is in free-running mode during the summer. A gas water heater produces domestic hot water with preheating using solar collectors of 6 m^2. The dwelling has a heat recovery unit with an efficiency of 90 % and a double-flow mechanical ventilation system [43]. The mechanical ventilation rate is 10 L/s/person in compliance with EN 16798-1 – Energy performance of buildings [36]. The occupancy, lighting, and equipment schedules for the bedrooms and living areas are modeled using data from the De Meester de Betzenbroeck audit [45]. The windows have internal solar protection like curtains and a 30 % window-to-wall ratio. Further information on dwelling energy efficiency is provided in [45]. The bedrooms are modeled with static thermal comfort thresholds, and other occupied areas are modeled with adaptive thermal comfort thresholds with respect to mean outdoor temperature. Sleep study findings from [47–49] support this modeling approach and recommend a maximum threshold temperature of 26 °C in the bedrooms. The envelope characteristics of the reference dwelling are listed in Table A3.. This reference dwelling has passive measures like solar shading with overhangs and sidefins to decrease external solar gains. The key design parameters used for modeling of the reference timber dwelling are listed in Table 2.

2.2.2. *Climate data*

The Modele Atmospherique Regional (MAR) v3.11.4 explained in [50] is the regional climate model for developing the weather files used in this study. MAR downscales a global model or reanalysis with a finer geographical and temporal resolution to obtain relevant meteorological outputs [51]. MAR is a 3D atmospheric model coupled to a 1D transfer system between the surface, vegetation, and atmosphere [52]. To create

Table 2
Design parameters used as simulation inputs for modeling of reference timber dwelling.

Design parameter	Values
No. of floors [-]	2 main floors and an attic
Total area [m^2]	174
No. of occupants	4
Clothing factor [clo]	0.5 – Summer 1.0 – Winter
Metabolic rate [Met]	0.9 – Light manual work
Total volume [m^3]	536
Lighting gains [W/m^2]	5
Kitchen equipment [W/m^2]	10
Infiltration rate [ACH]	0.5
Window-to-wall ratio [%]	30
Window thermal transmittance [W/m^{2}K]	0.5
Window solar heat gain coefficient [-]	0.687
External wall solar reflectance [-]	0.220
External wall thermal transmittance [W/m^{2}K]	0.148
Extyernal roof solar reflectance [-]	0.300
External roof thermal transmittance [W/m^{2}K]	0.346
Ground floor thermal transmittance [W/m^{2}K]	0.177
External floor thermal transmittance [W/m^{2}K]	0.257
Heating setpoint [°C]	21
Cooling setpoint [°C]	No active cooling
Ventilation rate [l/s-person]	10
Domestic hot water [l/m^2-day]	0.72

hourly meteorological outputs, MAR has a spatial resolution of 5 km over an integration region of 120 × 90 grid cells centered over Belgium as per [51]. Building designers use the Typical Meteorological Year (TMY) and the eXtreme Meteorological Year (XMY) data sets to assess building performance. This study uses XMY weather files with heat wave events for building simulations. The XMY weather data is an extension of the TMY data and is created by choosing the most extreme, i.e., outlier months from a given data set rather than usual months [53].

Although there are many ways to build these types of weather files, a protocol for developing these years is designed based on ISO 15927–4 – Hygrothermal performance of buildings [54] and is briefly described in [51]. Meteorological files containing heat waves are used to assess the thermal comfort in the reference dwelling for 2010s_Current, 2050s_Midfuture, and 2090s_Future scenarios. The three temperature thresholds are calculated to identify the heat waves in each time frame [51] using the percentiles of 99.5 % for Spic above which a heat wave is detected, 97.5 % for Sdeb, that determines when the heat wave begins and ends, and 95 % for Sint that allows the merging of two heat wave when there is no significant temperature drop using a 20-year mean daily temperature distribution. The heat wave detection methodology is briefly explained in [55]. For Brussels, these values were 25.7 °C, 22.7 °C, and 21.1 °C, respectively. The weather files are in comma-separated (CSV) format and are converted to EnergyPlus Weather (EPW) format for building simulation analysis using Elements software from [56]. All the weather files used in the study are open source in [57]. The heat waves from different scenarios are visualized for hourly dry-bulb temperature variations in Fig. 4.

3. Results

The climate change sensitivity of the reference high-performance timber dwelling was evaluated for various heat waves from 2010s_Current, 2050s_Midfuture, and 2090s_Future scenarios. The hourly indoor operative temperature variations before, during, and after the heatwaves from different scenarios at the building and zone level are illustrated in Fig. 5. The reference timber dwelling is modeled with an acceptable threshold of 19 °C [28], a maximum threshold of 26 °C [28], and a critical threshold of 30 °C [58]. It is evident that the building level operative temperatures above the critical threshold of 30 °C significantly increased from 48 °C-hours during 2010s_Current to 1584 °C-hours during 2090s_Future. The maximum indoor operative temperature in the reference dwelling increases from 40.6 °C to 47 °C during these scenarios. Furthermore, the operative temperature remains unhabitable 7 days after the heat wave during the 2090s_Future scenario. The tools for calculating these climate change-sensitive overheating indicators can be found in [59].

Fig. 6 illustrates the building and zonal level IOD values in the

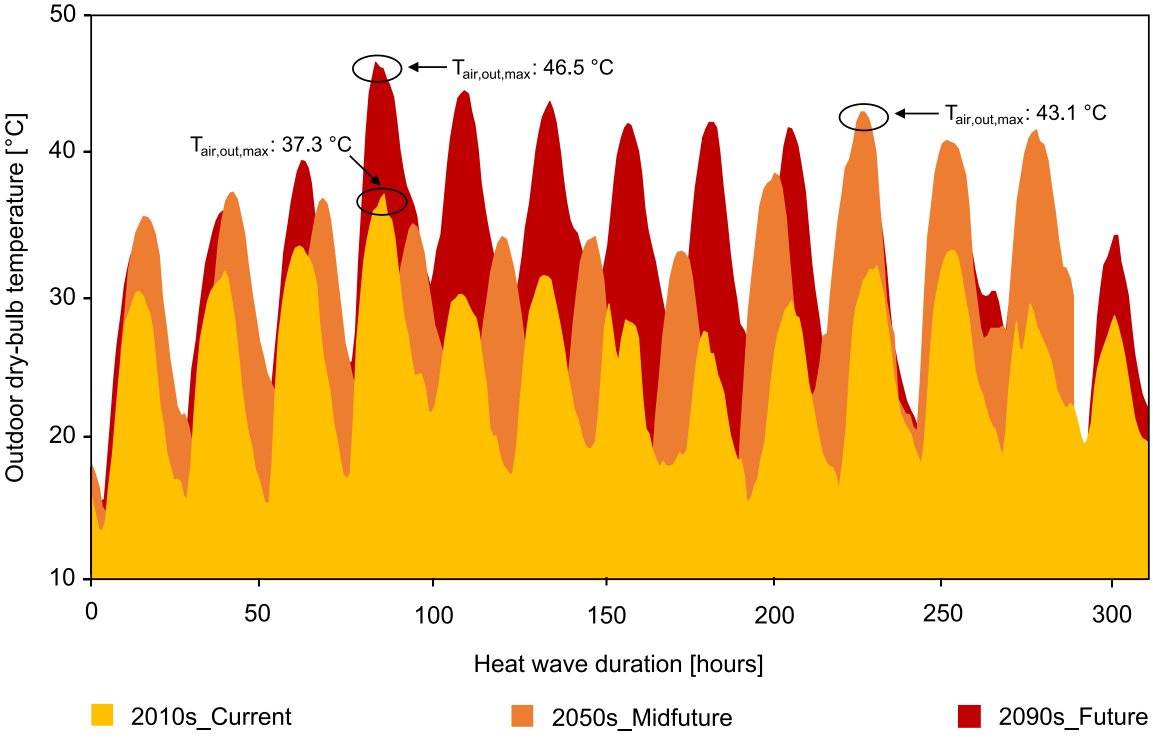


Fig. 4. Hourly outdoor dry-bulb temperature variations during heat waves from 2010s_Current, 2050s_Midfuture, and 2090s_Future scenarios.

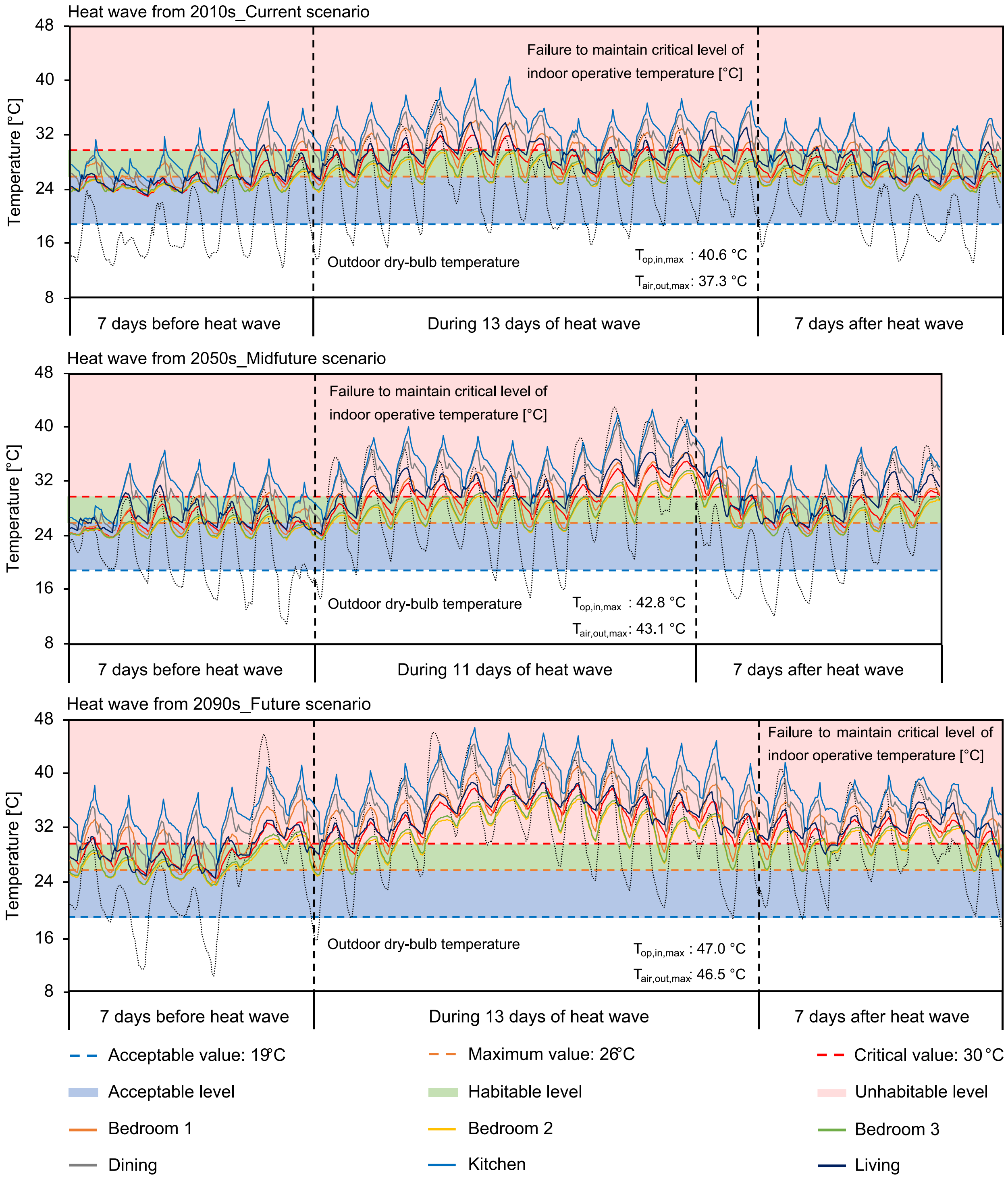


Fig. 5. Hourly indoor operative temperature values in reference dwelling before, during, and after the heat waves from 2010s_Current, 2050s_Midfuture, and 2090s_Future scenarios.

reference dwelling before, during, and after the heat waves from various scenarios. These results were developed by assuming a static threshold of 26 °C for the bedrooms and an adaptive threshold for the other occupied zones. There is a direct proportionality with increased indoor overheating in the reference dwelling 2010s_Current to 2090s_Future scenarios and rising to 3.4 °C during the heat wave from the 2090s_Future scenario. This indicates an extreme overheating impact in the reference dwelling per the thresholds defined by [29]. Furthermore, It should be noted that the calculated IOD values reached extreme and strong impacts during most observed periods. Higher IOD values result from more stringent overheating criteria based on static thresholds in bedrooms, while a significant decrease in IOD values can be noticed in other occupied zones that use adaptive thresholds. The IOD value during the heat waves increased by 101 % and 60 % for the 2090s_Future scenario compared to 2010s_Current and 2050s_Midfuture scenarios. The increased IOD values during heat waves can be explained as the reference building being a timber construction with high thermal insulation and a lack of air-conditioning.

The AWD values illustrated in Fig. 7 follow a similar trend with an increase in worsening outdoor conditions from 2010s_Current to

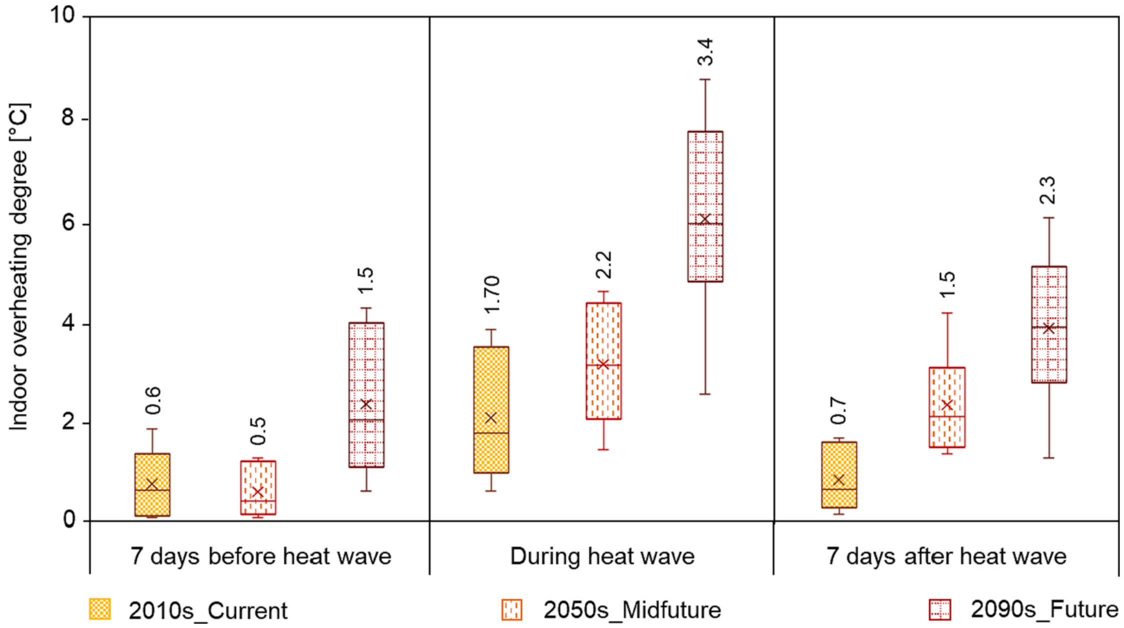


Fig. 6. Building and zone level indoor overheating degree values in the reference dwelling before, during, and after the heat waves from 2010s_Current, 2050s_Midfuture, and 2090s_Future scenarios.

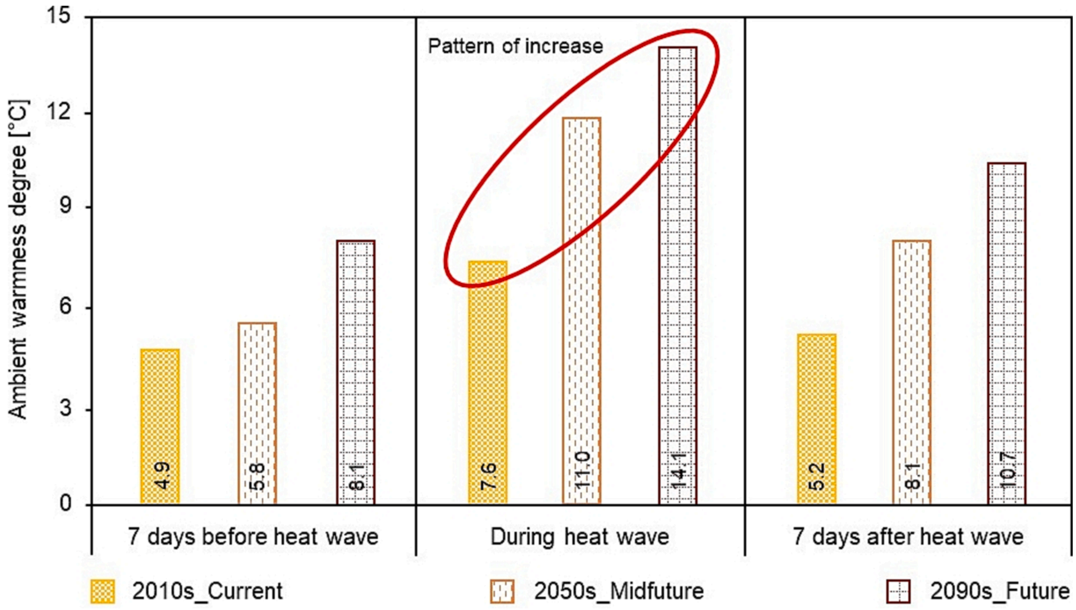


Fig. 7. Ambient warmness degree values before, during, and after the heat waves from 2010s_Current, 2050s_Midfuture, and 2090s_Future scenarios.

2090s_Future scenarios. These values reach up to 14.1 °C during the heat wave from the 2090s_Future scenario. In every situation, the difference in AWD value increases as climate change progresses. This is more significant during the heat wave events and for the 2090s_Future scenario. The AWD value during the heat waves increased by 84 % and 28 % for the 2090s_Future scenario compared to 2010s_Current and 2050s_Midfuture scenarios.

The CCOhR values are shown in Fig. 8. The CCOhR value records 3.2 before the heat waves, 3.7 during heat waves, and 3.4 after heat waves. In all three cases, the CCOhR is greater than 1. The results suggest that the reference high-performance timber dwelling can suppress the impacts of climate change to varying degrees of success towards the end of the century. This indicates that the rise in IOD values in indoor environments is slower compared to the rise in AWD values in outdoor environments. Notably, the AWD values are always significantly higher than IOD values, indicating better resistivity towards climate change. This can be attributed to the timber construction of the reference dwelling, which has a lower thermal mass as described in [60] and does not accumulate much heat before or during the heat waves. However, the IOD value during the heat wave for the current scenario is 1.7 °C, which strongly impacts the reference dwelling for existing conditions. Hence, the mitigation capacity of the reference dwelling should be supplemented by active and passive strategies to bring down IOD values.

4. Discussions

With the changing climate, more intense and frequent heat waves and indoor overheating are expected. Therefore, a framework for

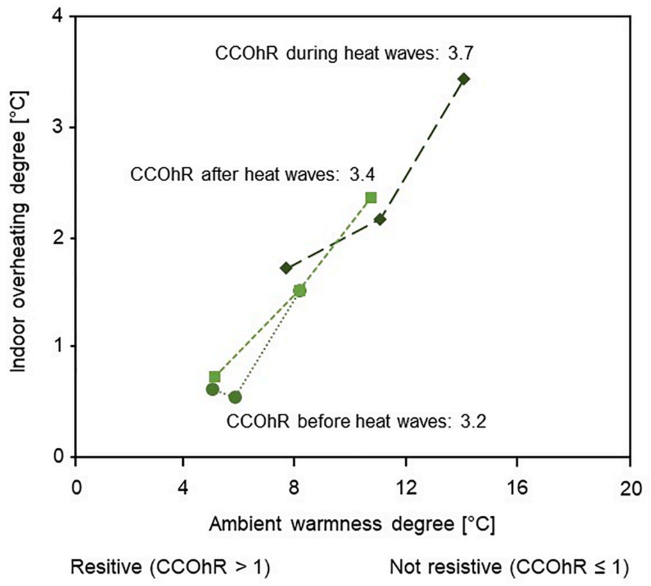


Fig. 8. Climate change overheating degree values in the reference dwelling during heat waves from 2010s_Current, 2050s_Midfuture, and 2090s_Future scenarios.

building thermal comfort in Europe was developed to support decision-makers by determining various comfort categories and models. These factors were determined based on current best practices from ISO 17772–1 – Energy performance of buildings to provide credible knowledge and support for robust decision-making. However, such comprehensive frameworks covering multiple aspects of building thermal comfort are rare. To the author's knowledge, this is the first framework that combines different comfort categories, models, evaluation methods, performance indices, and thresholds. This framework provides guidelines for climate change-sensitive thermal comfort evaluation for European buildings while considering the various preferences of decision-makers like building operation mode.

4.1. Main findings

1. In the proposed framework, comfort categories vary from Category I (e.g., senior housing, hospitals) to Category IV (old and derelict buildings) depending on building use and condition, and comfort models vary from static model (air-conditioned) to adaptive model (free-running) based on the building operation mode. Once these criteria are determined, then performance indicators and their thresholds, based on whether the analysis is climate change-sensitive or not, can be selected as in Fig. 1. The study proposed thresholds for the indicators from existing standards like [26,38], and existing literature like [29–31] that can be applied in the context of European buildings.
2. The proposed framework can be applied to various residential and commercial buildings across multiple climate zones in Europe. Based on the existing best practices, the framework offers decision-makers a comprehensive understanding of building thermal comfort evaluation and methods to quantify overheating and thermal discomfort. The paper's outcome will support the building designers in making objective, reliable, and accurate choices to improve indoor thermal conditions during extreme heat events like heat waves for current and future climate scenarios.
3. Implementing the framework on a high-performance timber dwelling for heat waves from future climate scenarios found that overheating risks in the reference dwelling for the heat wave from the end of the century were 101 % higher than during the heat wave from the current scenario. The ambient warmness of the outdoor environment also showed a significant increase toward the end of the century. The inability of passive measures like solar shading with overhangs and sidefins to mitigate overheating in the reference timber dwelling is evident from the study results. However, the reference dwelling suppressed climate change impacts in indoor overheating with varying degrees of success.
4. Furthermore, the indoor operative temperature remained above the critical value of 30 °C during the monitored period, accounting for up to 1,584 °C-hours towards the end of the century, marking a 3200 % increase. This indicates the inability of the reference dwelling to bounce back to a habitable level during intense heat waves. This also shows the necessity of effective renovation measures like active cooling to equip the reference dwelling for future heat waves. The efficiency of these measures can be evaluated accurately using the proposed framework.

4.2. Recommendations for practitioners

1. It is recommended to conduct more comparison studies on various building types, categories, and operation modes to evaluate climate change-sensitive thermal comfort using the proposed framework.
2. It is recommended to use performance indicators like IOD, AWD, and CCOhR for climate change-sensitive evaluations and indicators like HE and SET for evaluations that are not climate change-sensitive.
3. Additional weather files with intermediate periods of the 2030 s and 2070 s and different shared socioeconomic pathway scenarios should be used to improve the accuracy of climate change-sensitive evaluations.
4. Further studies into the cooling potential of active and passive measures and their combination are recommended to improve the building's resistance to overheating impacts in changing climate scenarios.

4.3. Strengths and limitations

The main strength of this study is that it developed a comprehensive framework that can be used to evaluate thermal comfort for various building types, comfort categories, and models using climate change-sensitive and insensitive KPIs. The coauthors developed this framework through multiple brainstorming sessions and revisions to validate the choices. The proposed framework is developed based on the existing best practices in the industry from ISO 17772-1 – Energy performance of buildings and state-of-the-art literature. Furthermore, the framework encompasses methods to assess the potential of overheating under various future climate scenarios through time-integrated and multizonal indices like IOD that improve the scope. The practical implementation of the framework on a high-performance timber dwelling adds to its strength, as only limited literature evaluates the performance of timber structures during heat waves. However, there are some limitations to this study. The proposed framework does not integrate other building performance aspects, like energy use and carbon emissions. Future research should build on these limitations. The framework should integrate the different passive and active cooling strategies to support the selection of different cooling design alternatives and for more detailed analyses of economic and environmental impacts. Additionally, the thresholds defined in the framework are in the scope of Europe. Therefore, the framework should be adapted with respect to study locations accounting for different climate zones and building regulations.

4.4. Implications for practice and research

1. Most European legislation, like the Energy Performance of Buildings Directive (EPBD), does not offer guidelines for evaluating the risks of indoor overheating. As a result, current building regulations and standards do not adequately address the concerns of indoor

overheating due to climate change, and the proposed framework must be included in future revisions of the EPBD directive.

2. Some aspects of the proposed framework were not evaluated using the current case study, like the static model operation and climate change insensitive analysis. Future studies should incorporate these undemonstrated aspects of the proposed framework. It is also recommended to incorporate additional overheating and thermal discomfort indices alongside the already suggested indicators.
3. Currently, there is a lack of a global database that covers potential indoor overheating issues. Future studies can use the proposed framework to evaluate these risks for current and future climate scenarios. More studies with benchmark models for different building types and climate zones are needed to create such a comprehensive knowledge database. Decision-makers can then access this knowledge base to identify potential overheating risks and mitigation strategies.
4. New performance indicators should include more parameters like relative humidity, air velocity, metabolic rate, and clothing factor for indoor environments, and solar radiation and relative humidity for outdoor environments. It is advised that future developments should define an additional post-processing process for sensitivity and optimization analysis to further the functionality.

5. Conclusions

A multi-criteria decision support framework was developed in this paper to evaluate building thermal comfort for different comfort categories and models for European buildings. The main challenge in developing such a framework is bringing together information that can be applied to multiple building typologies, categories, and operation modes based on existing best practices in Europe. The proposed framework integrates these aspects while combining climate change-sensitive like indoor overheating degree, ambient warmness degree, and climate change overheating resistivity, and insensitive indicators like hours of exceedance and standard effective temperature. The proposed framework will help to validate the building designers' decisions in thermal comfort evaluation and detect inconsistencies in the decision-making process. The proposed framework was then applied to the high-performance timber dwelling as a case study for a climate change-sensitive analysis involving heat waves from the future. The reference dwelling is a passive house certified as a nearly zero-energy dwelling.

The thermal comfort analysis shows a significant increase in indoor overheating by 101 % and 60 % for the 2090s_Future scenario compared to 2010s_Current and 2050s_Midfuture scenarios. In line with these findings, the ambient warmness of the outdoor environment also increased by 84 % and 28 % for the 2090s_Future scenario compared to the 2010s_Current and 2050s_Midfuture scenarios. However, the reference dwelling was able to suppress the impact of climate change towards the end of the century with varying degrees of success before, during, and after the heat waves. In this context, energy-efficient buildings that do not compromise summer thermal comfort in a changing climate make an ideal future solution. Integrating more building performance aspects, like energy use and carbon emissions, will improve the scope of the proposed framework for future research. More case studies, particularly of high-performance buildings that are free-running, mixed-mode, and air-conditioned mode, are needed to test the suitability of the proposed framework and to create a thorough knowledge database. With the current rate of climate change, the study recommends more climate change-sensitive studies and uses indoor key performance indicators that are sensitive to these changes in an outdoor environment.

CRediT authorship contribution statement

Deepak Amaripadath: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. **Ronnen Levinson:** Methodology, Validation, Visualization, Writing – review & editing. **Rajan Rawal:** Methodology, Validation, Writing – review & editing. **Shady Attia:** Conceptualization, Methodology, Supervision, Validation, Writing – review & editing.

Table A1

Envelope characteristics of the reference high-performance timber dwelling.

Envelope	Layers	Materials used	Thickness [m]	Thermal transmittance [W/m^{2}K]
Ground floor	Outer	Fiber cement panel	0.010	0.177
	Fourth	Blown-in cellulose insulation	0.250	
	Third	Oriented strand board panel	0.022	
	Second	Cement screed	0.030	
	Inner	Floor tiles	0.030	
Internal floor	Outer	Plywood	0.200	0.328
	Fourth	Plywood	0.020	
	Third	Plywood	0.024	
	Second	Acoustic layer	0.030	
	Inner	Plywood	0.015	
External floor	Outer	External rendering	0.244	0.257
	Second	MW stone wool rolls	0.144	
	Inner	Timber flooring	0.005	
External roof	Outer	Asphalt	0.010	0.346
	Third	MW glass wool roll	0.100	
	Second	Airgap	0.200	
	Inner	Plasterboard	0.013	
External wall	Outer	Wood siding	0.030	0.148
	Sixth	Lathing and counter-lathing	0.030	
	Fifth	Oriented strand board panel	0.020	
	Fourth	Cellulose-insulated wooden framework	0.250	
	Third	Oriented strand board panel	0.015	
	Second	Rockwool insulation	0.060	
	Inner	Wooden plank	0.018	
Internal partition	Outer	Plywood	0.020	0.611
	Second	Cellulose-insulated wooden framework	0.060	
	Inner	Plywood	0.018	
Doors	External	Painted oak	0.035	2.823
	Internal	Painted oak	0.035	2.823
Windows	External	Triple-glazed with a 30 % window-to-wall ratio		0.500

Ground floor: Floor between basement and occupied zones, Internal floors: Floors between occupied zones, External floors: floors adjacent to external air.

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.

Data availability

Data will be made available on request.

Acknowledgments

The project was funded by the Service Public de Wallonie (SPW), Belgium, under BElgian WAllonia REsearch (BEWARE) fellowships and European Union (EU) framework program for research and innovation, Marie Skłodowska-Curie Actions (MSCA) through contract no. 847587 for the Project SurChauffe. This material is also based upon work supported by the U.S. Department of Energy, Office of Science, Office of Biological and Environmental Research's Urban Integrated Field Laboratories research activity under Award Number DE-SC0023520. The study was also supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Office of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. We would like to thank the members of the School of Geographical Sciences and Urban Planning at Arizona State University and Southwest Urban Corridor Integrated Field Laboratory (SW-IFL) for their support. We would also like to thank the stakeholders of Project OCCuPANt. We would like to acknowledge the Sustainable Building Design Lab at the Faculty of Applied Sciences at the University of Liege for the valuable support and use of the state-of-the-art Super COmputeR ProcessIng wOrkstatioN (SCORPION) for building performance simulations and data analysis. This study is a part of the IEA EBC Annex 80 - Resilient Cooling of Buildings.

Appendix A

The envelope characteristics of reference high-performance timber dwelling are listed in Table A1.

References

[1] A. Amengual, V. Homar, R. Romero, H.E. Brooks, C. Ramis, M. Gordaliza, S. Alonso, Projections of heat waves with high impact on human health in Europe, Global and Planetary Change 119 (2014) 71–84, https://doi.org/10.1016/j.gloplacha.2014.05.006.

[2] H. -O. Pörtner, D. C. Roberts, M. M. B. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama, Climate Change 2022: Impacts, adaptation and vulnerability, IPCC 6th Assessment Report, 2022. [Online]. Available: https://report.ipcc.ch/ar6/wg2/IPCC_AR6_WGII_FullReport.pdf. Accessed on: Dec. 29, 2022.

[3] B.G. Armstrong, Z. Chalabi, B. Fenn, S. Hajat, S. Kovats, A. Milojevic, P. Wilkinson, Association of mortality with high temperatures in a temperate climate: England and Wales, Journal of Epidemiology & Community Health 65 (4) (2010) 340–345, https://doi.org/10.1136/jech.2009.093161.

[4] C. Koppe, S. Kovats, G. Jendritzky, and B. Menne, Heat Waves: Risks and responses. Copenhagen: Regional Office for Europe, World Health Organization, 2004. [Online]. Available: https://apps.who.int/iris/bitstream/handle/10665/107552/9789289010948-eng.pdf?sequence=1&isAllowed=y. Accessed on: Aug. 02, 2022.

[5] R. Basu, Relation between elevated ambient temperature and mortality: A review of the epidemiologic evidence, Epidemiologic Reviews 24 (2) (2002) 190–202, https://doi.org/10.1093/epirev/mxf007.

[6] 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, Building and Environment 122 (Sep. 2017) 307–323, https://doi.org/10.1016/j.buildenv.2017.06.031.

[7] NHBC. Overheating in new homes: A review of the evidence, National House Building Council, UK., 2012. [Online]. Available: https://www.nhbcfoundation.org/wp-content/uploads/2016/05/NF46-Overheating-in-new-homes.pdf. Accessed on: Aug. 04, 2022.

[8] Z.C. Hub Impacts of overheating: Evidence review, Zero Carbon Hub, London, England, Online https://www.cewales.org.uk/files/7314/4370/9984/Impacts_of_Overheating_-_Evidence_Review.pdf 2015 Available: Accessed on: Aug. 04, 2022.

[9] R.S. Kovats, S. Hajat, Heat stress and public health: A critical review, Annu. Rev. Public Health 29 (1) (Apr. 2008) 41–55, https://doi.org/10.1146/annurev.publhealth.29.020907.090843.

[10] J.-M. Robine, S.L.K. Cheung, S. Le Roy, H. Van Oyen, C. Griffiths, J.-P. Michel, F. R. Herrmann, Death toll exceeded 70,000 in Europe during the summer of 2003, Comptes Rendus Biologies 331 (2) (2008) 171–178, https://doi.org/10.1016/j.crvi.2007.12.001.

[11] D. Chen, Overheating in residential buildings: Challenges and opportunities, Indoor and Built Environment 28 (10) (2019) 1303–1306, https://doi.org/10.1177/1420326X19871717.

[12] ONS, "Excess mortality during heat-periods: Jun. 01 to Aug. 31, 2022," Office for National Statistics, 2022. [Online]. Available: https://www.ons.gov.uk/peoplepopulationandcommunity/birthsdeathsandmarriages/deaths/articles/excessmortalityduringheatperiods/englandandwales1juneto31august2022. Accessed on: May 22, 2023.

[13] S. Attia, C. Benzidane, R. Rahif, D. Amaripadath, M. Hamdy, P. Holzer, A. Koch, A. Maas, S. Moosberger, S. Petersen, A. Mavrogianni, J.M. Hidalgo-Betanzos, M. Almeida, J. Akander, H.K. Bakhtiari, O. Kinnane, R. Kosonen, S. Carlucci, Overheating calculation methods, criteria, and indicators in European regulation for residential buildings, Energy and Buildings 292 (2023), 113170, https://doi.org/10.1016/j.enbuild.2023.113170.

[14] K.J. Lomas, S.M. Porritt, Overheating in buildings: Lessons from research, Building Research & Information 45 (1–2) (2016) 1–18, https://doi.org/10.1080/09613218.2017.1256136.

[15] Z. Ren, X. Wang, D. Chen, Heat stress within energy efficient dwellings in Australia, Architectural Science Review 57 (3) (2014) 227–236, https://doi.org/10.1080/00038628.2014.903568.

[16] A. Laouadi, M. Bartko, M.A. Lacasse, A new methodology of evaluation of overheating in buildings, Energy and Buildings 226 (2020), 110360, https://doi.org/10.1016/j.enbuild.2020.110360.

[17] A. Pyrgou, V.L. Castaldo, A.L. Pisello, F. Cotana, M. Santamouris, On the effect of summer heatwaves and urban overheating on building thermal-energy performance in central Italy, Sustainable Cities and Society 28 (2017) 187–200, https://doi.org/10.1016/j.scs.2016.09.012.

[18] S. Porritt, L. Shao, P. Cropper, C. Goodier, Adapting dwellings for heat waves, Sustainable Cities and Society 1 (2) (Jul. 2011) 81–90, https://doi.org/10.1016/j.scs.2011.02.004.

[19] S. Ramakrishnan, X. Wang, J. Sanjayan, J. Wilson, Thermal performance of buildings integrated with phase change materials to reduce heat stress risks during extreme heatwave events, Applied Energy 194 (May 2017) 410–421, https://doi.org/10.1016/j.apenergy.2016.04.084.

[20] M. Zinzi, S. Agnoli, C. Burattini, B. Mattoni, On the thermal response of buildings under the synergic effect of heat waves and urban heat island, Solar Energy 211 (Nov. 2020) 1270–1282, https://doi.org/10.1016/j.solener.2020.10.050.

[21] A. Sakka, M. Santamouris, I. Livada, F. Nicol, M. Wilson, On the thermal performance of low income housing during heat waves, Energy and Buildings 49 (Jun. 2012) 69–77, https://doi.org/10.1016/j.enbuild.2012.01.023.

[22] Z. Zeng, W. Zhang, K. Sun, M. Wei, T. Hong, Investigation of pre-cooling as a recommended measure to improve residential buildings' thermal resilience during heat waves, Building and Environment 210 (Feb. 2022), 108694, https://doi.org/10.1016/j.buildenv.2021.108694.

[23] N. Willand, I. Ridley, A. Pears, Relationship of thermal performance rating, summer indoor temperatures and cooling energy use in 107 homes in Melbourne, Australia, Energy and Buildings 113 (Feb. 2016) 159–168, https://doi.org/10.1016/j.enbuild.2015.12.032.

[24] M. Vanpachtenbeke J. Van den Bulcke J. Van Acker S. Roels Hygrothermal performance of timber frame walls with brick veneer cladding: a parameter analysis in 12th Nordic Symposium on Building Physics (NSB 2020) vol. 172 2020 Tallinn, Estonia 10.1051/e3sconf/202017207002.

[25] M. Jeffree, "Wood - Building the Bioeconomy," European Institute for Wood Preservation, Brussels, Belgium, 2019. [Online]. Available: https://puutuoteteollisuus.fi/images/pdf/WOOD%20-%20BUILDING%20THE%20BIOECONOMY%20Final%20Version%2022.10.2019.pdf. Accessed on: May 04, 2023.

[26] GWMI, "The European wooden-construction sector is evolving rapidly," Global Wood Markets Info, Online https://www.globalwoodmarketsinfo.com/european-wooden-construction-sector-evolving-rapidly/ 2022 Available: Accessed on: Jun. 01, 2023.

[27] G. House "Global timber outlook, " Gresham House Specialist Asset Management, Online https://greshamhouse.com/wp-content/uploads/2020/07/GHGTO2020FINAL.pdf 2020 Available: Accessed on: Jun. 06, 2023.

[28] ISO, ISO 17772–1. Energy performance of buildings – Indoor environmental quality. Part 1: Indoor environmental input parameters for the design and assessment of energy performance in buildings International Standards Organization 2017 Geneva, Switzerland.

[29] S. Flores-Larsen, C. Filippín, F. Bre, New metrics for thermal resilience of passive buildings during heat events, Building and Environment 230 (Feb. 2023), 109990, https://doi.org/10.1016/j.buildenv.2023.109990.

[30] R. Rahif, M. Hamdy, S. Homaei, C. Zhang, P. Holzer, S. Attia, Simulation-based framework to evaluate resistivity of cooling strategies in buildings against overheating impact of climate change, Building and Environment 208 (Jan. 2022), 108599, https://doi.org/10.1016/j.buildenv.2021.108599.

[31] M. Sheng, M. Reiner, K. Sun, T. Hong, Assessing thermal resilience of an assisted living facility during heat waves and cold snaps with power outages, Building and Environment 230 (Feb. 2023), 110001, https://doi.org/10.1016/j.buildenv.2023.110001.

[32] ASHRAE ANSI, ASHRAE standard 169: Climatic data for building design standards 2013 American Society of Heating, Refrigerating and Air Conditioning, Engineers, Atlanta, GA, USA.

[33] S. Attia, R. Levinson, E. Ndongo, P. Holzer, O.B. Kazanci, S. Homaei, C. Zhang, B. W. Olesen, D. Qi, M. Hamdy, P. Heiselberg, Resilient cooling of buildings to protect against heat waves and power outages: Key concepts and definition, Energy and Buildings 239 (May 2021), 110869, https://doi.org/10.1016/j.enbuild.2021.110869.

[34] C. Zhang, et al., IEA EBC Annex 80 - Dynamic simulation guideline for the performance testing of resilient cooling strategies: Version 2, DCE Technical Reports No. 306 (2023). https://doi.org/10.13140/RG.2.2.12309.19687.

[35] D. Amaripadath, M. Velickovic, S. Attia, Performance evaluation of a nearly zero-energy office building in temperate oceanic climate based on field measurements, Energies 15 (18) (2022) pp, https://doi.org/10.3390/en15186755.

[36] CEN, EN 16798–1: Energy performance of buildings - Ventilation for buildings - Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics, European Committee for Standardization:, Brussels, Belgium, 2019.

[37] D. Amaripadath, R. Rahif, W. Zuo, M. Velickovic, C. Voglaire, S. Attia, Climate change sensitive sizing and design for nearly zero-energy office building systems in Brussels, Energy and Buildings 286 (2023), 112971, https://doi.org/10.1016/j.enbuild.2023.112971.

[38] ANSI/ASHRAE, ASHRAE standard 55: Thermal environmental conditions for human occupancy, American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, GA, USA, 2020.

[39] G. Betti, F. Tartarini, C. Nguyen, S. Schiavon, CBE Clima Tool: a free and open-source web application for climate analysis tailored to sustainable building design, Version 0.8.10 (2022). https://doi.org/10.48550/arXiv.2212.04609.

[40] W. Ji, Y. Zhu, H. Du, B. Cao, Z. Lian, Y. Geng, S. Liu, J. Xiong, C. Yang, Interpretation of standard effective temperature (SET) and explorations on its modification and development, Building and Environment 210 (2022), 108714, https://doi.org/10.1016/j.buildenv.2021.108714.

[41] Passive House. [Online]. Available: https://passiv.de/en/02_informations/02_passive-house-requirements/02_passive-house-requirements.htm. Accessed on: June 08, 2023.

[42] CIBSE, CIBSE Guide A: Environmental design. Chartered Institution of Building Services Engineers 2015 London, UK.

[43] S. Attia, C. Gobin, Climate change effects on Belgian households: A case study of a nearly zero energy building, Energies 13 (20) (Oct. 2020) 5357, https://doi.org/10.3390/en13205357.

[44] E. Mlecnik S. Attia S. Loon Net Zero Energy Building: a review of current definitions and definition development in Belgium Proc. of Passive House 2011 Brussels, Belgium.

[45] T. D. Meester Etude du comportement thermique et energétique d'une maison passive par modélisation dynamique 2008 Université Catholique de Louvain, Ottignies-Louvain-la-Neuve Belgium MSc Thesis https://dial.uclouvain.be/memoire/ucl/en/object/thesis%3A10413/datastream/PDF_01/view.

[46] S. Attia, "Building energy model for a timber nearly-zero energy building: Kettenis house in Belgium," Harvard Dataverse, Cambridge, MA, USA (2021), https://doi.org/10.7910/DVN/LC9LLU.

[47] T. Cao, J. Zhu, X. Xu, H. Du, Q. Zhao, Parametric study on the sleep thermal environment, Building Simulation 15 (5) (May 2022) 885–898, https://doi.org/10.1007/s12273-021-0840-5.

[48] L. Lan, Z. Lian, H. Huang, Y. Lin, Experimental study on thermal comfort of sleeping people at different air temperatures, Building and Environment 73 (Mar. 2014) 24–31, https://doi.org/10.1016/j.buildenv.2013.11.024.

[49] K. Okamoto-Mizuno, K. Mizuno, Effects of thermal environment on sleep and circadian rhythm, Journal of Physiological Anthropology 31 (1) (May 2012) 14, https://doi.org/10.1186/1880-6805-31-14.

[50] Kittel, C., Present and future sensitivity of the Antarctic surface mass balance to oceanic and atmospheric forcings: insights with the regional climate model MAR, Ph.D. Thesis, Université de Liège, Liège, Belgique. https://hdl.handle.net/2268/258491.

[51] S. Doutreloup, X. Fettweis, R. Rahif, E. Elnagar, M.S. Pourkiaei, D. Amaripadath, S. Attia, Historical and future weather data for dynamic building simulations in Belgium using the regional climate model MAR: Typical and extreme meteorological year and heatwaves, Earth System Science Data 14 (Jul. 2022) 3039–3051, https://doi.org/10.5194/essd-14-3039-2022.

[52] K. De Ridder, H. Gallée, Land surface-induced regional climate change in southern Israel, Journal of Applied Meteorology and Climatology 37 (11) (Nov. 1998) 1470–1485, https://doi.org/10.1175/1520-0450(1998)037%3C1470:LSIRCC%3E2.0.CO;2.

[53] D. Ferrari T. Lee Beyond TMY: Climate data for specific applications Proc. 3rd International Solar Energy Society conference – Asia Pacific region (ISES-AP08) November 2008 Sydney Beyond TMY paper WC0093.pdf.

[54] ISO, ISO 15927–4: Hygrothermal performance of buildings - Calculation and presentation of climatic data - Part 4: Hourly data for assessing the annual energy use for heating and cooling International Standards Organization 2005 Geneva, Switzerland.

[55] G. Ouzeau, J.M. Soubeyroux, M. Schneider, R. Vautard, S. Planton, Heat waves analysis over France in present and future climate: Application of a new method on the EURO-CORDEX ensemble, Climate Services 4 (Dec. 2016) 1–12, https://doi.org/10.1016/j.cliser.2016.09.002.

[56] Bigladder Software "Elements," Rocky Mountain Institute, Basalt Co, USA, Online https://bigladdersoftware.com/projects/elements/ 2016 Available: Accessed on: May 12, 2023.

[57] S. Doutreloup and X. Fettweis, "Typical & extreme meteorological year and heatwaves for dynamic building simulations in Belgium based on MAR model simulations," Zenodo, Nov. 09, 2021, https://doi.org/10.5281/zenodo.5606983.

[58] HSE, "Temperature at Work," Health & Safety Information, Merseyside, UK, Online https://www.unison.org.uk/content/uploads/2013/06/Briefings-and-CircularsTemperature-at-Work-Information-Health-and-Safety-Information-Sheet2.pdf 2010 Available: Accessed: Nov. 11, 2022.

[59] R. Rahif, S. Attia, IOhD (Calculation & illustration), IOcD (Calculation & illustration), AWD (Calculation & illustration), ACD (Calculation & illustration), CCOhR (Calculation), CCOcR (Calculation), Zonal OpT (illustration), and HWs (illustration), Zenodo (2022), https://doi.org/10.5281/zenodo.7326901.

[60] B. Slee A. Upadhyay R. Hyde Evaluating the influence of thermal mass and window size in a direct gain system on the annual and lifetime energy consumption of domestic Australian light weight construction Proc. 8th Windsor Conference: Counting the Cost of Comfort in a changing world Apr. 2014 Cumberland Lodge, Windsor, UK.