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Multi-criteria thermal resilience certification scheme for indoor built environments during heat waves

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ABSTRACT

With climate change, the indoor built environment is expected to significantly influence the occupant's safety and well-being. A novel multi-criteria thermal resilience certification scheme for indoor built environments during extreme heat events is proposed in this paper. The certification scheme considers overheating, thermal comfort, heat stress, and hygrothermal discomfort in built environments. These criteria are quantified using key performance indicators like indoor overheating degree, hours of exceedance, wet-bulb globe temperature, and heat index, respectively. This scheme is developed based on existing best practices like standards, rating systems, and literature. The scheme is implemented on a benchmark building energy performance model for detached post-World War II dwellings in Belgium as a case study using weather data measured from the City of Brussels. The indoor overheating in the reference dwelling is assessed with a static threshold of 27 °C for the bedrooms and adaptive thresholds for other areas. The analysis found that the building performance is within the defined threshold levels throughout the heat wave duration for all criteria. Therefore, the reference dwelling got a maximum attainable score of four points and is rated five-star for thermal resilience during heat waves. The proposed certification scheme is intended as a standardized framework and highlights the need for further revisions in building performance policies and guidelines.

1. Introduction

1.1. Study background

Extreme heat events like heat waves are more frequent and intense due to local and global climate change. Such occurrences have an adverse effect on indoor thermal environments in buildings and increase cooling energy use [1]. A recent study from [2] found about 61672 heat-related deaths with a steep increase in mortality rate with age during the summer of 2022 in Europe. Additionally, 3729 additional deaths in India and Pakistan during May 2015, 131 additional deaths in California in the United States during July 2016, and 347 additional deaths in Australia during January 2009 were recorded related to heat [3,4]. To reduce the detrimental impacts of climate change on the built environment, experts from all over the world are working together to improve thermal resilience through international collaborations such as the International Energy Agency (IEA) Energy in Buildings and Communities (EBC) Annex 80 – Resilient cooling of buildings [5]. The primary objective of this collaboration is to create, evaluate, and convey resilient cooling solutions and overheating mitigation. This is a significant avenue of research since studies from [6,7] indicate that over a billion people will experience intolerable indoor temperature due to lack of access to air-conditioning and warming climates. Building simulation communities started investigating how existing building stock might fare during a heat event [8,9] after the fatal heat waves that struck Europe in 2006 [10] and New York in 2003 [11].

1.2. Literature review

The impact of changing climates and its challenges on high-performance building operations in terms of thermal and energy performance is studied by [12]. The findings show an increase in indoor temperature and subsequent increase in cooling loads in the future, indicating the need for energy-efficient retrofit measures. Studies from [13] suggested a methodology to assess strategies to improve heat wave resilience by integrating building design, urban and infrastructure development, social research, and public health. The findings from [13] indicate the need for more focused building and planning measures to

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raise heat stress resilience significantly. Similarly, findings from [14] in San Francisco found significant variations in indoor air temperature between conditioned and unconditioned residential buildings. The study indicates the significance of stringent performance standards for thermal resilience in changing climates. The importance of overheating and thermal comfort in residential and tertiary buildings are addressed in [15], and automated movable shading was found to be an effective strategy against overheating. In line with this study, [16] assessed thermal performance in buildings and showed that insulated buildings had higher interior temperatures, needing more cooling during extremely hot weather than non-insulated buildings, thus making occupants more vulnerable to heat stress. Learned lessons from [17] indicate the significance of using a problem-oriented approach to assess the efficacy of climate-resilient measures. The study recommends that context-specific guidelines with proper coordination among the stakeholders are necessary to improve thermal resilience and health outcomes.

Existing initiatives from major standardization and research organizations focusing on building thermal resilience are listed in [18]. The suggestions from [18] point to the need for more thermal stress guidelines, thresholds, and resilience indicators, among others. Among the international initiatives, IEA EBC Annex 80 is a network that includes participants and interested parties spanning multiple countries [19]. This research network [5] focused on: a. defining resilience of cooling measures through assessment of various disciplines, including management of risks associated with disasters like heat waves and power outages as in [20], and selection of performance indicators from existing literature, b. providing solutions through guidelines to implement resilient cooling systems into both energy performance calculations using dynamic simulations [21] and approaches for indoor overheating estimation, c. showcasing the learned lessons from the field application of resilient cooling strategies in different building typologies, and d. offering policy guidelines for building resilience in terms of cooling strategies and energy efficiency [22].

Among these initiatives, RELi version 2.0 [23] from the United States Green Building Council (USGBC) proposed a recommendation for heat wave risk mitigation, including a step-by-step guideline for improving thermal survivability in buildings. The standard recommends maximum and minimum temperature limits for buildings like hospitals, nursing homes, pharmacies, and dwellings, among others to maintain optimal indoor temperatures. The standard also suggests passive measures like natural ventilation and active measures like air-conditioning during events like power outages, which might happen concurrently with heat waves [24]. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) created a multidisciplinary task group to coordinate resilience related activities and to approve a roadmap for resilience related plans [18]. Additionally, ASHRAE also released a position document in collaboration with Chartered Institution of Building Services Engineers (CIBSE) advocating for best practices for built environments that are resilient and sustainable [25]. Similarly, a significant step towards climate resilience integration in building and infrastructure design, guides, and codes is undertaken by National Research Council of Canada (NRC) under the Climate-Resilient Buildings and Core Public Infrastructure Initiative from 2016 to 2021 with the support of Infrastructure Canada and Pan-Canadian Framework on Clean Growth and Climate Change [26]. A representation of major initiatives undertaken related to resilience by different organizations based on their country of location is listed in Table 1.

In addition to the above-mentioned initiatives, thermal resilience in buildings has been addressed in existing literature. Findings from [27] focused on developing a framework for thermal resilient buildings. However, it is implemented for the heating season and further adjustments are suggested to evaluate resilience during cooling seasons. Moreover, the study only considered the effects of temperature and overlooked the impacts of humidity. Similarly in line with this study, [28] also proposed new metrics for passive building thermal resilience based on temperature, overlooking effects of humidity. Studies from [29] proposed a Thermal Resilience Index based on Standard Effective Temperature (SET) and labeling for cooling seasons. Additionally, this study points out the lack of acceptance criteria in thermal resilience and need for further studies to define different classes of thermal resilience. Research from [30,31] evaluated thermal resilience in different building typologies and proposed practical measures to improve thermal resilience during heat waves. The existing knowledge is supplemented by [32] that suggested the significance of updating various codes and rating systems to integrate thermal resilience. The findings from [32] also pointed out the need for clear thresholds to ensure occupant safety and standardized methods for assessing thermal vulnerability in buildings. Although there is extensive research on thermal resilience in built environments, there is a lack of comprehensive multi-criteria certification schemes to evaluate building vulnerability during heat waves.

Building certification schemes can either be multi-attribute or single attribute [33]. Certification schemes like Leadership in Energy and Environmental Design (LEED), Living Building Challenge, Nearly Zero-Energy Building (NZEB), Passive House, WELL Building Standard, and Building Research Establishment Environmental Assessment Method (BREEAM) are multi-attribute schemes as they assess the overall performance, including emissions in addition to energy and water use [33]. However, certifications like Energy Star focus solely on building energy and water use, which makes them single attribute schemes as per [33]. Among these certification schemes, Energy Star and NZEB schemes focus primarily on energy performance, whereas LEED, Living Building Challenge, Passive House, WELL, and BREEAM consider indoor environmental quality (IEQ) alongside energy performance. Among these schemes, WELL defines comfort as one of the seven parameters that impact occupant health. LEED rates the buildings using a point-based system from certified to gold, whereas BREEAM rates buildings based on a similar point-based system from Bronze to Platinum with minimum point requirement for each category by WELL. BREEAM rating benchmarks are created using a point-based system from unclassified to outstanding and a star rating from one to five [34]. An environmental weighting factor that considers the relative importance of each section is multiplied by the total number of credits earned in each category. Additionally, more robust requirements should be introduced to the certification process to ensure an ideal indoor thermal environment in changing climates.

1.3. Knowledge gaps and relevance

Thermal comfort in buildings has been addressed in existing literature like [35,36]. However, the review of existing literature indicates a lack of holistic assessment approaches considering multiple thermal performance criteria in built environments during extreme heat events. Most schemes do not include key performance indicators (KPIs) for multi-zonal and time-integrated evaluations for short-term heat events except [29]. Therefore, a comprehensive approach to thermal resilience assessment is imperative for future revisions in building regulations like the Energy Performance of Buildings Directive (EPBD). Such necessities are amplified when extreme heat events are becoming more frequent, longer, and larger globally due to climate change, according to the World Health Organization [37]. Additionally, the benchmark model for detached post-World War II dwellings is also relevant since these dwellings represent up to 48 % of the Belgian building stock. In addition, 85 % of these dwellings are used by the elderly above 65 years [38]. The aging occupants in these dwellings are particularly vulnerable to heat exposure during heat waves. Moreover, a huge proportion of these dwellings are free running with no air-conditioning. Hence, in a worsening climate scenario, the need for standardized frameworks to assess thermal resilience in built environments is irrefutable to ensure occupant comfort during heat waves.

Table 1
Building resilience initiatives undertaken by various organizations based on their country of location.

Initiative	Countries
IEA EBC Annex 80	**Participants:** Australia, Austria, Belgium, Brazil, Canada, China, Denmark, France, Germany, Italy, Norway, Singapore, Sweden, Switzerland, Türkiye, United Kingdom, United States of America **Interested parties:** Greece, India, Mexico, United Arab Emirates
USGBC RELi 2.0 standard	United States of America
ASHRAE Task Group	United States of America
ASHRAE/CIBSE Joint Statement	United States of America
NRCC Climate-Resilient Buildings and Core Public Infrastructure Initiatives	Canada

1.4. Objectives and novelty

Based on these observations, the main aim of this paper is to develop a multi-criteria thermal resilience certification scheme for built environments during extreme heat events. The multi-criteria scheme integrates overheating, thermal comfort, heat stress, and hygrothermal discomfort into one framework. It encompasses universally accepted standards, international rating systems, and state-of-the-art literature, allowing for comparing performance thresholds among several climatic zones with boundary conditions. The multi-criteria thermal resilience certification scheme can be used to evaluate existing, new, or renovated buildings by providing an evidence-based assessment of their thermal performance during extreme heat events like heat waves. Furthermore, the time-integrated indicator incorporated into the scheme allows multi-zonal evaluations supporting purpose-based thermal modeling. The developed scheme is assessed using a case study of a benchmark model for post-world war dwellings in Belgium. The reference dwelling is rated for thermal performance during a real heat wave event in Brussels. The study's main novelty is that it developed an in-depth certification scheme for thermal resilience to assess how well buildings operate during heat waves. The paper is a comprehensive study conducted as a part of the IEA EBC Annex 80, which adds to the work's originality.

2. Methodology

An overview of the methodology used for developing the certification scheme and implementing it in a benchmark model for post-World War II dwellings in Belgium is described here.

2.1. Multi-criteria thermal resilience certification scheme

The proposed multi-criteria thermal certification scheme is shown in Fig. 1. This certification scheme is designed based on concepts and KPIs identified from existing best practices as follows: a. standards like ISO 17772–1 – Energy performance of buildings [39], CIBSE TM 52 – The limits of thermal comfort: avoiding overheating [40], and ISO 7243 – Ergonomics of the thermal environment [41], b. certification schemes like LEED [42], and c. existing literature like [43–45]. The framework is developed as a part of collaborative work from IEA EBC Annex 80 – Resilient cooling of buildings [19]. Although there are existing EPBD requirements on building performances depending on Member States in the European Union (EU), this certification scheme can inform assessment metrics and concepts to assess thermal resilience in built environments during extreme heat events without necessarily having to look elsewhere to make advanced assessments. In general, the developed scheme considers four main criteria and KPIs for thermal resilience certification, as listed in Table 2. Since the certification assesses various aspects of thermal resilience during heat waves, the indicators used can have some overlap since they primarily use input variables like air temperature, relative humidity, etc. Additionally, the classification based on [45] is used for this study as IOD and building response are calculated with thresholds prescribed for the study location. Furthermore, heat wave characteristics are adapted to local climate conditions. While IOD and hours of exceedance (HE) focus on operative temperature (°C) in indoor environments, wet-bulb globe temperature (WBGT) incorporates air temperature (°C) and wet-bulb temperature (°C) calculated using air temperature (°C) and relative humidity (%). Heat Index integrates air temperature (°C) and relative humidity (%) to quantify heat stress.

The threshold limits for IOD and HE are adopted from ISO 17772–1 – Energy performance of buildings [39] based on building category and operation. The risk levels for IOD are obtained from [45], and an Excel-based tool for calculating IOD is available in [50]. The running mean temperature (T_{rm}) is calculated based on outdoor air temperatures from previous days. The threshold limits for WBGT and HI are taken from international certification schemes such as LEED and RELi [51]. The certification scheme uses a resilience rating based on points like international certification schemes like LEED [42] and WELL [52]. Furthermore, built environment performance during a seven-day heat wave period is used for resilience assessment, and this is based on the methodology from the LEED passive survivability test mentioned in [53]. Each criterion is equally weighted at a score of one in line with LEED certification scheme [42], and the maximum score is four, which will certify the building as five-star, and the lowest possible score is zero, which will certify the building as one-star. The resilience score is calculated as in Eq. (1). Additionally, there are no minimum score requirements for individual criteria. More information on resilience scoring and ratings can be found in Fig. 1. The scheme can be applied to new, existing, or renovated residential and commercial buildings.

$$Score = IOD_W + \left[\frac{HE_{hours}(\%) + WBGT_{hours}(\%) + HI_{hours}(\%)}{100} \right] \quad (1)$$

where IOD_W is the weighting factor for indoor overheating, $HE_{hours}(\%)$ is the percentage of HE hours that are within the temperature thresholds, $WBGT_{hours}(\%)$ is the percentage of WBGT hours that are within the thresholds, and $HI_{hours}(\%)$ is the percentage of HI hours that are within the thresholds.

2.2. Application on a post-World War II dwelling as a case study

The reference post-World War II dwelling is in Wezembeek-Oppem in Belgium at coordinates 50.84° N, 4.49° E, near Brussels, in mixed humid climate according to ASHRAE 169 – Climatic data for building design standards [54]. The benchmark dwelling represents detached dwellings constructed in Belgium from the late 1940s to 1969. It represents dwellings with a surface area of 150 to 300 m^2 in urban areas [38] The geometry, building materials, surface area, and occupant density are comparable in these detached houses built from the late 1940s to 1969, as a consequence of laws of 1939 that mandated building permit application from an architect. This prompted many homeowners to go for identical dwelling designs from catalogs provided by the architects for lower fees. Additionally, limited design alternatives were implemented to reduce construction costs, resulting in typical De Taeye-archetype houses constructed with ceramic roof tiles and red bricks [38]. The Belgian Federal Government planned to build 100000 houses in 1954 but ended up building 285166 by 1969 [38]. Lightweight concrete is used to construct the floors [55]. The reference dwelling has a rectangular

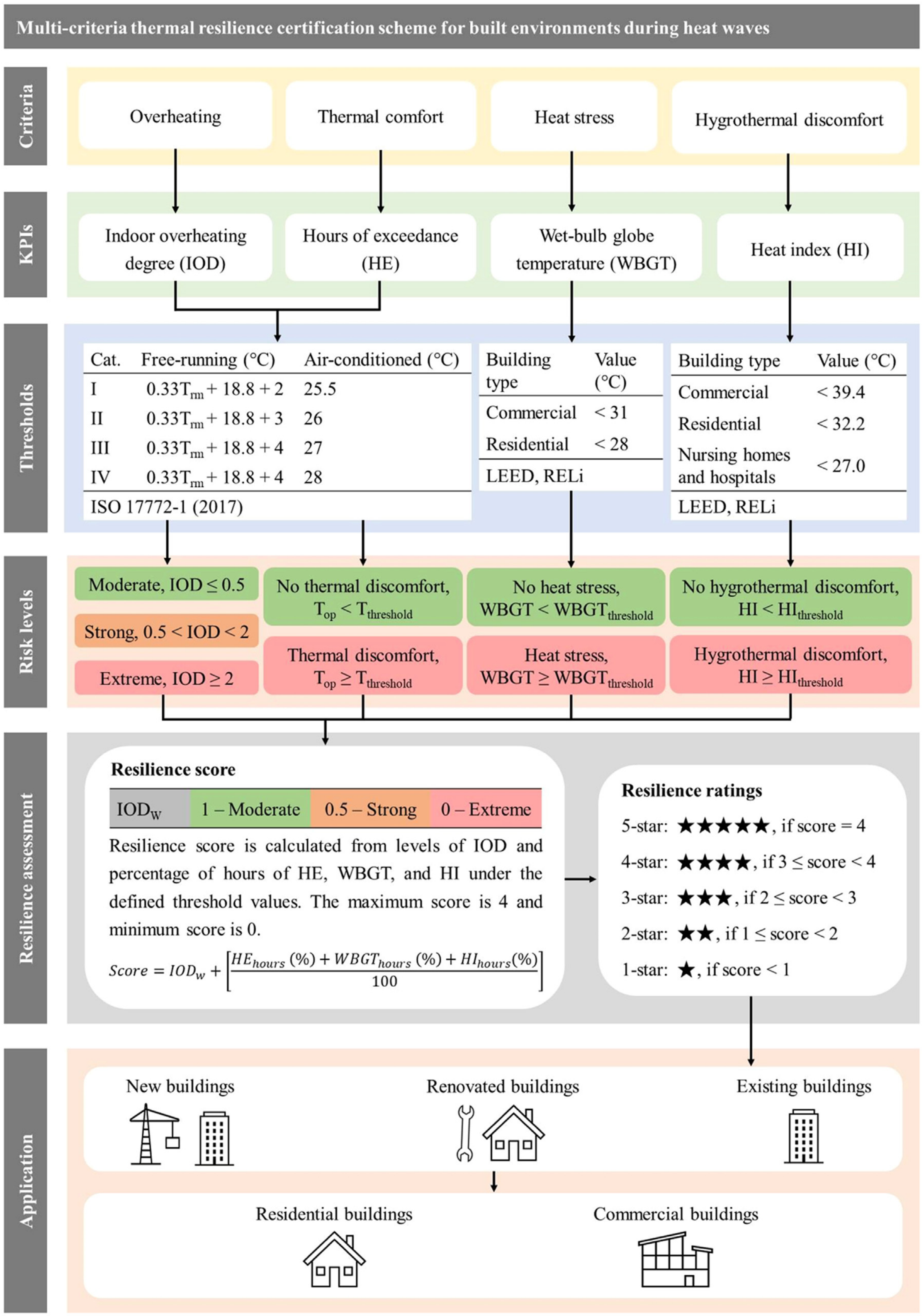

Fig. 1. Multi-criteria thermal resilience certification scheme for built environments during heat waves.

Table 2
Main evaluation criteria and key performance indicators used in the proposed thermal resilience certification scheme.

No.	Parameter	KPI	Equation	Literature	Implementation
1	Overheating	Indoor overheating degree (IOD)	$IOD = \frac{\sum_{z=1}^{Z}\sum_{i=1}^{N_{occ}(z)}[(T_{in,z,i} - T_{comf,upper,z,i})^{+} \times t_{i,z}]}{\sum_{z=1}^{Z}\sum_{i=1}^{N_{occ}(z)} t_{i,z}}$ where Z is number of total conditioned building zones, i is the occupied hour counter, $N_{occ}(z)$ is number of zonal occupied hours in zone z, $T_{in,z,i}$ is the indoor operative temperature (°C) in zone z at time step i, $T_{comf,upper,z,i}$ is the maximum comfort threshold in zone z at hour I [43].	Hamdy et al. 2017 [43]	Amaripadath et al. 2023 [4]
2	Thermal comfort	Hours of exceedance (HE)	$HE = \sum_{i=1}^{occupied\ hours} W_{fi}$ where $W_{fi} = 1;\ T_{op,i} - T_{op,i,upper} \geq 1°C\ for\ adaptive\ model\ and\ 0°C\ for\ static\ model$ $W_{fi} = 0;\ T_{op,i} - T_{op,i,upper} < 1°C\ for\ adaptive\ model\ and\ 0°C\ for\ static\ model$ [46]	CIBSE TM52, 2013 [40]	Heracleous and Michael 2018 [47]
3	Heat stress	Wet-bulb globe temperature (WBGT)	$WBGT = 0.67 \times T_W + 0.37 \times T_a$ where T_W is wet-bulb temperature (°C), T_a is air temperature (°C). T_W (°C) is calculated using temperature T_a (°C) and hourly relative humidity $RH\%$ (%) [48]. $T_W = T_a \times arctan(0.151977 \times (RH\% + 8.313659)^{\frac{1}{2}}) + arctan(T_a + RH\%) - arctan(RH\% - 1.676331) + 0.00391838 \times (RH\%)^{\frac{3}{2}} \times arctan(0.023101 \times RH\%) - 4.686035$	ISO 7243, 2017 [41]	Lemke and Kjellstrom 2012 [49]
4	Hygrothermal discomfort	Heat index (HI)	$HI = -8.78469475556 + 1.61139411 \times T_a + 2.33854883889 \times RH\% - 0.14611605 \times T_a \times RH\% - 0.012308094 \times T_a^2 - 0.0164248277778 \times RH\%^2 + 0.002211732 \times T_a^2 \times RH\% + 0.00072546 \times T_a \times RH\%^2 - 0.000003582 \times T_a^2 \times RH\%^2$ [31]	Steadman 1979 [44]	Sun et al. 2020 [31]

layout with two floors, unoccupied attics, and a pitched roof. In addition, it has a cellar and an underground garage. The envelope infiltration rate is 14.5 ACH. The house has an average surface area of 259 m^2 and a window-to-wall ratio (WWR) of 12 %. The external heat gains in the reference dwelling are low due to small windows. The dwelling has 2 occupants. The thermal zones in the dwelling are divided into living areas, i.e., the living, dining, kitchen, and sleeping areas, i.e., the bedrooms, and short-presence areas, i.e., the hallways and bathrooms. The dwelling has an average energy use of 17.7 kWh/m^2/year for electricity and 148.7 kWh/m^2/year for heating with domestic hot water. The dwelling is free-running with no mechanical ventilation and is naturally ventilated through the window openings during summer.

Data loggers were installed in the dwelling during the summers of 2018 and 2019 to conduct field measurements, gathering air temperature, relative humidity, carbon dioxide, and absolute pressure values every 15 mins stored in a cloud environment [38]. Occupancy schedules, lighting, plug loads, and domestic hot water are created using the survey results, energy use data, and field measurement data [38]. The accuracy of the building energy models is confirmed through model calibration according to ASHRAE Guideline 14 – Measurement of energy, demand, and water savings [56] using monthly energy bills for four years. For the use of electricity and natural gas, the calibration of the reference dwelling provided a Normalized Mean Bias Error (NMBE) of 2.75 % and 1.60 % and a Coefficient of Variance (Root Mean Square Error) (CV(RMSE)) of 0.02 % and 9.50 % for electricity and natural gas, respectively [38]. These values are within the thresholds of 5 % for NMBE and 15 % for CV(RMSE) recommended by ASHRAE Guideline 14 – Measurement of energy, demand, and water savings. The reference post-World War II dwelling with the simulation model, façades, and floor plans is shown in Fig. 2. The reference dwelling is a Category III building as in ISO 17772–1 – Energy performance of buildings [39]. Even though it is a free-running dwelling, the static model thresholds from ISO 17772–1 – Energy performance of buildings are used to evaluate the bedrooms based on studies from [4]. Other zones like the office, living, dining, and kitchen are modeled with adaptive model thresholds from ISO 17772–1 – Energy performance of buildings [39]. The simulation model is developed using DesignBuilder v6 and EnergyPlus v9. The building simulation model and more details for the reference dwelling can be accessed from [57]. All occupied zones in the reference dwelling are included in the calculation along with the whole dwelling using EnergyPlus.

A local weather station installed in the City of Brussels (coordinates: 50.86° N, 4.35° E) provided the weather data for the analysis. The weather station Davis Vantage pro2 plus with a sensor suite consisting of air temperature and relative humidity sensors in a passive radiation shield [58], is mounted six meters above the ground on a lamp post to prevent vandalism and within the urban canopy layer on the street with regular traffic and buildings on either side. The observations are made for the summer of 2022 at 15-minute intervals. More details on weather station setup and specifications are available in [59]. A heat wave is detected from August 10, 2022, to August 16, 2022, and embedded in the energy simulations using a Python script from [60] developed based on [61]. The study used the heat wave identification methodology from [62] based on outdoor daily mean air temperature, implemented in [4,63]. This heat wave identification methodology is recommended by the IEA EBC Annex 80 – Resilient cooling of buildings [21]. The ambient conditions of heat wave [59] like air temperature varied from 17.8 °C to 32 °C, and relative humidity varied from 21 % to 74 %, according to measured data as shown in Fig. 3.

3. Results

In the context of the proposed certification scheme, the reference post-World War II dwelling is evaluated for overheating, thermal comfort, heat stress, and hygrothermal discomfort in indoor built environments. The assessment showed that all the occupied areas except Bedroom 1 had satisfactory thermal resilience during the observed heat wave. Hence, these areas can be treated as thermal safety zones for the occupants. The zonal and building level air temperature (°C) and relative humidity (%) levels are shown in Fig. 4. The building level and air temperature ranged from 23.6 °C to 27.8 °C with a variation of 4.2 °C, and relative humidity ranged from 29.8 % to 56.4 % with a variation of 26.6 % during the heat wave. Among the zones, maximum and minimum air temperatures of 29.3 °C and 23.4 °C were observed in the kitchen and office, whereas the maximum and minimum relative humidity of 60.1 % and 27 % were found in the office.

The results of the thermal performance evaluations are shown in Fig. 5.

Fig. 2. Illustration of the reference dwelling, simulation model, façades, and floor layouts.

a. Overheating in the reference dwelling is evaluated using IOD (°C). The building level IOD is 0.01 °C, and the heat wave mildly impacted the reference dwelling. At the zone level, the kitchen, living, office, and bedroom 2 had an IOD value of 0 °C, making it less prone to overheating. A stricter static comfort model is used to analyze the bedrooms, and the results are still satisfactory. The reference dwelling received a one for overheating during the recent heat wave at the building level.
b. Thermal comfort in the reference dwelling is assessed using HE (h). Overall, no hours of exceedance in operative temperature is observed at building and zonal levels in the office, dining, living and kitchen for adaptive comfort limits. However, Bedroom 1 and Bedroom 2 showed 18 h and 2 h, exceeding the static comfort limit of 27 °C. These add up to 10.7 % and 1.2 % of the total occupied hours and are attributed to more stringent static comfort limits to evaluate the bedrooms. Of the 18 hours of exceedance in Bedroom 1, 12 h fell during the sleep hours of the elderly population [64], which adversely impact thermal comfort. Therefore, Bedroom 1 is not recommended for sleeping during heat waves as a caution. However, the reference dwelling scores one for thermal comfort at the building level during the current heat wave.
c. Heat stress in the reference dwelling is analyzed using WBGT (°C) [65]. WBGT hourly fluctuations fell within the specified limits. At no time are these values greater than the building and zone levels threshold during the heat wave. Living, dining, and kitchen areas showed higher WBGT values at the zonal level than bedrooms and offices. For the present heat wave, the reference dwelling receives a one on the scale for heat stress.

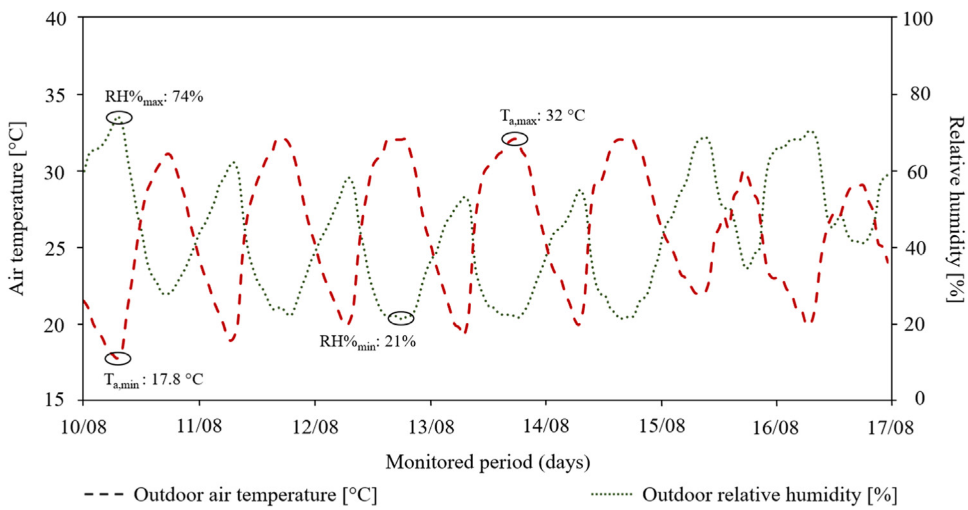

Fig. 3. Outdoor air temperature (°C) and relative humidity (%) during the heat wave in Brussels from August 10, 2022, to August 16, 2022.

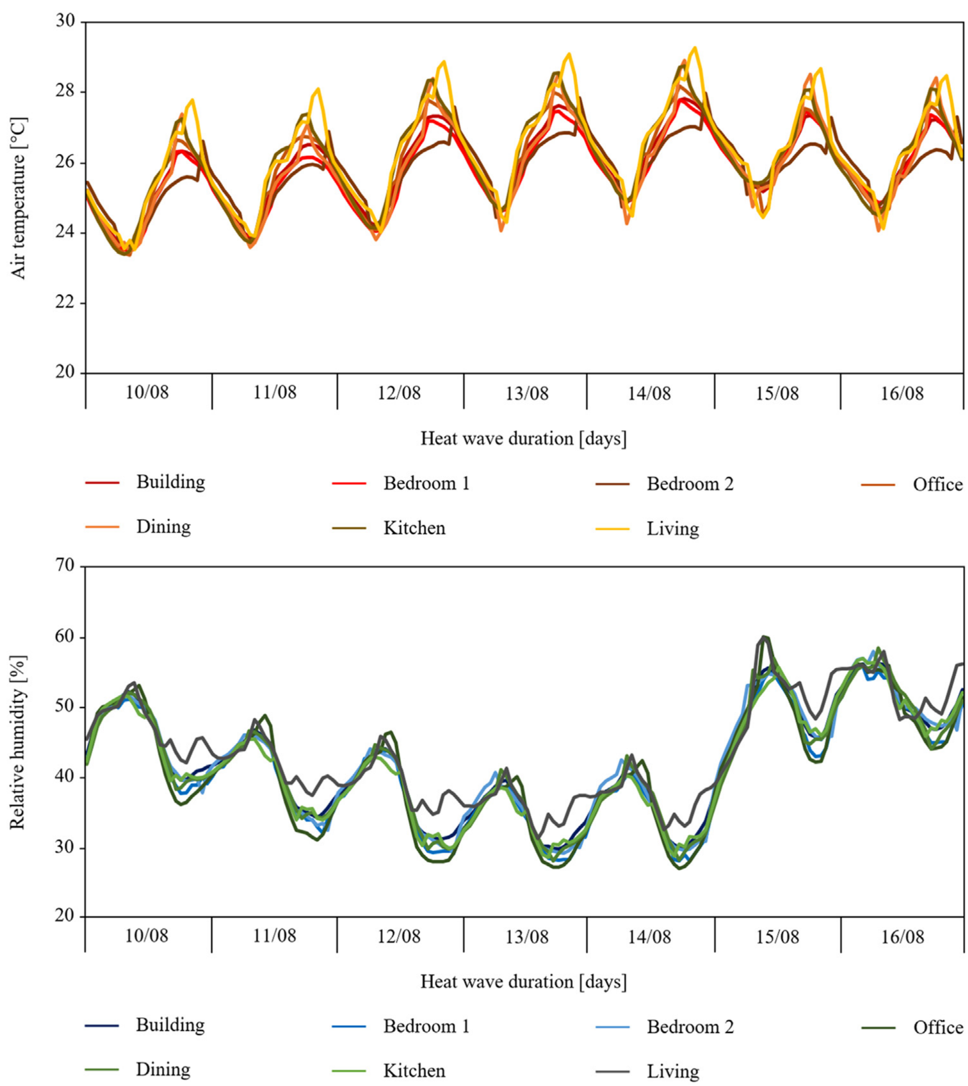

Fig. 4. Building and zonal level variations in air temperature (°C) and relative humidity (%) in the reference dwelling during the heat wave in Brussels from August 10, 2022, to August 16, 2022.

d. Hygrothermal discomfort in the reference dwelling is evaluated using HI (°C). HI changes on an hourly basis are considerably below the defined limits and did not exceed the threshold for building and zone levels. HI values in the living, dining, and kitchen areas on Floor 0 are greater than those in the bedroom and office areas on Floor 1. At the building level, the reference dwelling scores a one for hygrothermal discomfort during the present heat wave.

The certificate for resilience score and rating for the reference post-world war dwelling is shown in Fig. 6. As indicated, the benchmark dwelling scored a point for all four criteria evaluated. The reference

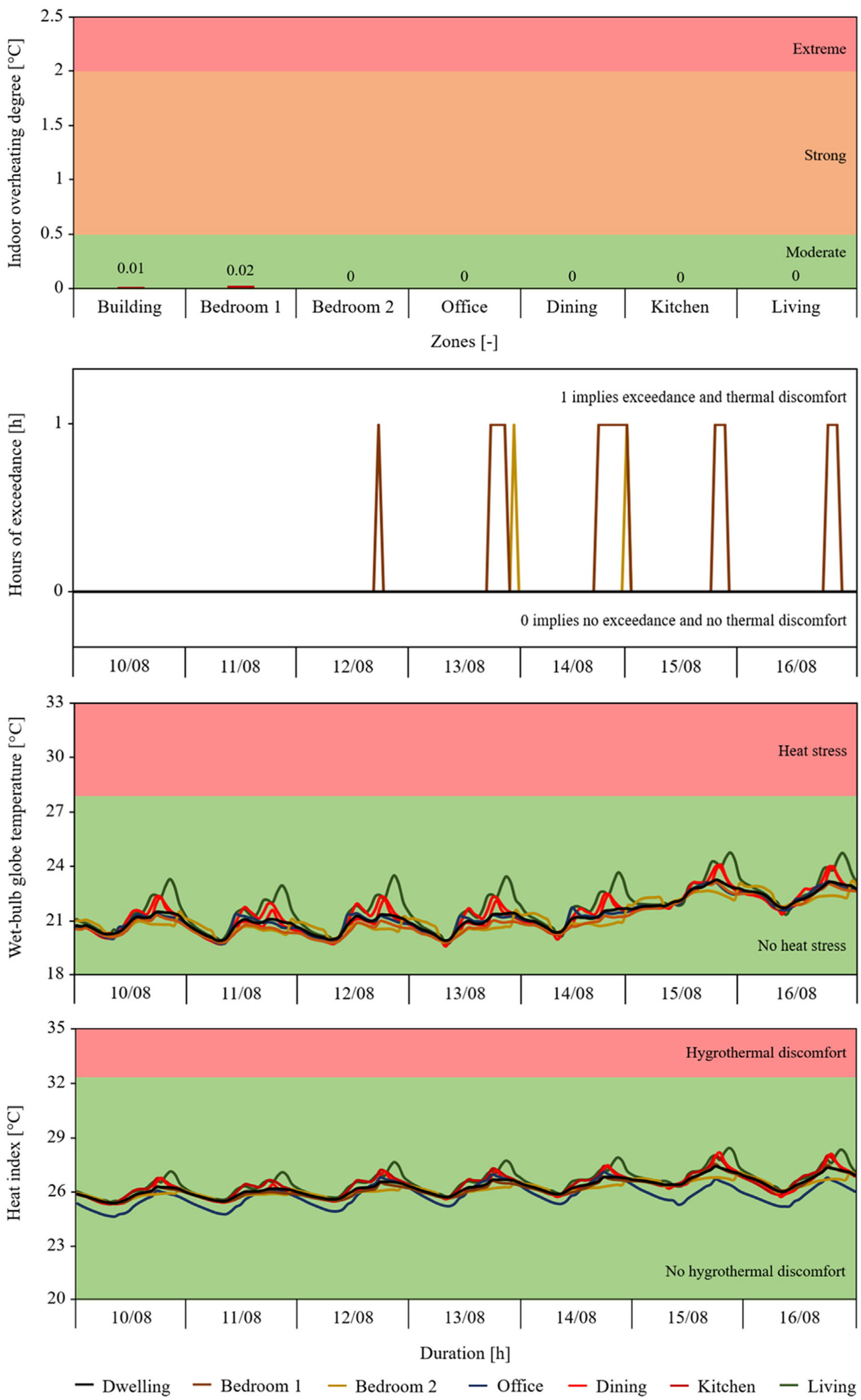

Fig. 5. Building and zonal level variations in certification criteria in the reference dwelling during the heat wave in Brussels from August 10, 2022, to August 16, 2022.

Resilience certificate

Case study	Criteria and KPI	Risk levels	Resilience score	Resilience rating
Building: Post-World War II dwelling  **Location:** Brussels, Belgium 	Overheating: Indoor overheating degree [°C]	0.01 °C, moderate	$1 + \left[\frac{100 + 100 + 100}{100}\right] = 4$	5-star: ★★★★★
	Thermal comfort: Hours of exceedance [%]	100% within the thresholds		
	Heat stress: Wet-bulb globe temperature hours [%]	100% within the thresholds		
	Hygrothermal discomfort: Heat index hours [%]	100% within the thresholds		

Fig. 6. Thermal resilience certificate for the benchmark post-World War II dwelling during the heat wave in Brussels.

post-World War II dwelling has earned four resilience points for thermal resilience during a heat wave event in Brussels. This makes the reference post-World War II dwelling five-star rated for thermal resilience. However, further acceptance of such schemes will require more studies involving modeling and field measurements.

4. Discussions

Although there is substantial research on thermal resilience in built environments, no standardized certification schemes currently consider multiple criteria for building thermal performance during extreme heat events. The building performance during heat waves may fail to maintain safe levels of the thermal environment, compromising the occupant's safety and comfort. Comprehensive assessment tools and certification schemes should be used during early stage building design and post-occupancy operational stage to pursue long-term occupant comfort and well-being in built environments. By providing effective frameworks like the certification scheme proposed in the study, built environments can be transformed positively to ensure acceptable thermal resilience during extreme heat events like heat waves. Existing best practices like standards, rating systems, and literature should be considered when designing the scope and targets for such certification schemes as is done here. By certifying existing buildings for thermal resilience, efficient retrofit strategies [66] can be introduced for buildings that are not resilient to heat waves.

Even though resilience certification is a crucial step in the right direction, it will not produce truly resilient buildings unless a standardized framework is adopted internationally. It will be challenging to compare one certified property to another due to the various standards and requirements that certification programs frequently have. Most member states in the European Union (EU) use thermal performance calculation methods based on static comfort models with stringent comfort limits and lack multi-zonal assessments that distinguish building zones based on purpose. The key performance indicators in the proposed certification scheme can be used for multi-zonal evaluations. The thermal resilience scheme proposed in this study can be used for evaluations regardless of building type, condition, and location while focusing on thermal analysis that is time-integrated and punctual, single-zone and multi-zone, adaptive and static, long-term and short-term heat events.

The reference dwelling evaluated in the study showed satisfactory performance across all four criteria as a part of the thermal resilience certification scheme. The reference dwelling scored four points and is rated five-star for thermal resilience during extreme heat events, minimizing the adverse effects on building occupants. The possible factors contributing to this dwelling performance include the high u-value of the building envelopes that allow better heat dissipation during summer, resulting in better internal thermal performance. This could also be attributed to the higher thermal mass due to the brick walls and the internal walls and floors made of concrete. Furthermore, a low WWR of 12 % would limit the external solar gains, contributing to better thermal performance.

4.1. Policy recommendations

With changing climates, thermal environments are expected to deteriorate in Belgian buildings [67]. Occupants will need safer and healthier buildings with the occurrence of longer and more intense heat waves. Built environments will be significantly improved by complying with thermal resilience certification schemes and receiving higher star ratings. Therefore, a standardized thermal resilience certification scheme is essential since it will improve the existing building codes and regulations and drive research and development of holistic cooling solutions. However, the proposed certification scheme should be constantly updated with developments in assessment tools and methods to avoid thermal performance issues in the future. The thresholds used in the framework should also be updated constantly according to climate zone classifications, including the cooling degree days (CDD) data [68]. Disclosure of a building's thermal resilience capability to the public should be an important update to ensure the occupant is a vital stakeholder. This will also help to boost public awareness in combatting the detrimental effects of extreme heat events. Future policy revisions should include any effects of building non-compliance to thermal resilience standards. Significant changes are being made in the European building sector to accelerate decarbonization and meet emission targets set by the Paris Agreement [69]. Thermal resilience standards should have clear guidelines that mandate that these developments to maintain the occupant's safety and well-being during extreme heat events.

4.2. Strengths and limitations

The strengths of this study are based on the following aspects. The certification scheme is designed based on KPIs and guidelines that can be applied to different building types, conditions, and operations, regardless of climate and location. The certification scheme draws assessment methods from existing best practices like standards, rating systems, and literature. This makes the proposed framework a performance-based comprehensive approach. It is created in consultation with stakeholders from IEA EBC Annex 80 – Resilient cooling of buildings [5]. This certification scheme will guide designers and practitioners in choosing the most effective methods and strategies to design thermally resilient buildings. The study used a benchmark model for post-world war residential dwellings in Belgium. Additionally, the benchmark model in the study provides a precise measure of building performance comparable to reality during the heat wave in Belgium. The main advantage of the proposed certification scheme is that it provides a holistic assessment approach that considers multi-criteria assessments in built environments. Such multi-indicator thermal performance certification will allow for intricate, yet comprehensive and informative valuations as indicated in [70]. Additionally, the existing studies are based on either heating season [28] or a single metric [29]. Moreover, standard effective temperature (SET) as a performance metric could be biased in studies from hot humid climates if the acclimatization of people is not considered according to [71]. The main limitation of this study is that the criteria used in the certification scheme should be weighed considering the climate zones, i.e., HI might be of more significance in humid climates but less significant in dry climates. Additionally, even though the building might give a satisfactory response at the building level, caution should be taken at the zone level. However, the study is of significant value to the existing literature by providing a comprehensive certification scheme based on existing best practices that can be integrated into future EPBD revisions.

4.3. Implications for practice and research

As per studies from [68], deteriorating thermal performance is a serious issue that will affect many Belgian dwellings during this century. Supporting the designers to adapt and renovate the buildings past these issues will require comprehensive frameworks like the proposed certification scheme that should be implemented by building regulatory bodies in Wallonia, Flanders, and Brussels. To a larger extent, in Europe, there is a need for a more standardized approach to thermal resilience calculation and reporting methods. This certification scheme will further contribute to developments aimed at a standardized framework and calculating thermal resilience in European buildings. However, the thermal expectation and the thermal feelings in different types of buildings can vary, and these aspects should be integrated into future developments of the framework to improve the scope and applicability. Additionally, to reduce carbon emissions, European environmental regulations will soon require building with wood and bio-based materials [69]. As a result, there will be a greater chance of overheating in these buildings due to low internal thermal mass [72]. This further adds to the need for multi-criteria thermal certification schemes for built environments in a changing climate, where longer and more intense heat waves are anticipated. Furthermore, future studies should define a weighted average for the dynamic response of a building during the start, steady, and decay periods of heat wave events.

Moreover, Europe has an aging population susceptible to respiratory and cardiovascular syndrome in a warming climate [73]. High temperatures have a detrimental impact, particularly on the elderly population, but more research is needed to understand the underlying mechanisms. As a result of global warming and population aging, it is anticipated that the effects of extreme heat events on vulnerable groups, such as the elderly, will worsen in European cities this century. Their poor capacity for acclimatization at high temperatures makes thermal resilience in the built environment relevant. The next development steps should include integrating KPIs and thresholds for public health, morbidity, and mortality with thermal resilience in built environments during extreme heat events. These developments will require further investigations that involve field measurements, occupant surveys, and benchmark simulation models for free-running, air-conditioned, and mixed-mode operations. Studies that account for building performance during concurrent heat waves and power outages will also be significant in future research.

5. Conclusions

Extreme heat events induced by changing climates have a substantial impact on the built environment. EU member states have been moving towards adopting carbon-neutral and energy-efficient approaches in the building sector to align with Paris Agreement targets. European regulations like the EPBD 2010/31/EU and the Energy Efficiency Directive (EED) 2012/27/EU were updated in 2018 to reflect the EU's clean energy transition goals. However, these regulations lack effective frameworks that evaluate how these energy-efficient measures will impact occupant safety and well-being. This has prompted the development of a proposed multi-criteria certification scheme to effectively support researchers, designers, and practitioners in assessing thermal resilience in built environments in this study. The thermal resilience evaluations can be done during the early-stage design or post-occupancy field evaluations. This paper proposes a comprehensive and varied set of methodologies to evaluate thermal resilience in built environments compared to existing assessment and certification methods being used. Additionally, given the prevalence of longer and more intense heat waves occurring around the globe, the proposed certification scheme will significantly impact the development of sustainable thermal resilient buildings. These evaluation tools are an effective means for significant and timely improvements in the thermal performance of built environments during extreme heat events in a timely manner.

There is a significant potential to improve thermal resilience in buildings, and comprehensive certification schemes proposed in this study, could be a practical tool. The certification scheme uses a point-based rating system as in existing best practices like LEED and WELL certifications. The current scheme rates the building for all four criteria with a maximum score of one point each. The building can be rated five-star for best-case scenario and 1-star for worst-case scenario. There is no minimum point requirement for any criteria evaluated. The scheme is implemented on a benchmark model for detached post-World War II dwellings in Belgium as a case study. The reference dwelling is assessed for overheating, thermal comfort, heat stress, and hygrothermal discomfort during a heat wave from Brussels. The analysis showed an IOD of 0.01 °C, whereas HE, WBGT, and HI values are within the defined thresholds throughout the entire length of the heat wave. This indicates that the reference dwelling performed well for all criteria, scoring the maximum possible score of one point each. The reference dwelling scored four points and is rated five-star for thermal resilience during a heat wave monitored in Brussels. However, future studies should incorporate the regression slope between IOD and Ambient Warmness Degree (AWD) to couple indoor built environments with outdoor environments to account for long-term climate change impacts [74] towards future scenarios. In line with the current study, future research should develop estimation approaches and thresholds for mixed-mode operations in climate-proof buildings. Furthermore, the developed framework should be applied as guidelines or incentive programs at regional and country levels to promote thermal resilience in built environments.

Data availability

Data will be made available on request.

Declaration of competing interest

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CRediT authorship contribution statement

Deepak Amaripadath: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Parham A. Mirzaei:** Writing – review & editing, Validation, Conceptualization. **Shady Attia:** Writing – review & editing, Validation, Supervision, Software, Conceptualization.

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Appendix A

The envelope characteristics of the reference dwelling are listed in Table A1.

Table A1. Envelope characteristics of the reference post-World War II dwelling.

Envelope	Layers	Materials used	Thickness (m)	U-value (W/m^2K)
Ground floor	Outer	Concrete reinforced with 2 % steel	0.1200	0.456
	Third	Spray-on R-12 Polyurethane insulation foam	0.0500	
	Second	Cement screed	0.0100	
	Inner	Ceramic floor tiles	0.0050	
External floor	Outer	External rendering	0.0250	0.250
	Second	MW stone wool rolls	0.1482	
	Inner	Timber flooring	0.0050	
Internal floor	Outer	Perlite plastering	0.0150	1.124
	Fifth	Air layer unventilated floor	0.0200	
	Fourth	Concrete reinforced with 2 % steel	0.1200	
	Third	Sandstone floor	0.0200	
	Second	Cement-bonded plastic board	0.0100	
	Inner	Timber flooring	0.0150	
External roof	Outer	Clay tiles	0.0250	1.227
	Second	Air gap	0.0200	
	Inner	Wood shingle roof	0.0900	
External wall	Outer	Bricks	0.1000	1.709
	Second	Unventilated cavity typology A	0.0700	
	Inner	Cast concrete – mediumweight	0.1400	
Internal partition	Outer	Gypsum plasterboard	0.0050	1.833
	Second	Air gap	0.1400	
	Inner	Gypsum plasterboard	0.0050	
Doors	External	Painted Oak	0.0350	2.823
	Internal	Painted Oak	0.0350	2.823
Windows	External	2 Type A glass layers separated by Air 12 mm		2.907
	Internal	2 Generic clear glass layers separated by Air 6 mm		2.178

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