Building and Environment 222 (2022) 109376

Contents lists available at ScienceDirect

Building and Environment

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

# Evaluating the indoor thermal resilience of ventilative cooling in non-residential low energy buildings: A review

Elahe Tavakoli [a,c], Adam O'Donovan [a,c,*], Maria Kolokotroni [b], Paul D. O'Sullivan [a,c]

[a] Department of Process, Energy and Transport Engineering, Munster Technological University, Cork Campus, Rossa Avenue, Bishopstown, Cork, Ireland
[b] Brunel University London, Uxbridge, Middlesex, UB8 3PH, UK
[c] MaREI, the SFI Research Centre for Energy, Climate and Marine, Ireland

ARTICLE INFO

*Keywords:*
Thermal resilience
Resilience definitions
Resilience criteria
Non- residential
Ventilative cooling
Low energy buildings
Passive measures

ABSTRACT

The quality of future working circumstances for many will be contingent on how low energy indoor spaces respond to challenges from accelerated ambient warming. Resilient cooling is increasingly relevant given the need to evaluate whether a building designed today is resilient against extreme disturbances to the thermal environment from events in the future. The most vulnerable spaces are likely to be those that adopt ventilative cooling. This study reviewed recent research relating to these buildings, discussing different definitions, metrics and approaches available to quantify indoor thermal resilience, also evaluating the extent to which existing published studies have captured each of the resilient criteria. Findings show that, while the vulnerability and resistance of indoor environments in low energy buildings has been investigated, more research is needed regarding the robustness and recoverability of ventilative cooling strategies. More studies are needed examining the resilience of designs that incorporate different heat sinks as well as multiple supplementary passive cooling interventions. There is also a lack of empirical data for ventilative cooling in low energy buildings to verify and support improvements in design practices and building regulations. Studies investigating the holistic response of occupants under extreme conditions in these spaces are also needed.

## 1. Introduction

### *1.1. Background and context*

Global warming is likely to reach 1.5 °C between 2030 and 2052 if it continues to increase at the current rate [1]. Published studies have suggested that the adverse effects of global warming lead to increased; ambient temperatures [2], pollution [3], health risk [4], electricity demand for cooling and $CO_2$-equivalents, with a general decrease predicted in heating energy demand [5]. Increasing global mean air temperature is likely to lead to the increased use of air conditioning and cooling demand in buildings, with the average global cooling demand in residential and non-residential buildings expected to increase by up to 750% and 275%, respectively, by 2050 [4,6]. Therefore, reducing cooling energy demand while maintaining thermal comfort will be a significant challenge in the future.

The resilience of indoor thermal environments in non-residential buildings to the consequences of global warming in the future will be vital to maintaining adequate levels of occupant thermal comfort and the associated health, well-being and productivity benefits that come with this. In the previous decade, the number of published studies (based on the abstracting and indexing site Scopus) that used the term "resilience" in the context of buildings has increased significantly (see Fig. 1). It is visible that the number of studies has accelerated, particularly since 2019. However, up until recently, the literature lacked tangible definitions of the thermal resilience of largely free-running (i.e. naturally ventilated) non-residential buildings against overheating [7].

Overheating has long been identified as an evaluation criterion for the quality of an indoor thermal environment in free-running or naturally ventilated buildings [8]. The criteria were in accordance with the weather data that would be used in a numerical model of the building to determine overheating risk and assess aspects of thermal resilience. Given the uncertainties of future climate, resilience studies need to support the design of buildings aiming for low vulnerability of indoor thermal environments to future overheating and adopt the best available technologies and strategies that future proof buildings and their indoor

* Corresponding author. Department of Process, Energy and Transport Engineering, Munster Technological University, Cork Campus, Rossa Avenue, Bishopstown, Cork, Ireland.
*E-mail address:* adam.odonovan@mtu.ie (A. O'Donovan).

https://doi.org/10.1016/j.buildenv.2022.109376
Received 22 February 2022; Received in revised form 20 June 2022; Accepted 5 July 2022
Available online 9 July 2022

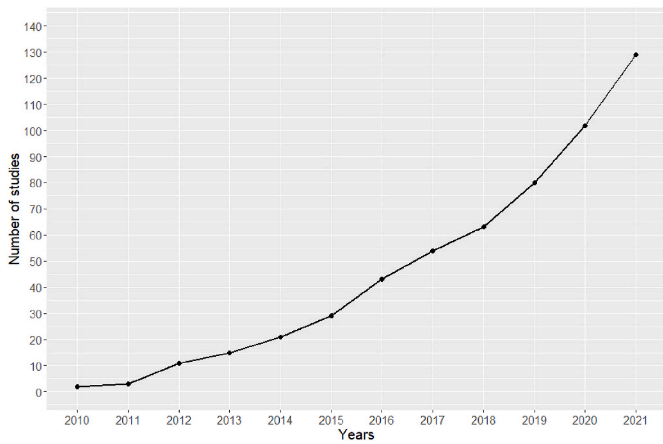



**Fig. 1.** The number of papers that used the word "resilience" in the title, abstract and keywords in the context of indoor environments in buildings.

environments. The recognition of the above facts has contributed to the recent increase of resilience as an evaluation criteria in building performance and approaches in the literature around building thermal resilience; a systematic review is required to assist in synthesising knowledge and identifying gaps [9–11].

Numerous research efforts to date have confirmed the significant impact of global warming on the thermal comfort and energy efficiency of buildings [12–18]. In contrast, other studies have discussed how using passive cooling, natural ventilation, and various control strategies can improve building comfort and energy performance in the future [10,19–22]. These studies have, in essence, assessed and quantified some aspects of indoor thermal resilience. Recent thermal resilience metrics generally encompass various disciplines covering thermal comfort, indoor environmental quality, passive cooling, natural ventilation, and energy efficiency. These metrics focus on occupant-centric resilience against overheating risk and aim to achieve building-centric thermal resilience goals. During the design stages of a building, performance simulation can be employed to create resilience "lock-in" in buildings through the optimisation of how systems regulate the indoor environment regarding different future climate scenarios [23]. It allows designers, engineers, and researchers to experiment with various design and system operations, such as the intermittency of passive interventions, and their impact on building performance. As demonstrated later in this paper, different building performance simulation tools are commonly employed to predict the performance of buildings in terms of energy consumption, carbon emissions and thermal comfort [11,14].

The scope of this study concerns what can be referred to as high performance non-residential buildings that utilise ventilative cooling (VC), designed or constructed with high performance building envelopes and environmental conditioning equipment according to recent energy efficient principles, with a resulting low thermal energy demand. Often the term "Nearly Zero Energy Building" or NZEB is used to refer to these buildings, both now and in the future. However, as NZEB is primarily a regulatory term and its technical definition can vary from country to country globally we avoid its use here, even though it is anecdotally accepted to refer to low energy high performance buildings. Instead, we will use the term "Low Energy" Building (LEB or LE Building) as the main intention is to differentiate the scope of the study from conventional buildings constructed before the modern energy efficient era. Given we are interested in the resilience of LE buildings to future events, we have taken 2010 as the beginning of our review [24] (coinciding with the adoption of the EPBD [25] in Europe and mirroring similar initiatives internationally) and used this date for the purpose of reviewing indoor thermal resilience metrics and definitions for non-residential low energy buildings.

In many cases, low energy buildings incorporate passive cooling strategies. Ventilative cooling is one of these strategies. There are many variations on the definition of passive cooling in the literature depending on whether you consider it from the viewpoint of technologies and their energy performance at the urban, building or ventilation system boundaries [26,27] (Ashrae Terminology, 2022) or the viewpoint of the driving forces, heat transfer medium and the heat sink/sources adopted [4]. For the purposes of this review, we have adopted the definition of VC from IEA-EBC Annex 62 but will also include what we call supplementary passive interventions that are intended to compliment the base VC system; this is because in most literature sources VC components and technologies are evaluated as part of a broader VC strategy (i.e. thermal mass activation, solar shading, airflow enhancing devices, cool envelope materials, vegetation etc. see Tables 7 and 8 below). We will use the acronym VC+ throughout the paper to refer these building archetypes, where the plus refers to the combination of VC & LE as well as also referring to the supplementary passive interventions where present. The definition of VC from Annex 62 is:

> Ventilative Cooling (VC) is defined as the application of the cooling capacity of the outdoor air flow by ventilation to reduce or even eliminate the cooling loads and/or the energy use by mechanical cooling in buildings, while guaranteeing a comfortable thermal environment. Ventilative Cooling utilizes the cooling and thermal perception potential of cool outdoor air and the air driving force can be either natural, mechanical or a combination of the two. The most common technique is the use of increased daytime ventilation airflow rates and/or night time ventilation [28].

The review also suggests a working definition of thermal resilience for VC+ archetypes and is based on the four resilience criteria; vulnerability, resistance, robustness and recoverability, which have been defined in previous studies [29,30]: "*A VC+ building is resilient to climate change when the performance of the ventilative cooling strategy including any complimentary passive interventions in the building allows it to withstand indoor comfort disturbances due to overheating and to be able to adapt its cooling capacity in the event of failure to mitigate further degradation of indoor thermal comfort and the increased need for space cooling energy*". It should be noted that in this study, all VC+ examples that are evaluated are *non-residential* archetype buildings and throughout the paper VC+ refers to non-residential buildings only.

### 1.2. Aims of study

Based on the definitions and context outlined in the preceding section, the aims of this study are to:

1) Provide a comprehensive and critical review of existing studies that identified the concept of resilience as an evaluating criterion or motivation and evaluate whether concepts of resilience are clearly defined in the context of indoor thermal environments.
2) Evaluate published numerical and empirical indoor thermal environment studies of VC+ buildings (from the last 11 years) that identified resilience as a criterion in assessing outcomes, and how well have they captured or addressed the critical characteristics of resilient buildings defined by several recently published definitions (2019–2021).
3) Identify the gaps in methods and approaches to date that need to be addressed by the research community to increase further the likelihood of resilient indoor environments for occupants in the future.
4) Evaluate previous literature which focused on VC+ buildings and determine which studies considered thermal resilience and what can be learned from this.
5) Provide readers with an understanding of the state-of-the-art gaps and future perspectives.

### 1.3. Proposed contribution

Given the future overheating risk, there is a need to complete a systematic review of existing literature focused on resilient cooling and the definition of building resilience in the context of overheating of potentially more vulnerable building-system archetypes such as VC+ indoor environments. This paper makes several contributions to the literature. Firstly, to the authors' knowledge, this is the first systematic review dedicated to the thermal resilience of VC+ indoor environments, which are essential given the future trajectory of building design and building regulations. Secondly, the outcomes of this study helps provide a better understanding of the application of resilience metrics, standards and simulation tools used to assess overheating compliance in buildings. Third and finally, this review uses several recently published resilience concepts to demonstrate the gaps of existing studies that identified resilience as an evaluation criterion to improve thermal resilience and identifies areas needing further research.

### 1.4. Organisation and structure of paper

The main scope of this study is on resilience design and improving the indoor thermal resilience performance of VC+ buildings. In section 2, a general review shows how studies in the literature define resilience both in general and for building-related definitions. Furthermore, this section offers an overview of current vulnerability definitions and metrics for VC+ buildings, VC techniques or strategies attempting to improve thermal resilience, and characterising the indoor thermal resilience of VC+ indoor spaces. Section 3 then describes the methodology adopted for the systematic review of studies that either numerically or empirically investigated aspects of resilience in indoor thermal environments, including how data was collected, how studies were evaluated using resilience criteria, and finally, a gap analysis and recommendations for future research. Section 4 discusses whether the results and methods in the studies reviewed considered resilience appropriately. A synthesis of the results is presented in Section 5, followed by concluding remarks and future perspectives in Section 6.

## 2. Survey of resilience definitions and concepts

### 2.1. General definitions

Resilience stems from the Latin verb resilire, or "*to leap back*" and is defined in the Oxford Dictionary of English as "*able to withstand or recover quickly from difficult conditions*" [31]. General dictionary definitions mention that the noun 'resilience' is a derivative of the 'resilient' adjective, which means capable of recoiling back into the original shape after deformation in terms of an object; or capable of withstanding or recovering rapidly from difficult conditions in terms of a person [32]. As was indicated in Fig. 1, the number of published articles using the term "resilience" has grown dramatically across numerous disciplines since 2005 [33]. Specifically for academic publications, based on a bibliometric analysis, there has been an increase in the use of the term resilience, especially since the early 1970s [34]. A review of the term "resilience" across various disciplines demonstrates three main categories or definitions of the concept, as shown in Fig. 2.

According to above categorization, resilience can be defined in three domains of psychological, engineering and ecological systems. As shown in Fig. 3, the term "resilienc" was initially defined in the context of ecological systems [35,36]. Resilience has also been pursued from the viewpoint of system management in recent decades, but mainly concerning communities. Although this view is essential, it is challenging to measure and has been chiefly discussed using qualitative assessments [37]. Research on resilience has also increased significantly, and a substantial proportion of resilience research is carried out in the context of psychology, specifically for children and adolescents [38,39]. The review of resilience uses revealed some discipline-oriented variations, with a correlation in its definition across various contexts. Windle et al. showed resilience definitions and represented how it can be evaluated [32]. Martin and Sundley suggested a dynamic composed of four interrelated dimensions for resilience: vulnerability, resistance, robustness, and recoverability [29]. While definitions have changed over time, core features have been retained through the evolution of thought around resilience. Many disciplines adapt the same core concept to suit the "local" needs of the phenomena of interest.

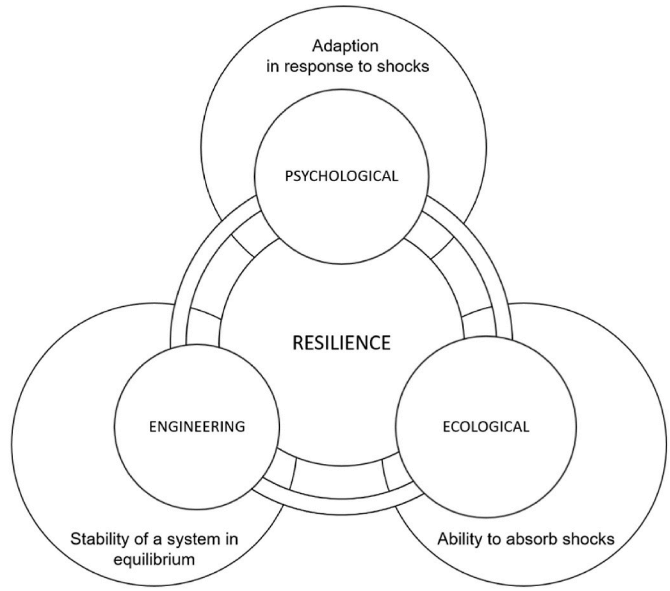



**Fig. 2.** Summary of general resilience definitions across various disciplines.

### 2.2. Building-related definitions

In terms of the energy performance of buildings, Fig. 4 demonstrates the definition of resilience in five levels to define the broad field of study, the relationship of resilience to the subject matter and the building-related resilience definitions of previous studies. Short et al. considered resilient buildings to use passive interventions such as shading [11]. Attia et al. [30] recently focused on existing resilience definitions and the various approaches based on 90 documents related to resilient buildings. Their paper suggests a definition and a set of criteria based on [29] (vulnerability, resistance, robustness, and recoverability) that can help improve air quality in buildings to mitigate the operational interference effects of heatwaves and power outages. Hasik et al. [36] discussed the literature of sustainability and resilience in buildings, including definitions and correlations between the two. The study proposed a set of sustainability and resilience metrics spanning areas of resource efficiency, service provision, site impacts, indoor environment, and structural integrity, with each area further including a subset of factors contributing to the perceived performance of a building. Other researchers have begun to introduce theoretical models that relate the structural and other performance characteristics of buildings with the possible behaviour of buildings under stress [48,49]. Leichenko [50] stated that buildings and infrastructure should be resistant and adaptable to the changing environment, such as storm events, global warming, and rising sea levels. Bruneau et al. [40] analysed neighbourhood seismic resilience, defining the features and aspects of community resilience and infrastructures. These elements are often significant for the continuous maintenance and recovery of individual buildings within a city. The subject of building codes has been briefly covered regarding construction stability in terms of reaction to varying loads on the structure and envelope.

Considering the general and building-related definitions of "resilience" from the literature, as shown in Figs. 3 and 4, it is essential to

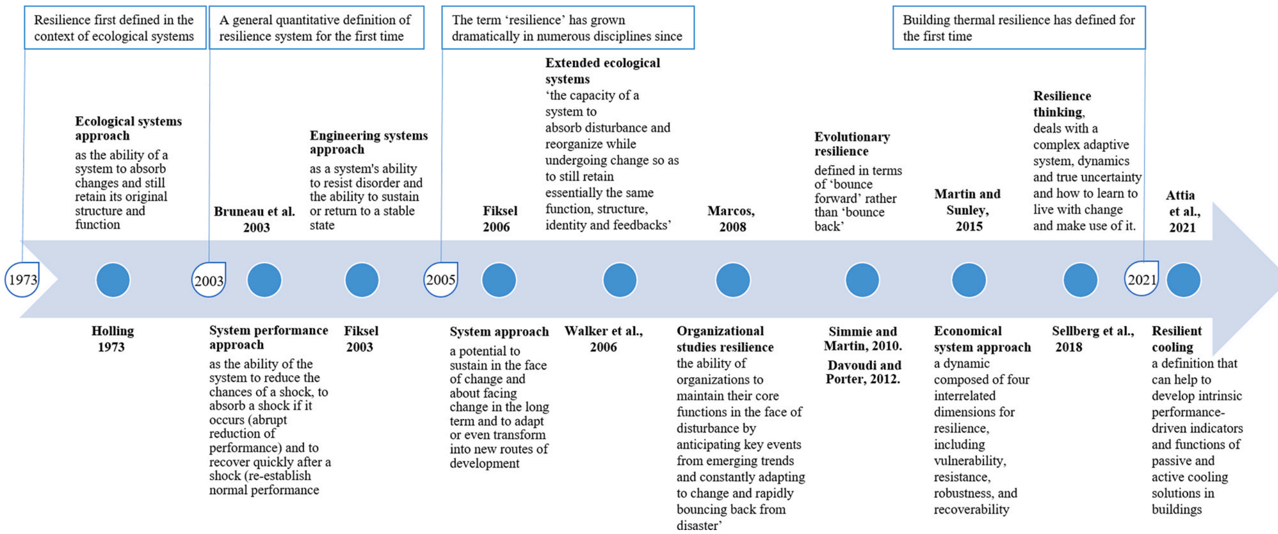



**Fig. 3.** Chronological evolution of resilience definitions across various disciplines [29,30,35,40–47].

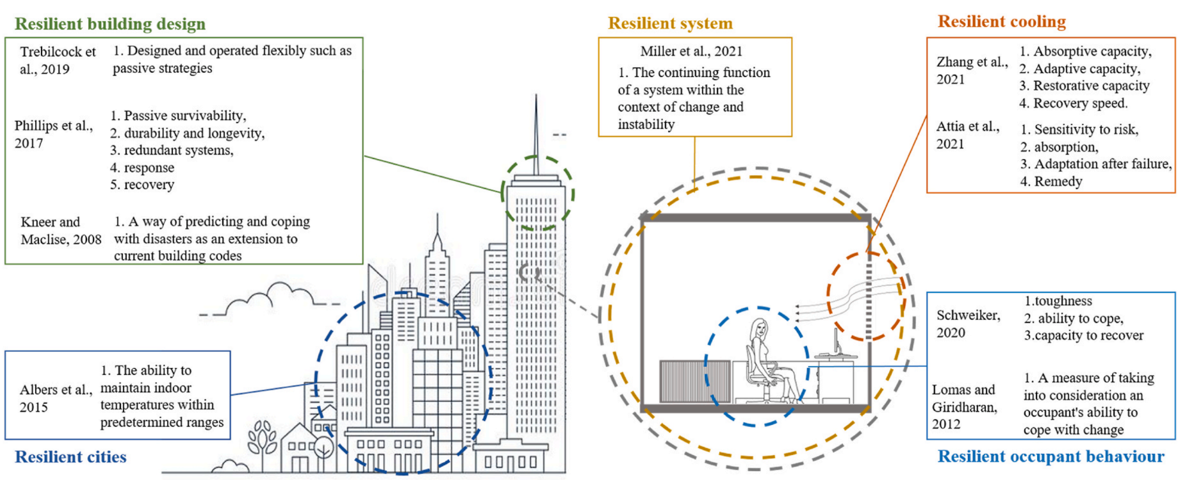



**Fig. 4.** Summary of building-related resilience definitions [17,30,51–57].

understand and define resilience in the early stages of building design as well as evaluate and adapt designs to incorporate resilient strategies to prevent future "lock-in" of vulnerable design approaches. The authors find that there appears to be a strong focus on using the term "resilience" during the last decade. However, up to until recently, the literature lacks tangible definitions of the indoor thermal resilience of ventilative cooling in buildings beyond overheating. Therefore, we suggest a working definition of thermal resilience in VC+ buildings against overheating, including four resilience criteria [29,30]:

> "*A VC+ building is resilient to climate change (vulnerability) when the performance of the ventilative cooling strategy including any complimentary passive interventions in the building allows it to withstand indoor comfort disturbances due to overheating (resistance) and to be able to adapt its cooling capacity in the event of failure (robustness) to mitigate further degradation of indoor thermal comfort and the increased need for space cooling energy (recoverability).*"

### 2.3. Characterising the indoor thermal resilience of VC+ buildings

Resilience can relate to a "bouncing back" after an external disturbance to the equilibrium of the parameter or system of interest. Recall that this can mean being "*capable of recoiling back into the original shape after deformation in terms of an object*". As well as the various metrics proposed in subsequent tables, if the indoor thermal environment can be characterised using a parametric distribution (i.e. a histogram of indoor air temperature, relative humidity etc) where the shape of the distribution over a certain time horizon is "elastic" or contingent on factors that act on the indoor thermal environment, then over the duration of the "*pre disturbance equilibrium – disturbance – response – return to equilibrium or failure*" cycle we should be able to characterise the ability of the thermal environment to adapt and bounce back under stress using this "morphological" approach. A similar type of approach has been suggested by other researchers in evaluating robust building design [58]. The parameter of interest chosen to evaluate the resilience of the indoor thermal environment, whether it's a physical phenomenon such as indoor air temperature or an inferential or statistical phenomena such as PMV, is important as thermal comfort indicators can capture resilience at the occupant boundary (see Fig. 4) while temperature distributions will capture the resilience of the building-system boundaries. The adaptive thermal comfort model for example incorporates the resilience at the occupant boundary in their adaptive capacity to respond to the disturbance event [53,56]. When an external disturbance takes place then the parametric distribution undergoes a transformation, the extent of which is dependent on the resistance capacity of the building-system. This transformation can be interpreted as a deformation from the equilibrium state shape. An elastic deformation (of the parametric distribution) suggests the building is resilient and can recover from the disturbance event. A plastic deformation suggests the indoor thermal environment cannot be returned to equilibrium conditions (or some limiting acceptable shape/distribution) and additional external intervention or complimentary technologies/strategies are required to recover after failure (see Fig. 5).

### 2.4. Evaluating vulnerability and resilience for VC+ buildings

Vulnerability in the context of buildings has been described recently by Attia et al. [30]. In this work, it suggested that a vulnerability assessment is a test of the comfort performance of a building given different disturbances, that might be short-term (extremes or heat waves) or long-term (future years), from average conditions to the worst conditions. Inherent in this definition is a criterion or set of criteria that are comfort dependent which can have significant variation depending on the occupant and the setting. In this study, it is evident that overheating (and not overcooling) is the main concern. A key concept about vulnerability is the definition of a threshold or set of thresholds, a criterion or set of criterion, or “a risk or a set of risks” [59] that define the scope of the building system or occupants that “bear the vulnerability” [59]. Metrics used in the context of overheating and thermal comfort have been extensively reviewed recently [60] for residential buildings in temperate climates. In addition to this, Hamdy et al. [61] and Rahif et al. [60] have proposed additional metrics which consider the change in internal conditions with changing weather conditions under current and future climates.

#### 2.4.1. Overheating metrics

The universality of any vulnerability definition is a challenge that has already been identified as an issue when it comes to assessing overheating risk in buildings [8]. This literature on overheating in buildings has formed the basis for the consideration of what is vulnerable and how we might define risks. At the core of our understanding of overheating are factors that influence risks to the occupants of buildings (shown in Fig. 6), which determine the level or severity of risk that deviations from desired conditions could have. These are reflected by many different standards and guidelines, as well as in scientific literature and show varying bounds for different types of occupants (i.e. high and low expectation levels) in different buildings, with different people.

Table 1 presents some standards and metrics used in the assessment of overheating in different contexts. The vast majority of these metrics focus on a zone level experience that can be assessed through simulation or measurement, with some focusing on a single criterion and others focusing on multiple criteria. A crucial part of comfort in all buildings, but particularly in buildings using VC+ which use mixed-mode (MM) and/or natural ventilation (NV), is adaptation [62–64]. Adaptive models which have been developed extensively over the last 30 years utilise the resilience of occupants to adapt and remain thermally comfortable in a much broader range of conditions than air conditioned (AC) buildings and can be dependent on a number of factors [65].

Table 2 presents typical neutral operative temperatures and upper threshold limits for 90% acceptability from standards and thermal comfort studies. Fig. 7 illustrates this data and the variation in neutral temperature and acceptable upper thresholds for these studies with respect to mean external conditions.

What is evident from this is that what constitutes “vulnerable” (or a disturbance or deviation from comfortable conditions) could be very different depending on the people, culture or thermal history that exists for individuals or populations across the world. Taking heat wave conditions of 25 °C and greater outside temperatures (which would be typical for temperate climates [75]), the difference in minimum (AC mode) and maximum (NV mode) neutral operative temperatures could be anywhere from 3.0 °C to 4.4 °C depending on the comfort assumptions used. The difference in maximum allowable upper threshold operative temperatures under the same outside conditions could be anywhere from 5.2 °C to 8.0 °C for the same assumptions. This “adaptive comfort dead-band” illustrates the flexibility and resilience of individuals in different countries when VC+ systems are used.

#### 2.4.2. Heat stress metrics

Outside of comfort and overheating research there are other aspects to thermal resilience and vulnerability that fall outside of the operative temperature-based models. Recent research has indicated that more work is needed when it comes to the metrics used to assess buildings in the context of heat stress [60]. This is also applicable when it comes to definitions of vulnerability. Even in comfort research certain parameters which are related to individual susceptibility to heat stress can be overlooked [76] where static values are often assumed for sedentary behaviour [73,77,78]. Vulnerability of buildings may also be considered as what humans (as mammals) can tolerate, or what is required for them to survive in conditions that can lead to heat related health problems. It is evident that outside of psychological or other differences there is fundamentally a physiological balance occurring that allows heat exchange to occur between the body of mammals and its surrounding environment, this balance requires different homeostatic responses from the body under different temperatures and humidity conditions. Table.3

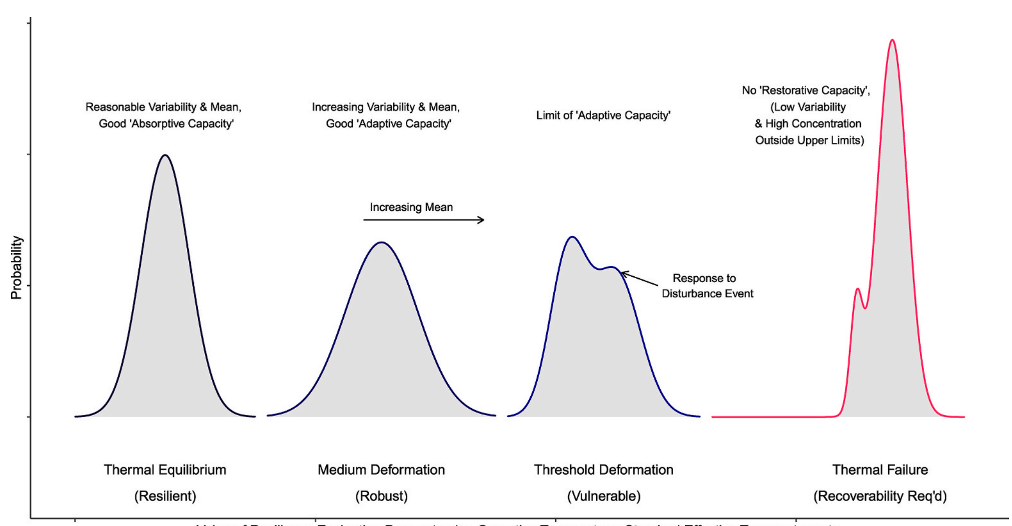



**Fig. 5.** Different levels of parametric deformation based on level of resilience intervention.

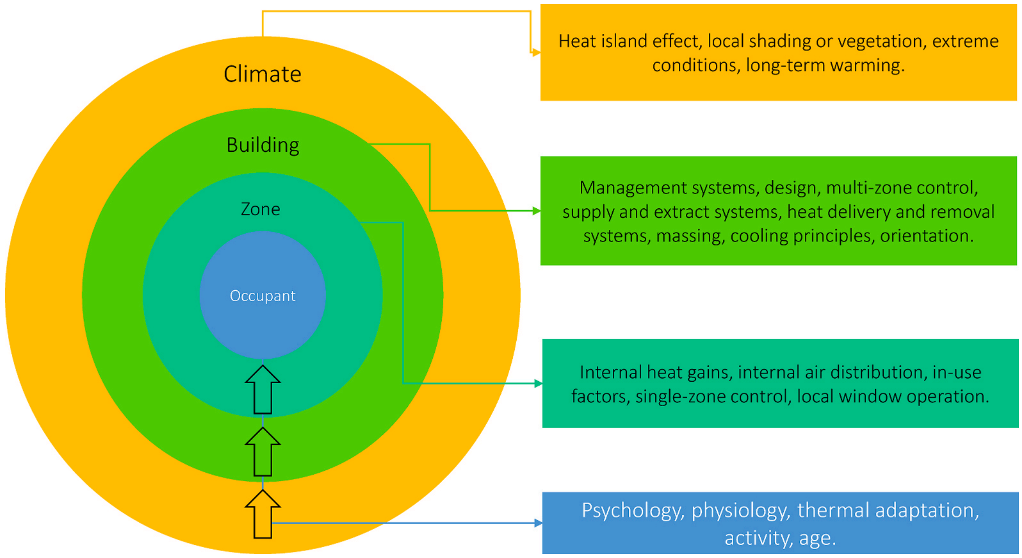



**Fig. 6.** Summary of disturbances and characteristics affecting overheating for occupants and their boundaries in relation to each other.

**Table 1**
Summary of overheating criteria in some existing international standards.

| Standards | Type of building/ Space | Criteria | Reference |
|---|---|---|---|
| BS EN 15251-2017 | Office | Overheating risks occur when $T_{op}$ is outside of: $T_{upper} = 0.33\ T_{rm}+21.3$ | [66] |
| ASHRAE 55-2017 | Office | Overheating risks occur when $T_{op}$ is outside of: $T_{upper} = (21.3 + 0.31T_{pma\ (out)}\ ^{\circ}C)$ | [67] |
| CIBSE TM36 | Office | $T_{op}>28\ ^{\circ}C$ for 1% of the occupied hours | [68] |
| CIBSE TM52 | Non-Residential Buildings | Overheating hours >3% of the occupied hours<br>Overheating degree-hours > 6 for any day<br>$\Delta T > 4$<br>$T_{op} > 28\ ^{\circ}C$ for 3% of the annual occupied hours | [69] |
| BB 101 | Schools | $T > 28\ ^{\circ}C$ for 120 h per year<br>$\Delta T > 5\ ^{\circ}C$<br>$T > 32\ ^{\circ}C$ | [70] |
| BS EN 16798 | Non-Residential Buildings | Overheating risks occur when $T_{op}$ is outside: $T_{upper} = 0.33\ T_{rm}+18.8 + 3$ | [71] |
| HTM 03-01 | Patient areas | $T > 28\ ^{\circ}C$ for 50 summertime hours per year | (*HTM 03-01*, 2013) |

**Table 2**
Examples of operative temperatures and upper thresholds from different international studies in non-residential buildings.

| Location or Region | Neutral Operative | Upper limit | Reference |
|---|---|---|---|
| CEN (EU) | $0.33{*}T_{rm} + 18.8$ | $0.33{*}T_{rm} + 18.8 + 2$ | [72] |
| ASHRAE (global) | $0.31{*}T_{out} + 17.8$ | $0.31{*}T_{out} + 20.3$ | [67] |
| ISO 7730 (global) | 24.5 | 25.5 | [73] |
| United Kingdom (UK) | $0.534{*}T_{out} + 11.9$ | – | of [65] |
| Japan (JP) | $0.206{*}T_{out} + 20.8$ | – | of [65] |
| Australia (AU) | $0.31{*}T_{out} + 17.6$ | – | of [65] |
| India (IN) | NV: $0.54{*}T_{rm} + 12.83$<br>MM: $0.28{*}T_{rm} + 17.87$ | NV: $0.54{*}T_{rm} + 12.83 + 2.4$<br>MM: $0.28{*}T_{rm} + 17.87 + 3.5$ | [64] |
| Pakistan (PK) | $0.36{*}T_{out} +18.5$ | – | of [65] |
| China (CN) | Civil (Cold): $0.767{*}T_{out} + 12.037$<br>Civil (Hot and Humid): $0.729{*}T_{out} + 12.717$ | – | [74] |

NV = natural ventilation | MM = mixed mode ventilation.

describes a number of typical heat stress indices used in the literature. Research in this domain of health-related heat stress is relevant to thermal resilience [79,80] and points to other levels of risk that need to be considered. These indices reflect the heat stress in the indoor environment. The most comprehensive of these regarding thermal resilience is the work of Sun et al. [79] who presented a review of resilience metrics to evaluate the thermal resilience of buildings. In this work, two types of metrics are proposed: 1) simplified biometeorological indices and 2) complex indices.

The simplified biometeorological indices are based on air temperature or a combination of air temperature and humidity. On the other hand, heat-budget models include the critical meteorological and physiological parameters needed to describe the physiological heat load: air temperature, water vapour pressure, wind velocity, and short and long-wave radiant fluxes. Fig. 8 describes the heat index (HI) which is used in heat stress studies. Unlike deviations from comfortable conditions, this model allows for an evaluation of the health risk given a combination of relative humidity and temperature conditions. Table 4 indicates the likely heat related consequences of exposure to conditions.

In addition to the HI there are a number of other metrics that are relevant to the heat stress experienced by occupants. One of these is the Standard Effective Temperature (SET) which is described in ASHRAE 55 [67] which has been used in the context of both comfort studies [77,91] and as a heat stress index [86]. The SET is a complex metric, that requires many more inputs than the HI. However, the index has been lauded as better than both adaptive and Fanger's predicted mean vote (PMV) method [92] in reflecting the physiological response of subjects. However, there has been a lack of application of the index due to not only its complexity but the different interpretations of the index [93]. Table 5 describes the different physiological states at different values of the SET.

Recent work by Laouadi et al. [86] applied to residential buildings defines overheating and heat stress using the SET metric to define the duration, severity and intensity of overheating events. In this work, they present not only different threshold values for day-time and night-time

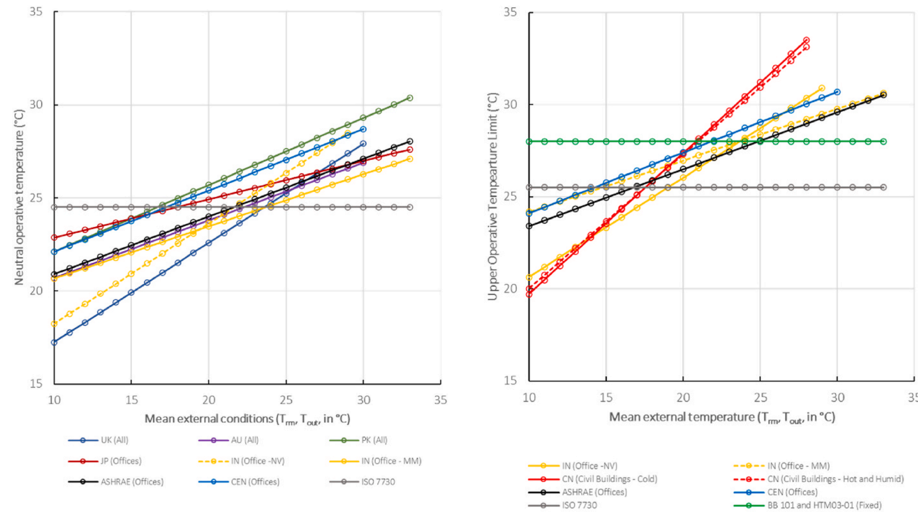



**Fig. 7.** Variation in comfortable temperatures depending on country, building, and setting based on Table 2 (Left: Neutral operative temperatures for different studies and standards, Right: Upper threshold temperatures for 90% acceptability).

**Table 3**
Typical heat stress indices used in the literature.

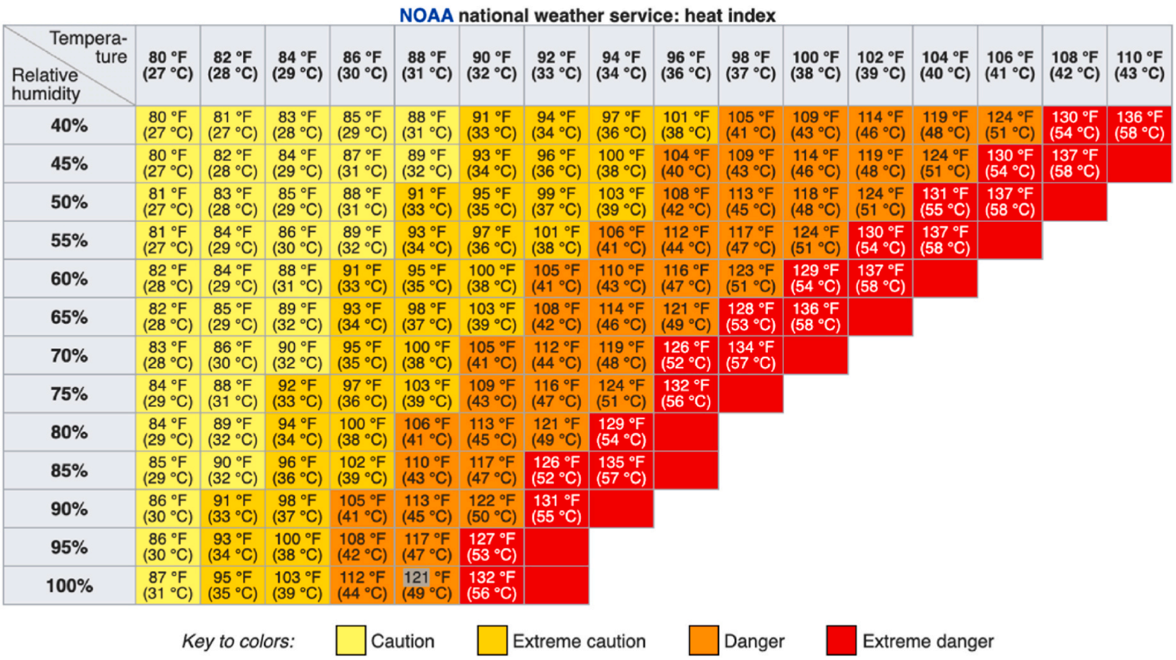
| Index | Equations | Ref |
|---|---|---|
| **Passive Survivability-Summer (PSS)** | The time until the indoor operative temperature reaches 30 °C (86 °F) from an original cooling setpoint of 25 °C (77 °F) in summer | [81] |
| **Humidex (°C)** | $H = T_a + 5/9\ (e - 10)$ | [82] |
| **Wet-Bulb Globe Temperature (°C)** | $WBGT = 0.7T_{nwb} + 0.2T_g + 0.1T_a$ | [83] |
| **Standard Effective Temperature (SET)** | $H_{sk} = h_s(t_{sk} - SET) + wh_{s,e}(p_{s,sk} - 0.5pSET)$ | [84, 85] |
| **OH duration (days)** | $D = \sum_{wake}^{Sleep}(SET_t - SET_d)^+ \bullet \Delta\tau \geq 4°Ch$ | [16, 86] |
| **OH severity (°Ch)** | $S = \sum_{i=1}^{N\_days}\{\sum_{sleep}^{wake}(SET_t - SET_n)^+.\Delta\tau + \sum_{sleep}^{wake}(SET_t - SET_d)^+.\Delta\tau\}$ | [16, 86] |
| **Intensity (°C)** | $I = S/(D*24)$ | [16, 86] |
| **Universal Thermal Climate Index** | $UTCI = f\ (T_a; T_{mrt}; v_a; v_p) = T_a + Offset\ (T_a; T_{mrt}; v_a; v_p)$ | [87] |
| **Heat index** | $HI = (-8.78469475556) + (1.61139411\ T_a) + (2.33854883889R) + (0.14611605\ T_aR) + (-0.012308094\ T_a^2) + (-0.0164248277778R^2) + (0.002211732\ T_a^2R) + (0.00072546TR^2) + (-0.000003582\ T_a^2R^2)$ | [79] |
| **Net Effective Temperature** | $NET = (T_a - 0.4) \times (T_a - 10) \times (1 - R/100)$ | [88] |
| **Physiologically Equivalent Temperature (PET)** | $M + W + RH + C + E_D + E_{Re} + E_{Sw} + S = 0$ | [89] |

but also the magnitude of overheating events in degree hour terms by summing both effects. In addition to this, the work also considers different suggested thresholds for young adults, older adults, adaptation, as well as different building types outside of residential applications. Given the scale and risk associated with a changing climate, it is important that future studies consider the use of additional heat related metrics such as these, as vulnerability assessments that consider heat stress effects outside of comfort present the potential risks to heat related illnesses (such as heat cramps, exhaustion, and stroke) and the potential fatalities that may occur. Outside of being used in the work of Sun et al. [79]; the HI index has also been used in recent work by Rempel et al. [94] as a metric to determine the passive survivability of residential buildings was simulated under heat wave conditions in the US. From this work, it is noticeable that when evaluating heat stress we are evaluating a more severe level of vulnerability, one that considers more severe threats to life and health. Many studies have highlighted the likely excess heat mortality and morbidity in heat waves or due to climate change in disciplines outside of the built environment [95–100]. These studies typically discuss all-cause mortality or morbidity and have identified vulnerabilities in infant and elderly populations [75,96], as well as discussions between rural and urban locations [100–102]. Based on the above, the vulnerability of populations is likely to differ, they may and are likely to vary according to many factors outside of the internal environment and thermal comfort related definitions. These factors could also be activity level [103], age [96], social status [104], education level [101] and psychological state.

### *2.4.3. Resilience metrics*

Outside of these heat stress metrics the past decade has seen the emergence of metrics which consider overheating more holistically. Some evaluate comfort or overheating on individual days or those that consider daily maximum temperatures (such as those in TM52) (TM52, 2013). There has also been consideration for the rate of change of overheating with respect to ambient warmness [61]. One of the key components about resilience metrics is the time-horizon [30]. Illustrated in Fig. 9, we can see that resilience can be based on what is foreseeable and what is unforeseeable.

These could be characterised by long-term expectations and short-term events where disturbances (that are not exclusively climate based) affect the building system and result in failure. This concept has also been considered and discussed in work related to heat stress indices but with regard to more severe consequences [79,94]. Fig. 9 described originally by Moazami et al. [105]; differentiates robust buildings from resilient ones, where the key difference is that resilient buildings fulfil functional requirements to foreseeable disturbances as well as major disruptions. It is also seen that a building may even fail or be disrupted but it can recover. The same concept is described by Attia et al. [30] where they describe varying time scales (day to multiple years), building scales (zone to city), as well as varying disruptions (heat waves, power outages etc.). The main difference for robust over resilient buildings indicated in this work is that resilient buildings return to designed conditions, whereas robust buildings cannot. This implies that a deformation occurs for both with one being plastic and the other elastic (see section 2.5). Table 6 indicates some metrics that have been used in recent scientific literature based on the review of [107] as well recent work when evaluating resilience through simulation based approaches [108]. These "resilience" metrics indicate the rate of change of vulnerability over time, which is often considered through multiple




| Relative humidity \ Temperature | 80 °F (27 °C) | 82 °F (28 °C) | 84 °F (29 °C) | 86 °F (30 °C) | 88 °F (31 °C) | 90 °F (32 °C) | 92 °F (33 °C) | 94 °F (34 °C) | 96 °F (36 °C) | 98 °F (37 °C) | 100 °F (38 °C) | 102 °F (39 °C) | 104 °F (40 °C) | 106 °F (41 °C) | 108 °F (42 °C) | 110 °F (43 °C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 40% | 80 °F (27 °C) | 81 °F (27 °C) | 83 °F (28 °C) | 85 °F (29 °C) | 88 °F (31 °C) | 91 °F (33 °C) | 94 °F (34 °C) | 97 °F (36 °C) | 101 °F (38 °C) | 105 °F (41 °C) | 109 °F (43 °C) | 114 °F (46 °C) | 119 °F (48 °C) | 124 °F (51 °C) | 130 °F (54 °C) | 136 °F (58 °C) |
| 45% | 80 °F (27 °C) | 82 °F (28 °C) | 84 °F (29 °C) | 87 °F (31 °C) | 89 °F (32 °C) | 93 °F (34 °C) | 96 °F (36 °C) | 100 °F (38 °C) | 104 °F (40 °C) | 109 °F (43 °C) | 114 °F (46 °C) | 119 °F (48 °C) | 124 °F (51 °C) | 130 °F (54 °C) | 137 °F (58 °C) | |
| 50% | 81 °F (27 °C) | 83 °F (28 °C) | 85 °F (29 °C) | 88 °F (31 °C) | 91 °F (33 °C) | 95 °F (35 °C) | 99 °F (37 °C) | 103 °F (39 °C) | 108 °F (42 °C) | 113 °F (45 °C) | 118 °F (48 °C) | 124 °F (51 °C) | 131 °F (55 °C) | 137 °F (58 °C) | | |
| 55% | 81 °F (27 °C) | 84 °F (29 °C) | 86 °F (30 °C) | 89 °F (32 °C) | 93 °F (34 °C) | 97 °F (36 °C) | 101 °F (38 °C) | 106 °F (41 °C) | 112 °F (44 °C) | 117 °F (47 °C) | 124 °F (51 °C) | 130 °F (54 °C) | 137 °F (58 °C) | | | |
| 60% | 82 °F (28 °C) | 84 °F (29 °C) | 88 °F (31 °C) | 91 °F (33 °C) | 95 °F (35 °C) | 100 °F (38 °C) | 105 °F (41 °C) | 110 °F (43 °C) | 116 °F (47 °C) | 123 °F (51 °C) | 129 °F (54 °C) | 137 °F (58 °C) | | | | |
| 65% | 82 °F (28 °C) | 85 °F (29 °C) | 89 °F (32 °C) | 93 °F (34 °C) | 98 °F (37 °C) | 103 °F (39 °C) | 108 °F (42 °C) | 114 °F (46 °C) | 121 °F (49 °C) | 128 °F (53 °C) | 136 °F (58 °C) | | | | | |
| 70% | 83 °F (28 °C) | 86 °F (30 °C) | 90 °F (32 °C) | 95 °F (35 °C) | 100 °F (38 °C) | 105 °F (41 °C) | 112 °F (44 °C) | 119 °F (48 °C) | 126 °F (52 °C) | 134 °F (57 °C) | | | | | | |
| 75% | 84 °F (29 °C) | 88 °F (31 °C) | 92 °F (33 °C) | 97 °F (36 °C) | 103 °F (39 °C) | 109 °F (43 °C) | 116 °F (47 °C) | 124 °F (51 °C) | 132 °F (56 °C) | | | | | | | |
| 80% | 84 °F (29 °C) | 89 °F (32 °C) | 94 °F (34 °C) | 100 °F (38 °C) | 106 °F (41 °C) | 113 °F (45 °C) | 121 °F (49 °C) | 129 °F (54 °C) | | | | | | | | |
| 85% | 85 °F (29 °C) | 90 °F (32 °C) | 96 °F (36 °C) | 102 °F (39 °C) | 110 °F (43 °C) | 117 °F (47 °C) | 126 °F (52 °C) | 135 °F (57 °C) | | | | | | | | |
| 90% | 86 °F (30 °C) | 91 °F (33 °C) | 98 °F (37 °C) | 105 °F (41 °C) | 113 °F (45 °C) | 122 °F (50 °C) | 131 °F (55 °C) | | | | | | | | | |
| 95% | 86 °F (30 °C) | 93 °F (34 °C) | 100 °F (38 °C) | 108 °F (42 °C) | 117 °F (47 °C) | 127 °F (53 °C) | | | | | | | | | | |
| 100% | 87 °F (31 °C) | 95 °F (35 °C) | 103 °F (39 °C) | 112 °F (44 °C) | 121 °F (49 °C) | 132 °F (56 °C) | | | | | | | | | | |

**Fig. 8.** Heat index chart developed by U.S. National Oceanic and Atmospheric Administration (NOAA) is used to look up the heat index by temperature (°C) and relative humidity (%) (taken from Ref. [90]).

**Table 4**
Definition of four levels of Heat Index (taken from Ref .[90]).

| Heat Index in Celsius | Heat Index in Fahrenheit | Heat Index Level |
|---|---|---|
| **Less than 26.7 °C** | Less than 80 °F | Safe: no risk of heat hazard |
| **26.7 °C - 32.2 °C** | 80–90 °F | Caution: fatigue is possible with prolonged exposure and activity. Continuing activity could result in heat cramps. |
| **32.2 °C - 39.4 °C** | 90–103 °F | Extreme caution: heat cramps and heat exhaustion are possible. Continuing activity could result in heat stroke. |
| **39.4 °C - 51.7 °C** | 103–125 °F | Danger: heat cramps and heat exhaustion are likely; heat stroke is probable with continued activity. |
| **over 51.7 °C** | over 125 °F | Extreme danger: heat stroke is imminent. |

**Table 5**
SET and heat related thermal sensations and physiological states for different ranges (taken from Ref. [86]).

| SET (in °C) | Thermal Sensation | Physiological State |
|---|---|---|
| **>37.5** | Very hot | Failure of thermoregulation |
| **34.5–37.5** | Hot | Profuse sweating |
| **30.0–34.5** | Warm | Sweating |
| **25.6–30.0** | Slightly warm | Slight sweating, vasodilation |
| **22.2–25.6** | Neutral | Neutral |

simulations. However, a data-driven approach could also be adopted with data from multiple years.

For the most part what differentiates these metrics from overheating metrics is that resilience metrics are typically reported in respect to: 1) different time horizons or events [61,109,110], 2) at different scales (typically zone or at building level) [61,109], 3) in some cases consider the relationship between ambient conditions over time and internal overheating, which indicates some sensitivity of the building to long-term warming [61,107], and 4) some also consider penalties for different internal deviations, as well as benchmarking [109].

### *2.4.4. Critical evaluation of metrics and future considerations*

*2.4.4.1. Vulnerability.* One of the main concerns about many of the resilience metrics presented in the literature is their consideration of vulnerability. Many lack consideration for many internal environmental parameters outside of the operative or air temperature. Work from fields of heat stress (indicated previously) highlights the benefit and potential necessity of including either simple models such as HI or more complex variations of this including the SET. A balance of both methods could be to consider a corrected effective temperature (CET) which incorporates both the practicality of the operative temperature and the need to consider humidity. In addition to this, there is a need to consider the "accumulation of heat stimuli" [111] in a manner that does not only consider whether a threshold has been passed but that considers the overheating tolerance of occupants and the probability of groups or populations of occupants considering spaces to have overheated. One other limitation of existing metrics is that the majority of metrics report averaged or cumulative values of overheating incidences but fail to categorise the severity of these for a given time period. The work of Homaei & Hamdy [109] addresses some of these deficiencies and allows for penalties for different thresholds, as well as at different scales. This approach which considers multiple criteria has some similarities to the approach of different thresholds in TM52, however, its application is presented for short-term events. The use of multiple criteria considering holistic (percentage based) metrics as well as significant thresholds for failure are key to future assessments, particularly when considering different types of occupants. In the context of VC + buildings, the vulnerability of the system may also come into question. The system may be limited in many ways. The restriction of openings for health and safety [112] reasons may be a significant limitation [113,114] but there is also the need to consider other issues such as the disturbances due to local pollution and noise levels, or the need to provide appropriate ventilation for infectious disease control. The effect of the local climate may also be a vulnerability which effects the building and the system in question. This is particularly an issue with dense urban areas which experience heat island effects [115–117]. There is limited research indicating the resilience at the urban or city scale. There is also limited research considering the effect of other limiting factors that influence

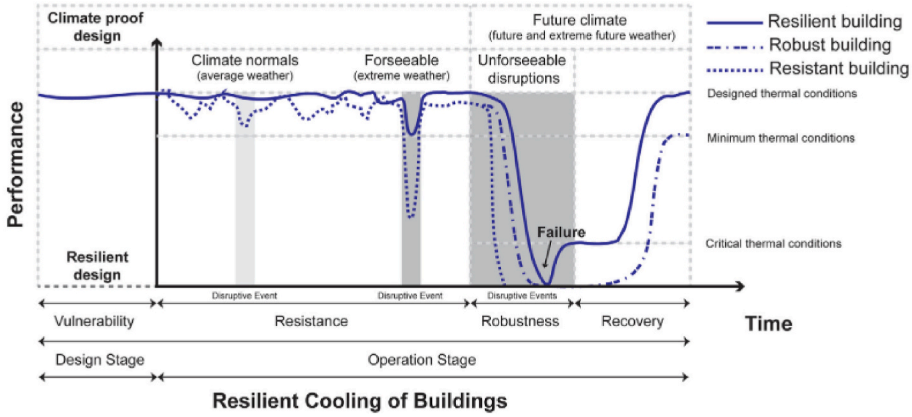



**Fig. 9.** Phase of Vulnerability, Resistance, Robustness and Recovery of a system (image taken from Attia et al. [30]. which based on Moazami et al. [105]; Sengupta et al. [106].

**Table 6**
Examples of thermal resilience indices described in scientific literature.

| Index | Equations | Ref |
|---|---|---|
| **Indoor Overheating Degree (IOD)** | $\mathrm{IOD} = \frac{\sum_{z=1}^{Z}\sum_{i=1}^{N_{occ(z)}}\left[(T_{in,o,z,i} - T_{comf,z,i})^{+} t_{i,z}\right]}{\sum_{z=i}^{Z}\sum_{i=1}^{N_{occ}} t_{i,z}}$ | [61, 78] |
| **Ambient Warmness Degree (AWD)** | $\mathrm{AWD} = \frac{\sum_{i=1}^{N}\left[(T_{out,a,i} - T_b)^{+} t_i\right]}{\sum_{i=1}^{N} t_i}$ | [61, 107] |
| **Overheating escalation factor ($a_{IOD/AWD}$)** | $a_{IOD/AWD} = \frac{IOD}{AWD}$ | [60, 61] |
| **Weighted Unmet Thermal Performance (WUMTP)** | $\mathrm{WUMTP} = \sum_{i=1}^{12} S_i W_{p,i} W_{H,i} W_{E,i}$ <br> $\mathrm{WUMTPA_{overall}} = \frac{\sum_{z=1}^{Z} WUMTP_Z}{\sum_{z=1}^{Z} A_z}$ | [109] |
| **Resilience Class (RCI)** | $\mathrm{RCI} = \frac{WUMTPA_{overall,ref}}{WUMTPA_{overall}}$ | [109] |
| **Climate Change Overheating Resistivity (CCOR)** | $1/\mathrm{CCOR} = \frac{\sum_{Sc=1}^{Sc=M}(IOD_{Sc} - \overline{IOD}) \times (AWD_{Sc} - \overline{AWD})}{\sum_{Sc=1}^{Sc=M}(AWD_{Sc} - \overline{AWD})^2}$ | [108] |
| **Heat Exposure Index (HEI)** | $\mathrm{HEI} = \int_{11pm}^{7am} (T_{a,i} - T_{set-point})^{+}_{T_{a,i} \geq T_{set-point}} dt$ | [110] |

the cooling performance. Based on the vulnerability measures discussed it is evident that there is a lack of consensus in the field about which measures to use. However, what is evident is that combinations of different thresholds considering a broader range of variables for different people and buildings are required as well as different upper limits in the consideration of failure states given performance, comfort and more severe health risks.

*2.4.4.2. Resistance.* Considering the application of these metrics to future “foreseeable” extremes it is evident that metrics are lacking. The best consideration of this is the work of Hamdy et al. [61] which considers how resistant buildings are by evaluating and relating changes in internal conditions to external ones, by using an escalation factor. However, the main correlating variable in this regard is external air temperature. It should be noted that there are other works that consider foreseeable extremes using future weather data with different metrics but no correlations are drawn explicitly [118,119]. Relating external and internal conditions through an escalation factor provides a very interesting insight into the ambient warmness effect in these buildings. One limitation when applying degree hour approaches is the use of a base temperature that is not building specific. Some work has addressed this partially [78], but more work is needed in characterising the ambient warmness in relation to VC + buildings more comprehensively as well as connecting annual warming events to building characteristics. There is also a limitation in the averaging of internal and external metrics which do not capture the spread of the data, more work is needed in considering these easy-to-use approaches and how statistical approaches could be used to reveal more about the relationships between internal and external environments based on these metrics. In addition to this, more work is needed in considering and disaggregating the causes of overheating from other potential heat sources outside of ambient warmness (i.e. solar gains, internal gains [28,120]) and explaining the sensitivity of models to these sources. Some of these considerations have been addressed by previous work [121] focused specifically on VC. However, more work is needed in extending and simplifying complicated approaches to evaluating sensitivity.

*2.4.4.3. Robustness and recoverability.* There is a lack of metrics which consider robustness and recoverability in a more specific and focused manner. The use of a scoring or class system goes towards addressing the key differences between robust and resilient designs [109]. Previous work has presented resilience classes which apply robustness thresholds to capture this, there is a challenge in defining metrics which capture this more effectively. Given the infancy of the resilience research field regarding the indoor environment there is at this point some ambiguity about some of the definitions and differences between both resilient and robust designs. Both consider back-up plans [30] but at this point the key distinction is that one fails to restore to equilibrium. Practically speaking there is also a limitation in considering what is “unforeseen”. Clearly this is a theoretical assessment of extremely unlikely events which have typically been considered in other fields by considering for example a one in 100-year event. What differentiates assessments of both robustness and recovery (and by extension resilience) is consideration for short “high-impact” events which could have “a substantial and detrimental societal impact” and could lead to or “cause a significant loss of life” [122]. As such it is critical that more metrics are proposed to address these short periods and address key features of recovery including the “recovery time” [52] and management plans at different scales to protect human life. This may include the need to determine safe places of refuge to optimise resources. One shortcoming of the existing methods is that there are very few standard heat wave datasets for which to test very extreme events over different timescales (3 day–10-day events). Finally, it is evident that more qualitative approaches may be required at early-stage design to allow practitioners assess "bouncing forward" which encompasses ability to learn from experience (failure and success) [51] and adaption influenced by ongoing change [123].

### 2.5. VC+ approaches for improving thermal resilience

Passive cooling and passive cooling strategies have been described as a “multi-layered and multi-disciplinary process” [124]. Described by Santamouris and Kolokotsa [124] and later by Bhamare et al. [125] as being broadly discussed in three main categories: 1) prevention (of heat gains), 2) modulation (of heat gains), and 3) heat dissipation. Dissipation techniques can be characterised by four main processes: 1) Ground cooling (coupling buildings to the ground), 2) Convective or VC (using ambient air), 3) Evaporative cooling (using water as a heat sink), and 4) Radiative cooling (using the sky as a heat sink) [124]. The focus of this review is on VC+ methods which includes some supplementary passive prevention and modulation methods. Previous work from Annex 62 (Table 7) has highlighted many VC technologies and which ones are supplemented by additional passive interventions [28]. Table 7 below presents the types of VC techniques plus some prevention and modulation methods that have been used or evaluated in the literature for non-residential buildings. Based on Table 7 it is evident that there are many diverse VC+ solutions that can be used to mitigate overheating incidences in various non-residential building types. Work by Bhamare et al. [125] indicates reductions in internal air temperatures of between 1 °C and 20 °C for radiative cooling solutions, 3.5 °C–14 °C for direct evaporative cooling solutions, 2 °C–14 °C for different types of solar chimneys, 2 °C–8 °C for Trombe walls, 2 °C–12 °C for wind driven NV, 1.5 °C–6.5 °C for roof ponds, and 3 °C–9 °C for solutions focused on the use of vegetation in urban areas. In addition to this, work by O' Donovan et al. (2021) has demonstrated considerable reductions in internal air temperatures of between 4.0 °C and 8.1 °C through the use of passive interventions including solar shading and night time ventilation. As such VC+ systems (particularly combinations of systems) present an opportunity not only to be the most energy efficient solution but also maintain thermally comfortable conditions in non-residential buildings.

## 3. Methodology for the review of studies evaluating indoor thermal resilience

In order to address the aims 2, 3 & 4 of the study, and based on methodologies used in previous studies [30,164–166], the approach adopted can be divided into three main steps:

### *3.1. Data collection and study screening through literature search*

In this step of the methodology, a systematic mapping study was conducted where the data collection process consisted of five stages: 3.1.1) Sample identification, 3.1.2) Screening and elimination, 3.1.3) Scope limitation, 3.1.4) Feature collection and identification, and 3.1.5) Feature distinction (see Fig. 10).

#### *3.1.1. Sample identification*

During this stage, a sample of the literature was collected, which consisted of book chapters, reviews, journal articles and conference proceedings. The search identified articles that used the following strings in the title, abstract and/or keywords from 2010 to September 2021 using the Scopus search engine. The strings and logic used are indicated in Fig. 11, which includes four strings.

#### *3.1.2. Screening and elimination*

This stage involved screening and eliminating irrelevant articles, e.g., content duplicated in multiple documents, out of context of buildings etc. The number of studies that matched the initial search criteria in the first stage was 134 articles, out of which 53 articles were duplicated.

#### *3.1.3. Scope limitation*

This stage involved the specific screening of documents relevant to non-residential buildings, considering whether the study has been done in terms of an indoor environment, thermal comfort, natural ventilation, passive cooling, overheating or overcooling in the context of non-residential buildings or not. The screening results showed that three findings were just the title of the conferences, 20 papers related to housing, and 37 papers had non relevant subjects, including 23 papers related to urban and 14 papers related to network and systems' overheating. In total, 24 documents in the context of resilient non-residential buildings passed the final screening stage and were included in the evaluation.

#### *3.1.4. Feature collection and identification*

The main focus of this study is on 24 related documents in non-residential buildings. The following information was collected and compared: 1) Uses type, location, Koppen climate type, 2) Whether the case study is VC + or not, 3) Use of the resilience term, including the resilience definition and criteria, 4) Methods of evaluating and improving resilience, including the short- or long-term prediction, measured parameters, field study, measurement tools, simulation tools, climate scenarios, and standards.

**Table 7**
Examples of VC+ techniques used in non-residential buildings in literature.

| References | Building Types | Locations (Country code) | VC+">+ Technologies | Passive Category | | | Dissipation Sink | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Modulation | Prevention | Dissipation | A | G | W | S |
| [56,119,126–135] | Office, School, All, Test-cell | BE, UK, IE, HU, CY, IT, DE, GR, All | Natural Ventilation | | | X | x | | | |
| [118,119,127,133,136,137] | Office, School, All | BE, UK, IE, HU, CY, DE, All | Night Ventilation | | | x | x | | | |
| [56] | Hospital | UK | Fans | | | x | x | | | |
| [138–143] | Test-cell, Office, School | DE, CN, IN, IT | Earth-to-Air HX | | | x | | x | | |
| [144–147] | All, Test-cell | IN, BR, CN, UK | Direct Evaporative Cooling | | | x | | | x | |
| [148–150] | Test-cell, All | IR, KU, IN | Indirect Evaporative Cooling | | | x | | | x | |
| [151,152] | All | All, IQ | Roof ponds | | | x | | | x | |
| [153] | Test-cell | IR | Trombe wall | | | x | | | x | |
| [146,154–156] | All | IN, TH, GR | Night-time radiative | | | x | | | | x |
| [118,119,127,128,131,133,135,157] | Office, School | BE, UK, IE, HU, CY, IT, DE, CA | Solar shading | | x | | | | | |
| [133] | School | UK | Reflective materials | | x | | | | | |
| [158,159] | All, Test-cell | MY, AU | Vegetation | | x | | | | | |
| [128,131,160,161] | School, Office | DE, CY, US, MY | Glazing | | x | | | | | |
| [137] | School | CY | Insulation | | x | | | | | |
| [128] | School | DE | Thermal mass activation | x | | | | | | |
| [128,146,162,163] | School, Office, Test-cell, All | DE, CN, IN | Phase change materials | x | | | | | | |

**Table.8**
Ventilative cooling components and supplementary passive technologies applied in the investigated reported in the Annex 62 well documented case studies, (reproduced from Annex 62 Design Guide) [28].

| Ventilative Cooling Components and Technologies | | | Air Flow Guiding components | | | | | Air Flow Enhancing Components | | | | Supplementary Cooling Technologies | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Case Study No. | Type and Location | Windows | Insulated louvre | Overflow vents between rooms | Air pipes and air supply devices | Roof vents | Chimney | Fan | Ground cooling | Evaporative cooling | Ground Source heat pump | Earth to air Heat Exchanger | Radiant solar heat and cooling | PCM storage |
| 01 | IE | Zero2020 | | x | | | | | | | | | | | |
| 02 | NO.1 | Brunla school | x | | | | | | x | | | | | | |
| 03 | NO.2 | Solstad Kindergarten | x | | | x | | | x | | | | | | |
| 04 | AT.1 | UNI Innsbruck | x | | x | | | | | x | | | | | |
| 05 | AT.2 | wkSimonsfeld | x | | | | x | | | x | | | | | |
| 06 | BE.1 | Renson | x | | | | | x | | | | | | | |
| 07 | BE.2 | KU Leuven, Ghent | x | | | | | | | | x | | | | |
| 08 | JP.1 | Nexus Hayama | x | | | | x | | | | | | | x | |
| 09 | JP.2 | GFO | | x | | x | | | x | | | | | | |
| 10 | PT | CML Kindergarten | x | x | | | | | | | | | | | |
| 11 | UK | Bristol University | | | | x | | | x | | | | | | x |

### 3.1.5. Feature distinction

This study focuses on assessing published studies that identified the term resilience (as an evaluating criterion or a basis for assessment) in the context of thermal comfort and indoor environment of non-residential buildings based on defined resilience criteria. Among these 24 papers, 22 were chosen as more relevant to thermal resilience and evaluated based on the four resilience criteria.

## 3.2. Resilience evaluation

In this study, the resilience criteria defined by Attia et al. [30] and Martin and Sunley [29] were used as a basis for evaluating these 22 papers. Again, the criteria for resilience are vulnerability, resistance, robustness and recoverability. In this review, as the focus is specifically on the thermal resilience of non-residential VC + buildings, the definition and interpretation of resilience and application of these criteria have been adjusted to reflect the application. In order to assess whether a study adequately considered each of these resilience criteria or not, based on Attia et al. [30] and Martin and Sunley [29] definitions, one question was defined to evaluate each criterion; these evaluation questions are shown in Table 9.

In addition to identifying whether these studies considered resilience, this evaluation also considered the methods used, the accuracy of instruments and simulations, and what internal environmental variables and standards were used in evaluations. The types of climate scenarios used were also assessed if a simulation-based approach was adopted.

## 3.3. Gap analysis and recommendations

Using this assessment of existing studies on indoor thermal resilience, supported by the broader review of the existing research and literature in section 2.0, the gaps in the existing literature and recommendations for future research will be discussed and presented.

# 4. Thermal resilience evaluation

This section presents the primary findings of the review of previous resilient studies to date assessing overheating in the context of VC+ as summarized in Table 10 and Table 11. Table .10 shows that none of the listed studies proposed a definition of resilience except for one (Study No. 19). Only two of the studies surveyed (Study No. 2 and No. 5) used an NZEB case study in their evaluations. Figs. 12 and 13 indicates the types of climate zones that have been considered in the literature as well as their consideration for resilience criteria.

As shown in Fig. 12, most studies have been carried out in a temperate oceanic climate (Cfb) and a Mediterranean climate (Csa). Fig. 12 also demonstrates that the portion of the type of case studies are roughly the same in educational, office and hospital buildings. These 22 studies were assessed based on the resilience criteria defined in section (3.2), Table 9, as shown in Fig. 13. Fig. 13 indicates the number of studies that assess different resilience criteria. Most of the studies assessed two resilience criteria even though they have not mentioned resilience criteria and just used the term “resilience”. Most (72.7%) studies assessed vulnerability (the possibility of overheating risk for case studies), and 63.6% assessed resistance (the potential of using supplementary passive interventions to improve thermal comfort against overheating risk). Furthermore, just 4.5% of studies considered robustness (backup plans have been considered if the VC+ system failed). None of the studies assessed recoverability (recovery plans to develop systems and occupants’ performance to adapt to overheating).

Fig. 14 highlights other key characteristics of these non-residential studies so that most studies evaluated the possibility of overheating in the long-term (59.1%) and used NV as a strategy to mitigate heat build-up (86.4%). Regarding assessment methods, 68.2% of studies were completed through experimental measurement; however, only 36.4% of those declared loggers’ accuracy. The method used by most of the

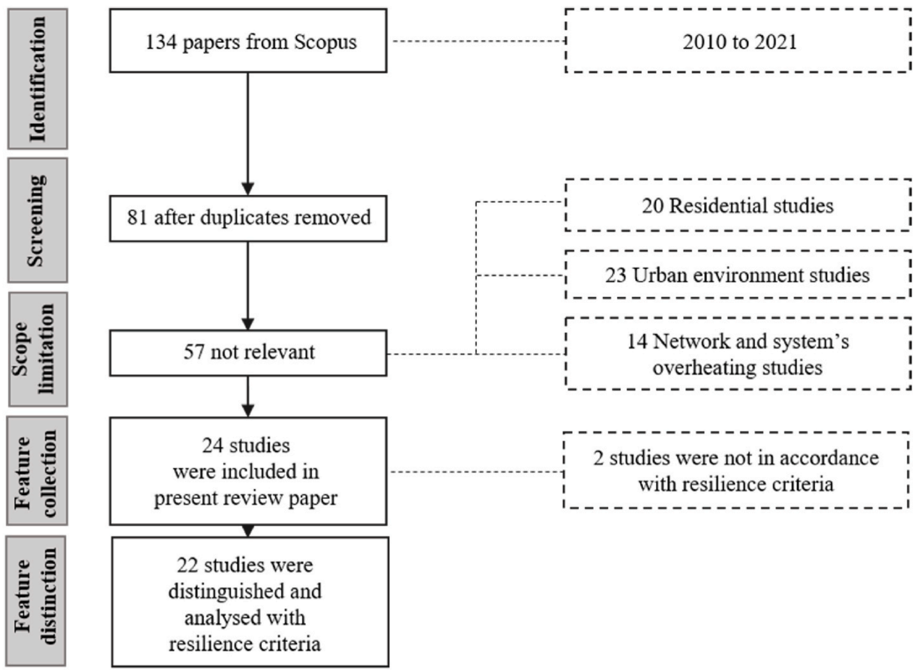



**Fig.10.** The findings of the searching process and assessing papers.

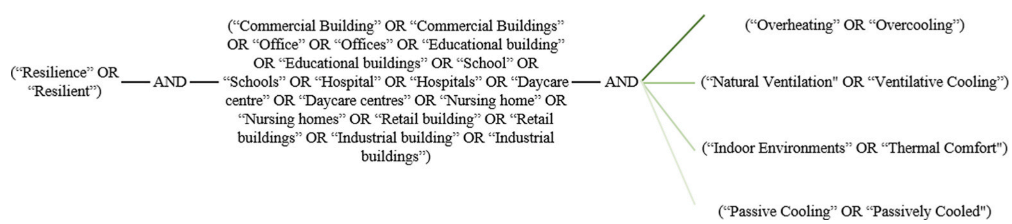



**Fig. 11.** The search strings for systematic literature review.

studies is a simulation (86.4%), and 59.1% of these simulations used calibrated models. Table 11 demonstrates the assessed methods, including experimental parameters, accuracy, simulation tools used, climate scenarios, calibration and standards that have been used in them.

Fig. 15 shows the parameters measured and the standards referenced in the sample of papers described in Table 11, which relate specifically to VC+ buildings. It should be noted that as shown in Table 11 some studies used more than one parameter measured, standard, climate scenario and simulation tool. Thus Figs. 15 and 16 considered each study for each parameter separately. The review of existing standards demonstrates that thermal comfort criteria are typically based on indoor operative temperatures. This figure indicates that the most common experimental parameters used to assess thermal resilience are air temperature (12 of 22 papers), relative humidity (4 of 22 papers) and operative temperature (3 of 22 papers), while the standards that are referenced most frequently are EN 15251 (12 of 22 papers), CIBSE (4 of 22 papers) and HTM03 (2 of 22 papers). Most simulation tools used in related studies to resilience criteria in the context of non-residential buildings shown in Fig. 16 are Energyplus (40%), IES-VE (30%) and TRNSYS (15%). Evaluating the climate scenario which has been used for simulation of non-residential buildings against overheating in related studies to resilience criteria, shown in Fig. 16, demonstrates that more than 50% of studies used UKCP09, UKCP02 (5 of 22 papers), TMY (6 of 22 papers) and DSY (4 of 22 papers).

## 5. Discussion

In this study, we developed a logical framework by proposing a question for each criterion (Table 9) as a measurement system to screen and evaluate thermal resilience criteria in VC+ non-residential buildings (Fig. 13) in 22 relevant papers (Table 10). Most of the studies assessed two resilience criteria, vulnerability (the possibility of overheating risk) and resistance (the potential of using passive intervention measures to improve thermal comfort against overheating risk). Despite many studies using "resilience" in their papers very few offer a definition and none mention specific resilience criteria (which was not formally defined until very recently [30]). Furthermore, only one of studies that were evaluated (Study No. 12) considered robustness (backup plans have been considered if the VC system failed). None of the studies assessed recoverability (recovery plans to develop systems and occupants' performance to adapt to overheating) and a multi-criteria approach for resilience that involves all four resilience criteria. In addition to this, only two of the studies (Studies No. 1&2) are identified as NZEBs [118,119].

### 5.1. Vulnerability and resistance of VC+

Existing research in the non-residential domain presents limited examples of measured performance, in the context of measured overheating specifically [56,113,133,174,180–182] especially compared with the body of research examined in work described in residential buildings or settings [8]. Excluding investigations into the future consequences of climate change, existing measurements highlight large

**Table 9**
The resilience criteria, assessing methods and evaluation questions of them.

| The resilience criteria of PC-NZEBs | | Assessing methods | Evaluation questions |
|---|---|---|---|
| Vulnerability | The impact of overheating risk on thermal comfort in VC + buildings | -Experimental (for calibrating the existing model) -Simulation (for predicting building performance against overheating using future climate scenarios) | Whether the possibility of overheating risk (long/short term) has been evaluated in the building? |
| Resistance | The potential of using VC + approaches in buildings to improve thermal comfort against overheating risk. | - Simulation | Whether the potential of using passively cooling systems to improve thermal comfort against overheating risk (long/short term) has been evaluated or not? |
| Robustness | Consider proposed backup plans and system control possibilities to adapt to conditions if the natural ventilation system fails. | - Simulation | Whether any backup plans have been considered if the passive cooling system failed? |
| Recoverability | Recover and develop systems and occupants' ability to return to the pre-risk state. | - Simulation | Is there any consideration of learning plans influenced by continuous change to develop systems and occupant performance to adapt to overheating? |

differences between indoor spaces when it comes to overheating performance [56,113,174,180–182], which already illustrates the sensitivity within buildings which is likely to disimprove due to climate change. Outside of simulation-based research, there is evidence already emerging that some spaces in non-residential buildings are overheating [113,180]. These studies (that examine buildings that are not LEBs) highlight potential VC + solutions to this including: the provision of cross ventilation [182], the consideration for window restrictors and the use of solar shading [113]. In the context of hospital settings, it is suggested that more drastic actions may be required to manage the heat in buildings including: rescheduling vulnerable groups to earlier times in the day, and providing a cool room or a place of relief for hospital staff [180]. Some studies also highlight the difference in sensitivity of occupants compared with existing standards and indicate that vulnerable groups such as the elderly and children (in the context of schools and care settings) are likely to be more sensitive to changes in internal conditions and standards may need to change to reflect this [113,181]. This highlights the need to examine the comfort and perception of these occupants. From our evaluation it is evident that studies which focus on the vulnerability of buildings use different metrics to report findings, which is often representative of the buildings involved. For hospital settings for example, static thresholds are often used as some occupants cannot make adaptive actions [113]. Simulations in current conditions highlight overheating incidences in existing VC+ buildings in different locations across many climates and settings [118,119,131,183], and mirror the general findings in field study research showing variance within buildings. Existing research focused on simulated performance (compared with field work) also highlights the potential improvement of existing performance through the use of passive interventions such as: solar shading [119,133], natural ventilation [137] and night ventilation [119,133,183]. [183] (Study No.21) simulated the difference in overheating in current conditions in a VC+ school building in Italy. In this work it was found that the number of hours with internal operative temperatures in excess of 28 °C can be reduced from 80% to between 2% and 12% through the provision of both night ventilation and solar shading. Duran & Lomas [118] also highlight solutions in current conditions for a simulated office building location in London. In this work

**Table 10**
Summary of previous resilient studies to date assessing overheating in the context of VC + buildings.

| Resilience studies to date assessing overheating | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| No | Ref | Year | Case Study | Climate (KG Class) | Defined resilience? | NZEB? | NV? | Resilience Criteria | | | |
| | | | | | | | | CR1 VUL | CR2 RES | CR3 ROB | CR4 REC |
| 1 | [118] | 2021 | Office (UK) | Cfb | × | × | ✔ | ✔ | ✔ | × | × |
| 2 | [119] | 2021 | Office (Ireland) | Cfb | × | ✔ | ✔ | ✔ | ✔ | × | × |
| 3 | [167] | 2018 | School (Cyprus) | Csa | × | × | ✔ | ✔ | ✔ | × | × |
| 4 | [12] | 2010 | Office (UK) | Cfb | × | × | ✔ | ✔ | ✔ | × | × |
| 5 | [168] | 2021 | School (Swiss) | Dfb | × | ✔ | ✔ | ✔ | ✔ | × | × |
| 6 | [14] | 2019 | Office (Spain) | Csa | × | × | ✔ | ✔ | ✔ | × | × |
| 7 | [169] | 2019 | Office (Mediterranean) | BSh, Sk, BWh, Cfa, Csa, Dfb | × | × | ✔ | × | × | × | × |
| 8 | [170] | 2020 | Educational (Spain) | Csa | × | × | ✔ | × | × | × | × |
| 9 | [171] | 2020 | Office (Italy) | Csa | × | × | × | × | × | × | × |
| 10 | [17] | 2019 | Office (Chilean) | Csc Csb | × | × | ✔ | × | × | × | × |
| 11 | [172] | 2016 | Office (New Zealand) | Cfb | × | × | × | × | × | × | × |
| 12 | [56] | 2012 | Hospital (UK) | Cfb | × | × | ✔ | ✔ | ✔ | ✔ | × |
| 13 | [133] | 2020 | School (UK) | Cfb | × | × | ✔ | ✔ | ✔ | × | × |
| 14 | [173] | 2020 | School/Hospital (Canada) | Dfb | × | × | × | ✔ | × | × | × |
| 15 | [174] | 2015 | Hospital (UK) | Cfb | × | × | ✔ | ✔ | ✔ | × | × |
| 16 | [175] | 2015 | Hospital (UK) | Cfb | × | × | ✔ | × | × | × | × |
| 17 | [176] | 2014 | Hospital (UK) | Cfb | × | × | ✔ | ✔ | × | × | × |
| 18 | [11] | 2012 | Hospital (UK) | Cfb | × | × | ✔ | ✔ | ✔ | × | × |
| 19 | [79] | 2020 | Nursing home (US) | Cfa, Csa, Dfa | × | × | ✔ | ✔ | ✔ | × | × |
| 20 | [177] | 2016 | Day care center (Italy) | Cfa | × | × | ✔ | ✔ | ✔ | × | × |
| 21 | [178] | 2017 | School (Italy) | Csb, Csa, Csa | × | ✔ | ✔ | ✔ | ✔ | × | × |
| 22 | [131] | 2021 | School (Cyprus) | Csa | × | × | ✔ | ✔ | ✔ | × | × |

**Table 11**
The methods and standards in previous resilient studies to date assessing overheating in the context of PC-NZEBs.

| No | Ref | Resilience (Short term or Long term?) | Assessing methods | | | | | Standards |
|---|---|---|---|---|---|---|---|---|
| | | | Experimental | | Simulation | | | |
| | | | Parameters measured | Logger Accuracy? | Tools | Climate scenario | Calibrated? | |
| 1 | [118] | Long | × | × | EnergyPlus | UKCP09 | No | × |
| 2 | [119] | Long | $T_o$, $T_a$, RH | Yes | TRNSYS 17 | TMY, 2050 | Yes | EN15251, EN16798-1 |
| 3 | [167] | Long | × | × | IES-VE | TMY, 2050 and 2090 | No | EN15251, CIBSE TM52 |
| 4 | [179] | Long | × | × | EnergyPlus | UKCP02 | No | CIBSE TM36, CIBSE Guide A |
| 5 | [168] | Long | × | × | DIAL | Geneva Cointrin IPCC B1, A2,MAX | × | EN15251, ISO7730 |
| 6 | [14] | Long | $T_a$ | Yes | EnergyPlus | HadCM3 | Yes | EN15251, ASHRAE Standard 55 |
| 7 | [15] | Short | × | × | EnergyPlus | TMY | No | EN15251, ASHRAE Standard 55 |
| 8 | [170] | Short | $T_a$, RH, $CO_2$ | Yes | EnergyPlus | SWEC database | Yes | RITE-IDA2 |
| 9 | [171] | × | Daily activity, Overall satisfaction, Work performances, Daily fatigue, Stress | No | × | × | × | LEED, BREEAM, CASBEE, |
| 10 | [17] | × | Operating (window, shading, fans or heaters, setpoint of the HVAC), $T_a$, $T_g$, RH, V | Yes | × | × | × | Chile Thermal Comfort Standards |
| 11 | [172] | × | Comfort & Well-being | Yes | × | × | × | ASHRAE Standard 55 |
| 12 | [56] | Long | $T_o$, $T_a$ | Yes | IES-VE | UKCP09 | Yes | EN15251 |
| 13 | [133] | Long | $T_a$, RH | Yes | TRNSYS | EPW DSY3 | Yes | EN15251, CIBSE TM52 |
| 14 | [173] | Short | $T_a$ | No | Energyplus | regional climate | Yes | EN 15251 |
| 15 | [174] | Long | $T_a$ | No | IES-VE | TRY DSY | Yes | CIBSE TM52, EN15251, HTM03-01 |
| 16 | [175] | Short | $T_{in}$, $T_{out}$, SR | Yes | DLM | Weather data of the hot summer,2006 | Yes | EN15251, CIBSE TM52 |
| 17 | [176] | Long | $T_{mean}$, ACH | No | IES CFD | UKCP09, TRY DSY | Yes | HTM03-01, EN15251 |
| 18 | [11] | Long | $T_{in}$, | No | IES | UKCP09, TRY, DSY, | Yes | CIBSE Guide A, HTM03-01, EN15251 |
| 19 | [79] | Short | $T_{in}$ | No | EnergyPlus | TMY | Yes | ASHRAE Standard 55, |
| 20 | [177] | Long | $T_{in}$, $T_{out}$, $CO_2$ | No | EnergyPlus | TMY | Yes | ASHRAE Standard 62, EN 15251 |
| 21 | [178] | Short | × | × | TRNSYS 16 | × | × | ISO7730 |
| 22 | [137] | Long | × | × | IES-VE | TMY, 2050 and 2090 | Yes | EN15251, CIBSE TM52 |

$T_o$: Operative temperature, $T_a$: Air temperature, RH: Relative humidity, $CO_2$: Carbon dioxide, HVAC: Heating, ventilation, and air conditioning, $T_g$: Glass transition temperature, V: Air velocity, $T_{in}$: Indoor air temperature, $T_{out}$: Outdoor air temperature, SR: Solar radiation, $T_{mean}$: Mean temperature, ACH: Air change.

(Study No.1) the importance of combining shading (in the form of overhangs and external blinds) as well as mixed-mode ventilation in mitigating overheating is highlighted. For current conditions it was shown that buildings with day-time NV only can have a percentage of overall building thermal discomfort (OBTD) hours as high as 18% for buildings retrofitted according to national regulations, and as high as 55% for those retrofitted to EnerPHit standards. The provision of mixed-mode ventilation, shading and night-time ventilation was shown to decrease this risk to less than 1% for both building retrofit scenarios. Work by O' Donovan et al. [119] (Study No.2) focused on a VC + office space (which exceeded national NZEB standards) and found that in current conditions for continental climates day-time ventilation only could lead to close to 30% of the occupied hours being more than the upper adaptive comfort limits for those with a normal level of expectation. The use of strategies that combined day-time and night-time ventilation as well as solar shading were shown to be effective at mitigating this discomfort to acceptable levels (<5%). Stephen et al. [133] (Study No.13) found similar results when simulating the performance of a primary school located in Southampton in the UK. It was shown that the existing VC system alone would fail to comply with TM52 in current conditions (Criteria 1: 13.6%), however, the use of shading and night-ventilation led to the same school complying with TM52 (Criteria 1: 0.8%) in the same conditions. In similar work by Heracleous et al. [137] (Study No.22) a series of retrofit scenarios were considered for a school located in Cyprus. A combination of fabric upgrades, heat recovery ventilation, night-time ventilation and solar shading resulted in a reduction of cooling degree hours from 90.7 to between 0 and 2.9.

When it comes to future overheating, climate change will have a significant effect on the performance of VC+ strategies, but for some strategies and climates more than others. Work by Bravo Dias et al. [184] highlights the shape of future weather patterns and their likely effect on the use of passive intervention measures in the context of LEBs. In this work it is indicated that outside of countries located in Scandinavia and the British Isles it is likely that Europe will suffer from a reduced effectiveness of VC+ strategies. In the UK, Duran and Lomas [118] (Study No.1) suggest that passive cooling measures can guarantee

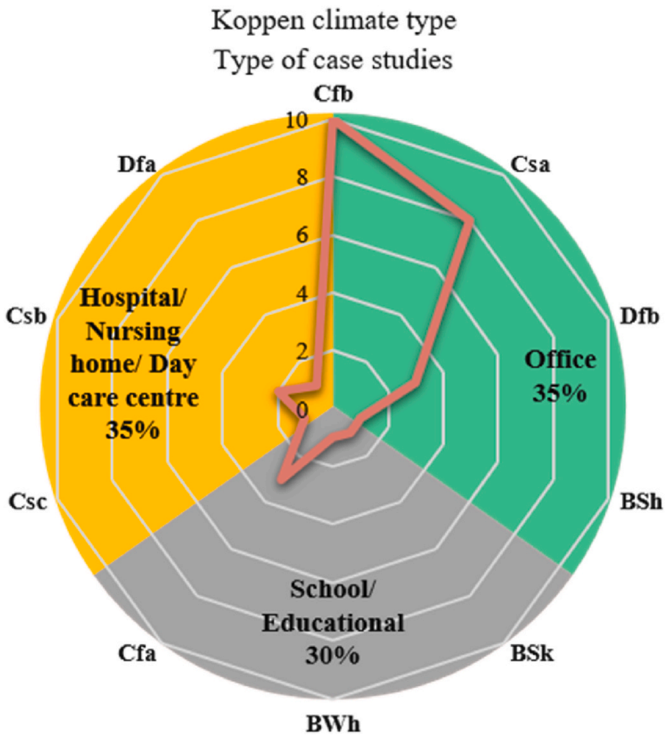



**Fig. 12.** The climate type of papers that related to resilience criteria in the context of non-residential buildings.

comfortable conditions in 2050 with national regulations, however, EnerPHit standards are likely to require mixed-mode ventilation to achieve the same level of thermal comfort. Lomas and Giridharan [56] (Study No.12) indicate that simple VC measures such as the use of fans could enable hospital wards to be comfortable (according to Category I of EN 15251) even in extreme years up to 2080. O' Donovan et al. [119] (Study No.2) indicates that even in future extreme conditions it is likely that passive control strategies will be sufficient to maintain comfortable conditions in low energy offices in Ireland up to 2050. However, the same strategies may not be sufficient to maintain comfortable conditions in low energy offices in Hungary in the same time period. Heracleous et al. [131] (Study No.22) indicates that VC with passive interventions (VC+) will reduce the cooling demand in an existing school located in Cyprus by between 91.4% and 99.5% in 2050, and by 84.9%–96.1% in 2090. Pagliano et al. [185] indicates that a VC + child care centre, located in Milan Italy, is likely to not overheat in 2020 conditions, is likely to exceed upper limits of Category I in EN 15251 (now replaced by EN 16798-1, however upper limits have not changed) by 0.8% in 2050 and is likely to exceed upper limits of Category I by 4.9% in 2080. The evidence from central and southern Europe also indicates a stark and significant rise in cooling demand due to a warming climate which is not likely to affect all regions equally [124,184]. Of the studies evaluated, it is indicated that increases in cooling demand of between 50% and 80% are likely in 2050 [131,185], up to 123% in 2080 and between 135% and 213% in 2090. The vulnerability of VC+ strategies has resulted in some studies (Study No.18) highlighting the potential need for mechanical interventions for extreme years for hospital spaces [11]. It has been shown that even with the adoption of VC+ it is likely that energy consumption of solutions will increase for particular applications [174]. Adaptive models (which require passive interventions) can play a major role in reducing the energy consumption of buildings, with reductions of between 8% and 60% depending on the climate [14,186–188], while keeping buildings comfortable for what is large portions of the year even in future conditions [14,119]. Passive survivability is a key characteristic of resilient buildings [54], and buildings that have passive backup plans could be very important if power outages occur. Sun et al. [79] indicates this showing how the provision of VC+ strategies (such as natural ventilation) can be effective in reducing dangerous conditions. It is likely that VC+ strategies will remain resistive in many countries over the next decade. Of the studies evaluated it has been shown (Study No.15) that VC+ buildings will maintain comfortable conditions for large portions of the year in typical conditions [11,119,137]. Many studies highlight the improvement in comfort conditions which can be resistive in typical and future years for upwards of 90% of the occupied hours [11,131,185]. Despite this, it is in extreme years or extreme events that VC+ strategies may not be "100% safe" [79] (Study No.19) and are vulnerable in that regard. To address this vulnerability, it is likely that supplementary systems will be required for extreme events [52,79]. The make-up of these supplementary systems could be anywhere from the transport of air through fans [56], the use of other heat dissipation techniques described earlier or the use of mechanical cooling [11,119].

### 5.2. *Robustness and recoverability VC+*

Currently, there are limited examples in research literature which indicate the performance of back-up plans in detail. Short et al. [11] (Study No.18) provide a VC+ solution when NV is not sufficient which has been found to be suitable up to 2080. It is also discussed in Sun et al. [79], (Study No.19) in the context of using NV as a back-up during system failure. The obvious and perhaps "less" energy efficient solution is to use AC. However, despite the likely increase in AC by 2050 and the negative energy implications [189], systems connected to the electrical grid may not be able to provide the recovery to safe or even comfortable conditions in the absence of grid supplied power [79]. Solutions such as back-up power systems or storage technology will be required to ensure that spaces remain resilient in the face of energy disturbances [79] (Study No.19).

## 6. Recommendations, conclusions and future work

The use of VC+ can be a very energy efficient option; however, it is likely that in many locations throughout Europe and the world that VC+ will not be sufficient alone and there is a need to focus on improving the resistance of buildings that use VC+ exclusively as well as considering the recovery of VC+ using supplementary passive systems in the first instance. The literature presented here illustrates how despite the need for our buildings to become more resilient in the coming decades, building-related definitions, frameworks for evaluation purposes and data that serves as a feedback loop indicating the vital signs in our non-residential building stock is limited and all needs addressing. The projected stark increases in external temperatures (coupled with high humidity) and likely thermal deformation of the internal environment are likely to lead to significant morbidity and excess mortality over short periods of time and this requires particular attention when heat wave planning is considered. Merging and collaboration between multi-disciplinary research teams as well as more open source empirical performance data for VC+ buildings could be needed to deliver the best scientific results and the most comprehensive recovery plans. The evaluation presented indicates that VC+ buildings can be resistive when they combine multiple measures which focus on the fundamentals or principles of passive cooling.

### 6.1. *Recommendations*

Based on this evaluation of the literature for non-residential buildings the following is recommended to improve the resilience of future buildings:

1) Future designs should always be stress tested in future extreme conditions [118,119].

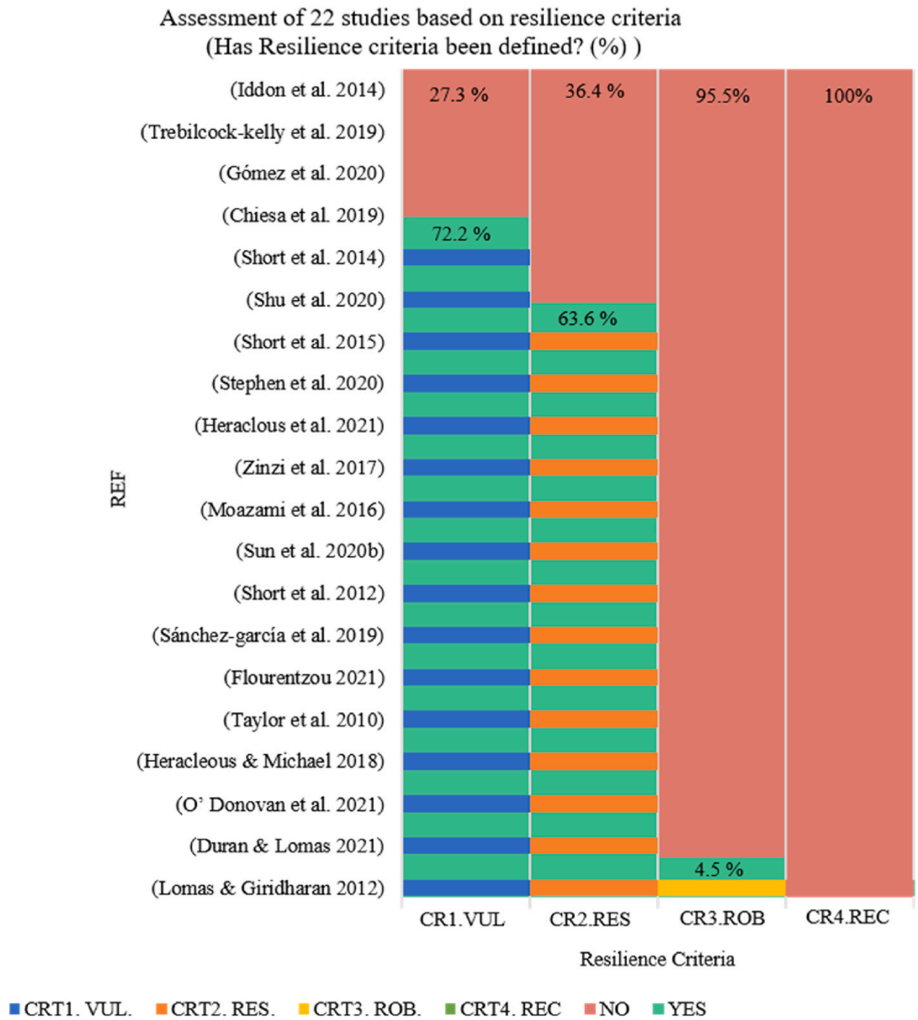



**Fig. 13.** The assessment of resilience criteria in the 22 related papers in the context of non-residential buildings.

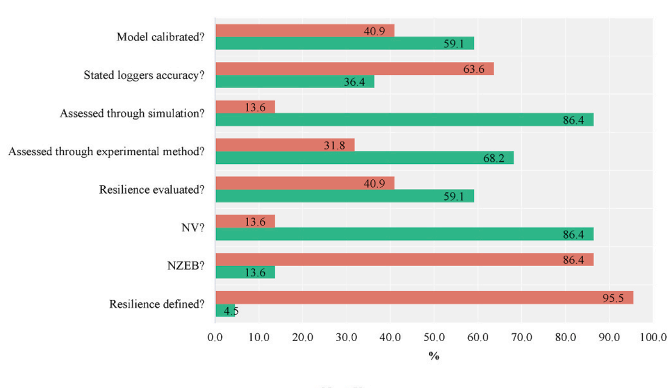



**Fig. 14.** The key characteristics of the papers that related to resilience criteria in the context of non-residential buildings.

From the literature examined design can play a key role in reducing overheating and those efforts should be made to stress test designs accordingly in new builds and retrofits.

2) Multiple supplementary passive interventions should be used to ensure resistance in designs [118,119,137,185].

3) The integration of these passive interventions (utilising multiple passive dissipation sources) with active measures should be considered for the best total performance [79].

Based on the sample presented, there is a need in many extreme scenarios (outside of typical years) to have additional VC + measures or beyond. This may require MV or AC systems also but NV and other systems can play a key role if systems fail.

4) There is an urgent need for more empirical evidence of resilient designs in the non-residential domain, this is particularly lacking in modern LEB (or NZEB) settings [118,119].

Current research has many limitations which require future work. However, practically there is a need for designs to be evaluated post-design and more data is required to confirm bouncing forward, ability to learn from the success and failings of solutions that were designed to perform well in this regard.

### 6.2. *Conclusions and future work*

There are many limitations in existing literature that require addressing as was mentioned. Based on this evaluation the following gaps have been identified which require further work:

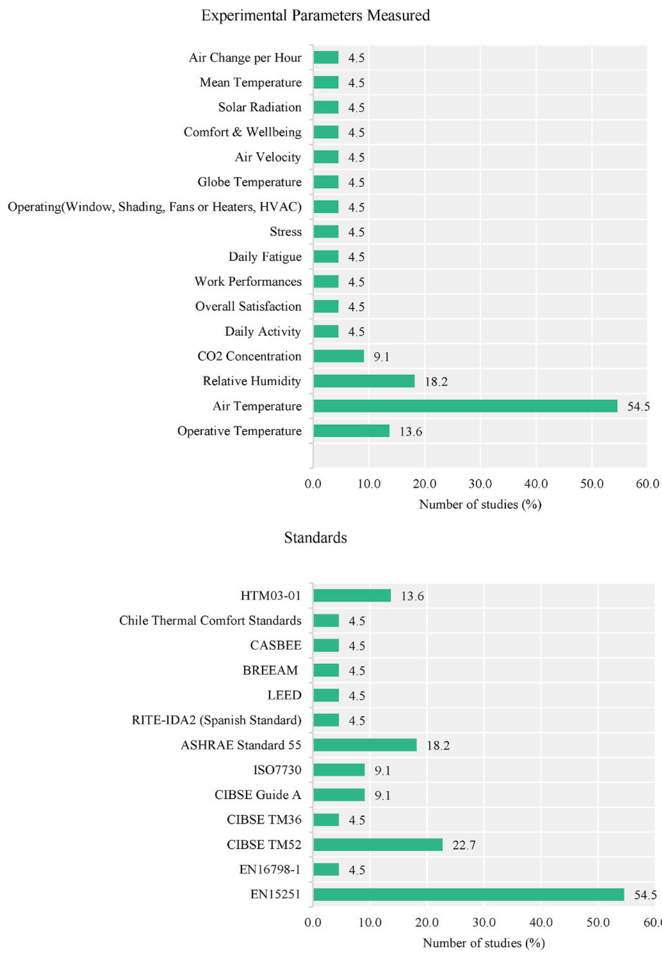



**Fig. 15.** The parameters measured and assessment based on standards as referred by the 22 related papers.

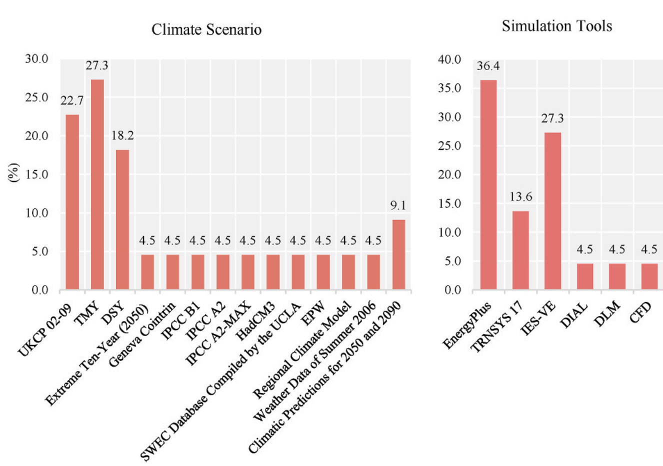



**Fig. 16.** The climate scenario and simulations tools which has been used in the 22 related papers.

1) Additional work is needed in examining the resilience of designs which incorporate different heat sinks (water, ground sky etc.).

Current literature indicates that some of these solutions are more advanced than others. However, the supplementation of traditional VC+ systems such as natural ventilation and solar shading, with water or ground based solutions is likely to be necessary to lead to optimal energy and comfort performance in future conditions.

2) More work is needed in evaluating the robustness and recoverability of all solutions including VC+, for extreme one day events as well as for more prolonged heat waves, particularly in the context of cultural, social, and psychological differences that may exist for different people in different climatic conditions.
3) Consideration should be given to heat wave plans and what the optimal places of refuge should be in these circumstances.

Current literature in the building research domain presents limited examples of tests of failure or the consideration of whether *stay at home* notices are the best option to reduce the risk of death. Multi-disciplinary research is required to determine the effect education, supplementary passive interventions and heat wave emergency management plans can have on mitigating excess mortality in VC + buildings.

4) Despite the development of "resilience" metrics and definitions in the context of buildings these metrics need to be applied more broadly and more examples for non-residential buildings, and updates to definitions should progress rapidly. The current use of operative temperature-based models is likely not to capture the totalised occupant experience or vulnerability in adverse conditions.

Related to the previous point, there are many examples of metrics which should be considered in typical building evaluations where designs are stress tested or data is used in heat stress studies to determine the wider ramification for occupant health.

5) More work is needed in evaluating the response of occupants under extreme conditions to warn of potential health related issues for different people worldwide.

The adaptation of occupants could be play a key role in providing flexibility in designs by widening the distribution of internal conditions and flattening the curve of excess heat. VC+ strategies that not only focus on the holistic building should be considered in the context of the occupant's degree of adaptation and allowing for their sensible and latent heat exchange with their surrounding environment.

## CRediT authorship contribution statement

**Elahe Tavakoli:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Adam O' Donovan:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Maria Kolokotroni:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Paul D. O'Sullivan:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Paul D. O'Sullivan reports financial support was provided by Sustainable Energy Authority of Ireland.

## Acknowledgements

This research has been funded by the Sustainable Energy Authority of Ireland (SEAI) RD&D fund 2019, grant number RDD/00496.

## References


[1] IPCC, IPCC: Climate Change 2021: the Physical Science Basis, Cambridge University Press, 2021, p. 42. *In Press*, https://www.ipcc.ch/report/ar6/wg1/.
[2] A. Beizaee, K.J. Lomas, S.K. Firth, National survey of summertime temperatures and overheating risk in English homes, Build. Environ. 65 (2013) 1–17, https://doi.org/10.1016/j.buildenv.2013.03.011.
[3] M. Santamouris, Advances in Building Energy Research Heat Island Research in Europe : the State of Heat Island Research in Europe : the State of the Art, vols. 37–41, Earthscan, 2007. July 2012.
[4] M. Santamouris, D. Kolokotsa, On the impact of urban overheating and extreme climatic conditions on housing, energy, comfort and environmental quality of vulnerable population in Europe, Energy Build. 98 (2015) 125–133, https://doi.org/10.1016/j.enbuild.2014.08.050.
[5] V. Ciancio, F. Salata, S. Falasca, G. Curci, I. Golasi, P. de Wilde, Energy demands of buildings in the framework of climate change: an investigation across Europe, Sustain. Cities Soc. 60 (March) (2020), 102213, https://doi.org/10.1016/j.scs.2020.102213.
[6] IEA, Executive Summary, vols. 23–28, 2018, https://doi.org/10.1787/weo-2018-2-en.
[7] Annex80, I. E, IEA EBC Annex 80 on Resilient Cooling for Residential and Small Non-residential Buildings Annex Text, 2019.
[8] K.J. Lomas, S.M. Porritt, Overheating in buildings: lessons from research, Build. Res. Inf. 45 (1–2) (2017) 1–18, https://doi.org/10.1080/09613218.2017.1256136.
[9] CIBSE, Environmental Design. In *Design History: A Students' Handbook*, 2016, https://doi.org/10.4324/9780203118283-89.
[10] T.O. Adekunle, T.O. Adekunle, Under moderate weather conditions Summer performance , comfort , and heat stress in structural timber buildings under moderate weather conditions. https://doi.org/10.1108/SASBE-11-2018-0059, 2019.
[11] C.A. Short, K.J. Lomas, R. Giridharan, A.J. Fair, Building resilience to overheating into 1960's UK hospital buildings within the constraint of the national carbon reduction target: adaptive strategies, Build. Environ. 55 (2012) 73–95, https://doi.org/10.1016/j.buildenv.2012.02.031.
[12] P. Taylor, P. De Wilde, W. Tian, Journal of Building Performance Simulation the role of adaptive thermal comfort in the prediction of the thermal performance of a modern mixed-mode office building in the UK under climate change, October (2010) 37–41, https://doi.org/10.1080/19401490903486114, 2014.
[13] M.E. Loughnan, M. Carroll, N. Tapper, Int. J. Behav. Dev. (2014), https://doi.org/10.1007/s00484-014-0939-9.
[14] D. Sánchez-garcía, C. Rubio-bellido, J. Jesús, A. Pérez-fargallo, Energy & Buildings towards the quantification of energy demand and consumption through the adaptive comfort approach in mixed mode office buildings considering climate change. https://doi.org/10.1016/j.enbuild.2019.02.002, 2019, 187, 173-185.
[15] G. Chiesa, N. Huberman, D. Pearlmutter, Geo-climatic potential of direct evaporative cooling in the Mediterranean Region: a comparison of key performance indicators, Build. Environ. (2019), https://doi.org/10.1016/j.buildenv.2019.01.059.
[16] A. Laouadi, M. Bartko, M.A. Lacasse, A new methodology of evaluation of overheating in buildings, Energy Build. 226 (2020), 110360, https://doi.org/10.1016/j.enbuild.2020.110360.
[17] M. Trebilcock-kelly, J. Soto-muñoz, L. Marín-restrepo, Adaptive thermal comfort for resilient office buildings. https://doi.org/10.1088/1742-6596/1343/1/012148, 2019.
[18] M. Zune, L. Rodrigues, M. Gillott, Energy & Buildings the vulnerability of homes to overheating in Myanmar today and in the future : a heat index analysis of measured and simulated data, Energy Build. 223 (2020), 110201, https://doi.org/10.1016/j.enbuild.2020.110201. https://xp20.ashrae.org/terminology/index.php?page_num=4&next=next&current_search=P&type_search=letter. Jun 2022.
[19] U. Berardi, P. Jafarpur, Assessing the impact of climate change on building heating and cooling energy demand in Canada Canadian weather year for energy calculation special report on emission scenarios, Renew. Sustain. Energy Rev. 121 (December 2019) (2020), 109681, https://doi.org/10.1016/j.rser.2019.109681.
[20] K. Jylhä, K. Ruosteenoja, J. Jokisalo, K. Pilli-sihvola, Data in Brief Hourly test reference weather data in the changing climate of Finland for building energy simulations, Data Brief 4 (2015) 162–169, https://doi.org/10.1016/j.dib.2015.04.026.
[21] Y. Yang, V.M. Nik, Assessing the Impacts of Climate Change on the German Building Stock Division of Building Physics, Lund University, Lund , Sweden, 2019, pp. 3563–3568. Division of Building Technology , Chalmers University of Technology , Gothenburg , Sweden Institute for Future Environments.
[22] C.Y. Yi, C. Peng, Energy & Buildings an archetype-in-neighbourhood framework for modelling cooling energy demand of a city ' s housing stock, Energy Build. 196 (2019) 30–45, https://doi.org/10.1016/j.enbuild.2019.05.015.
[23] L. Brotas, J. Lafuente, The impact of the Urban Heat Island in the energy consumption and overheating of domestic buildings in London, in: Proceedings of 8th Windsor Conference: Counting the Cost of Comfort in a Changing World, April 2014, 2014, pp. 805–815. http://nceub.org.uk/W2014/webpage/pdfs/session6/W14147_Lafuente.pdf.
[24] A.J. Marszal, P. Heiselberg, J.S. Bourrelle, E. Musall, K. Voss, I. Sartori, A. Napolitano, Zero Energy Building - a review of definitions and calculation methodologies, Energy Build. 43 (4) (2011) 971–979, https://doi.org/10.1016/j.enbuild.2010.12.022.
[25] P. Moseley, A. Lacourt, J. Laustsen, P. Wouters, M. Papaglastra, T. Thomopoulos, M. Dimitriadis, P. McElmuray, E. Ochsenkuehn, A. Fytrou, K. Poseidon, Implementing the energy performance of buildings directive (EPBD), in: COUNTRY REPORTS, 2019.
[26] B. Richard, H. Nasarullah, S. Abdul, A review of sustainable cooling technologies in buildings, Renew. Sustain. Energy Rev. 15 (6) (2011) 3112–3120, https://doi.org/10.1016/j.rser.2011.03.032.
[27] D.G.L. Samuel, S.M.S. Nagendra, M.P. Maiya, Passive alternatives to mechanical air conditioning of building : a review, Build. Environ. 66 (2013) 54–64, https://doi.org/10.1016/j.buildenv.2013.04.016.
[28] Annex62, I. E, *Ventilative Cooling Design Guide Energy in Buildings and Communities Programme* (Issue March), 2018.
[29] R. Martin, P. Sunley, On the notion of regional economic resilience: Conceptualization and explanation, J. Econ. Geogr. 15 (1) (2015) 1–42, https://doi.org/10.1093/jeg/lbu015.
[30] S. Attia, R. Levinson, E. Ndongo, P. Holzer, O. Berk 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 Build. 239 (2021), 110869, https://doi.org/10.1016/j.enbuild.2021.110869.
[31] C. Soanes, S. Angus, Oxford Dictionary of English, Oxford University Press, 2005. http://www.oxfordreference.com/view/10.1093/acref/9780199571123.001.0001/acref-9780199571123.
[32] G. Windle, What is resilience ? A review and concept analysis. https://doi.org/10.1017/S0959259810000420, 2014. May.
[33] J.A. Baggio, K. Brown, D. Hellebrandt, Boundary object or bridging concept ? A citation network analysis of resilience, Ecol. Soc. 20 (2) (2015).
[34] L. Xu, D. Marinova, Resilience thinking : a bibliometric analysis. https://doi.org/10.1007/s11192-013-0957-0, 2013.
[35] C. Holling, Resilience and stability of ecological systems, Annu. Rev. Ecol. Syst. 4 (1973) (1973) 1–23.
[36] V. Hasik, J.P.S. Chhabra, G.P. Warn, M.M. Bilec, Investigation of the Sustainability and Resilience Characteristics of Buildings Including Existing and Potential Assessment Metrics, 2017, pp. 1019–1033.
[37] K.A. Jha, T.W. Miner, Z. Stanton-Geddes, Building urban resilience, in: Building Urban Resilience, 2013, https://doi.org/10.1596/978-0-8213-8865-5.
[38] J.S. Silk, E. Vanderbilt-Adriance, D.S. Shaw, E.E. Forbes, D.J. Whalen, N.D. Ryan, R.E. Dahl, Resilience among children and adolescents at risk for depression: mediation and moderation across social and neurobiological contexts, Dev. Psychopathol. 19 (3) (2007) 841–865, https://doi.org/10.1017/S0954579407000417.
[39] K.K. Lin, I.N. Sandler, T.S. Ayers, S.A. Wolchik, J. Linda, K.K. Lin, I.N. Sandler, T. S. Ayers, S.A. Wolchik, J. Linda, K.K. Lin, I.N. Sandler, T.S. Ayers, S.A. Wolchik, L. J. Luecken, Resilience in parentally bereaved children and adolescents seeking preventive services resilience in parentally bereaved children and adolescents seeking preventive services. https://doi.org/10.1207/s15374424jccp3304, 2010, 4416, January 2015, 37-41.
[40] M. Bruneau, S.E. Chang, R.T. Eguchi, G.C. Lee, T.D. O'Rourke, A.M. Reinhorn, M. Shinozuka, K. Tierney, W.A. Wallace, D. Von Winterfeldt, A framework to quantitatively assess and enhance the seismic resilience of communities, Earthq. Spectra 19 (4) (2003) 733–752, https://doi.org/10.1193/1.1623497.
[41] J. Fiksel, Designing resilient, sustainable systems, Environ. Sci. Technol. 37 (23) (2003) 5330–5339, https://doi.org/10.1021/es0344819.
[42] J. Fiksel, Sustainability and resilience: toward a systems approach, Sustain. Sci. Pract. Pol. 2 (2) (2006) 14–21, https://doi.org/10.1080/15487733.2006.11907980.
[43] B.H. Walker, J.M. Anderies, A.P. Kinzig, P. Ryan, Exploring resilience in social-ecological systems through comparative studies and theory development: introduction to the special issue, Ecol. Soc. 11 (1) (2006), https://doi.org/10.5751/ES-01573-110112.
[44] J. Marcos, Organisational Resilience: the Key to Anticipation, Adaptation and Recovery, Cranfield School of Management, 2008 (Issue May).
[45] J. Simmie, R. Martin, The economic resilience of regions: towards an evolutionary approach, Camb. J. Reg. Econ. Soc. 3 (1) (2010) 27–43, https://doi.org/10.1093/cjres/rsp029.
[46] S. Davoudi, K. Shaw, L.J. Haider, A.E. Quinlan, G.D. Peterson, C. Wilkinson, H. Fünfgeld, D. McEvoy, L. Porter, Resilience: a bridging concept or a dead end? "Reframing" resilience: challenges for planning theory and practice interacting traps: resilience assessment of a pasture management system in Northern Afghanistan urban resilience: what does it mean in planni, Plann. Theor. Pract. 13 (2) (2012) 299–333, https://doi.org/10.1080/14649357.2012.677124.
[47] M.M. Sellberg, P. Ryan, S.T. Borgström, A.V. Norström, G.D. Peterson, From resilience thinking to Resilience Planning: lessons from practice, J. Environ. Manag. 217 (2018) 906–918, https://doi.org/10.1016/j.jenvman.2018.04.012.
[48] S.L. Cutter, L. Barnes, M. Berry, C. Burton, E. Evans, E. Tate, J. Webb, A place-based model for understanding community resilience to natural disasters, Global Environ. Change 18 (4) (2008) 598–606, https://doi.org/10.1016/j.gloenvcha.2008.07.013.
[49] E. Menna, S. Zambetti, R. Morini, A. Donzelli, A. Disanza, D. Calvigioni, D. Braida, C. Nicolini, M. Orlando, G. Fossati, M. Cristina Regondi, L. Pattini, C. Frassoni, M. Francolini, G. Scita, M. Sala, M. Fahnestock, M. Matteoli, Eps8 controls dendritic spine density and synaptic plasticity through its actin-capping activity, EMBO J. 32 (12) (2013) 1730–1744, https://doi.org/10.1038/emboj.2013.107.
[50] R. Leichenko, Climate change and urban resilience, Curr. Opin. Environ. Sustain. 3 (3) (2011) 164–168, https://doi.org/10.1016/j.cosust.2010.12.014.

[51] W. Miller, A. Machard, E. Bozonnet, N. Yoon, C. Zhang, A. Liu, A. Sengupta, J. Akander, A. Hayati, M. Cehlin, O.B. Kazanci, R. Levinson, Developing an understanding of resilient cooling : a socio-technical approach, City Environ. Intract. 11 (November 2020) (2021), 100065, https://doi.org/10.1016/j.cacint.2021.100065.
[52] C. Zhang, O.B. Kazanci, R. Levinson, P. Heiselberg, B.W. Olesen, G. Chiesa, B. Sodagar, Z. Ai, S. Selkowitz, M. Zinzi, A. Mahdavi, H. Teufl, M. Kolokotroni, A. Salvati, E. Bozonnet, F. Chtioui, P. Salagnac, R. Rahif, S. Attia, G. Zhang, Resilient cooling strategies – a critical review and qualitative assessment, Energy Build. 251 (2021), 111312, https://doi.org/10.1016/j.enbuild.2021.111312.
[53] M. Schweiker, Rethinking resilient comfort – definitions of resilience and comfort and their consequences for design, operation, and energy use, in: 11th Windsor Conference on Thermal Comfort 2020: Resilient Comfort, May, 2020, pp. 34–46.
[54] R. Phillips, L. Troup, D. Fannon, M.J. Eckelman, Do resilient and sustainable design strategies conflict in commercial buildings ? A critical analysis of existing resilient building frameworks and their sustainability implications, Energy Build. 146 (2017) 295–311, https://doi.org/10.1016/j.enbuild.2017.04.009.
[55] R.A.W. Albers, P.R. Bosch, B. Blocken, A.A.J.F. van den Dobbelsteen, L.W.A. van Hove, T.J.M. Spit, F. van de Ven, T. van Hooff, V. Rovers, Overview of challenges and achievements in the climate adaptation of cities and in the Climate Proof Cities program, Build. Environ. 83 (December 2014) (2015) 1–10, https://doi.org/10.1016/j.buildenv.2014.09.006.
[56] K.J. Lomas, R. Giridharan, Thermal comfort standards , measured internal temperatures and thermal resilience to climate change of free-running buildings : a case-study of hospital wards, Build. Environ. 55 (2012) 57–72, https://doi.org/10.1016/j.buildenv.2011.12.006.
[57] E. Kneer, L. Maclise, Consideration of Building Performance in Sustainable Design : A Structural Engineer ' S Role, 2008, pp. 1–15.
[58] A. Moazami, S. Carlucci, S. Geving, Robust and resilient buildings: a framework for defining the protection against climate uncertainty, IOP Conf. Ser. Mater. Sci. Eng. 609 (7) (2019), https://doi.org/10.1088/1757-899X/609/7/072068.
[59] V. Gitz, A. Meybeck, Risks, Vulnerabilities and Resilience in a Context of Climate Change. Building Resilience for Adaptation to Climate Change in the Agriculture Sector 2006, 2012, pp. 19–36.
[60] R. Rahif, D. Amaripadath, S. Attia, Review on time-integrated overheating evaluation methods for residential buildings in temperate climates of Europe, Energy Build. 252 (2021), 111463, https://doi.org/10.1016/j.enbuild.2021.111463.
[61] M. Hamdy, S. Carlucci, P.J. Hoes, J.L.M. Hensen, The impact of climate change on the overheating risk in dwellings—a Dutch case study, Build. Environ. 122 (August 2003) (2017) 307–323, https://doi.org/10.1016/j.buildenv.2017.06.031.
[62] R.J. De Dear, G.S. Brager, Thermal comfort in naturally ventilated buildings : revisions to ASHRAE Standard, Energy Build. 55 (34) (2002) 549–561.
[63] J. Liu, R. Yao, R. McCloy, An investigation of thermal comfort adaptation behaviour in office buildings in the UK, Indoor Built Environ. 23 (5) (2013) 675–691, https://doi.org/10.1177/1420326X13481048.
[64] S. Manu, Y. Shukla, R. Rawal, L.E. Thomas, R. de Dear, Field studies of thermal comfort across multiple climate zones for the subcontinent: India Model for Adaptive Comfort (IMAC), Build. Environ. 98 (2016) 55–70, https://doi.org/10.1016/j.buildenv.2015.12.019.
[65] Q. Zhao, Z. Lian, D. Lai, Thermal comfort models and their developments: a review, Energy Built. Environ. 2 (1) (2021) 21–33, https://doi.org/10.1016/j.enbenv.2020.05.007.
[66] NSAI, IS EN 15251 - Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Ligthing And Acoustics, 2007.
[67] ANSI/ASHRAE, Thermal Environmental Conditions for Human Occupancy, 2013. *Standard 55-2013, 2013*.
[68] C. TM36, CIBSE TM36: Climate Change and the Indoor Environment, 2005.
[69] C. TM52, CIBSE TM52: the Limits of Thermal Comfort, vols. 1–25, 2013.
[70] BB101, Guidelines on Ventilation Thermal Comfort and Indoor Air Quality in Schools - BB101. August, 2018.
[71] BS EN 16798, 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, 2019.
[72] CEN, EN 16798-1 - Energy Performance of Buildings - Ventilation for Buildings - Part 1: Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustic, 2019.
[73] NSAI, IS EN ISO 7730 - Ergonomics of the Thermal Environment - Analytical Determination and Interpretation of Thermal Comfort Using Calculation, 2006.
[74] B. Li, R. Yao, Q. Wang, Y. Pan, An introduction to the Chinese Evaluation Standard for the indoor thermal environment, Energy Build. 82 (2014) 27–36, https://doi.org/10.1016/j.enbuild.2014.06.032.
[75] P. Ekamper, F. van Poppel, C. van Duin, J. Garssen, 150 years of temperature-related excess mortality in The Netherlands, Demogr. Res. 21 (December) (2009) 385–426, https://doi.org/10.4054/DemRes.2009.21.14.
[76] M. Luo, X. Zhou, Y. Zhu, J. Sundell, Revisiting an overlooked parameter in thermal comfort studies, the metabolic rate, Energy Build. 118 (2016) 152–159, https://doi.org/10.1016/j.enbuild.2016.02.041.
[77] A. O'Donovan, P.D. O'Sullivan, M.D. Murphy, A field study of thermal comfort performance for a slotted louvre ventilation system in a low energy retrofit, Energy Build. 135 (2017) 312–323, https://doi.org/10.1016/j.enbuild.2016.11.049.
[78] R. Rahif, A. Fani, P. Kosinski, S. Attia, Climate change sensitive overheating assessment in dwellings : a case study in Belgium, in: Proceeding of the International Building Simulation Conference, Proceedings, 2021.
[79] K. Sun, M. Specian, T. Hong, Nexus of thermal resilience and energy efficiency in buildings : a case study of a nursing home, Build. Environ. 177 (March) (2020), 106842, https://doi.org/10.1016/j.buildenv.2020.106842.
[80] S. Flores-Larsen, C. Filippín, Energy efficiency, thermal resilience, and health during extreme heat events in low-income housing in Argentina, Energy Build. 231 (2021), 110576, https://doi.org/10.1016/j.enbuild.2020.110576.
[81] A. Ozkan, T. Kesik, W. O'Brien, Visualization of passive performance parameters through time-based metrics and discussion of a survey for validation of the approach, Build. Simulat. Conf. Proc. 5 (2017) 2598–2607, https://doi.org/10.26868/25222708.2017.601.
[82] S. Conti, P. Meli, G. Minelli, R. Solimini, V. Toccaceli, M. Vichi, C. Beltrano, L. Perini, Epidemiologic study of mortality during the Summer 2003 heat wave in Italy, Environ. Res. 98 (3) (2005) 390–399, https://doi.org/10.1016/j.envres.2004.10.009.
[83] S. Zare, H.E. Shirvan, R. Hemmatjo, F. Nadri, Y. Jahani, K. Jamshidzadeh, P. Paydar, A comparison of the correlation between heat stress indices (UTCI, WBGT, WBDT, TSI) and physiological parameters of workers in Iran, Weather Clim. Extrem. 26 (December 2017) (2019), 100213, https://doi.org/10.1016/j.wace.2019.100213.
[84] A.P. Gagge, A.P. Fobelets, L.G. Berglund, Astandard predictive index of human response to the thermal environment, Build. Eng. 92 (2B) (1986) 709–731, 92 (2B)(1).
[85] G. Ye, C. Yang, Y. Chen, Y. Li, A new approach for measuring predicted mean vote (PMV) and standard effective temperature (SET), Build. Environ. 38 (1) (2003) 33–44, https://doi.org/10.1016/S0360-1323(02)00027-6.
[86] A. Laouadi, M. Bartko, A. Gaur, M.A. Lacasse, *Climate Resilience Buildings : Guideline for Management of Overheating Risk in Residential Buildings* (Issue April 2021), 2021.
[87] K. Błazejczyk, G. Jendritzky, P. Bröde, D. Fiala, G. Havenith, Y. Epstein, A. Psikuta, B. Kampmann, An introduction to the Universal thermal climate index (UTCI), Geogr. Pol. 86 (1) (2013) 5–10, https://doi.org/10.7163/GPol.2013.1.
[88] J. Zhang, W. Lai, Z. Zhao, H. Wang, Detecting spatial differences in thermal stress across China, Theor. Appl. Climatol. 138 (1–2) (2019) 541–552, https://doi.org/10.1007/s00704-019-02831-x.
[89] A. Matzarakis, B. Amelung, Physiological equivalent temperature as indicator for impacts of climate change on thermal comfort of humans, Adv. Global Chan. Res. 30 (2008) 161–172, https://doi.org/10.1007/978-1-4020-6877-5_10.
[90] Illinois, T. B. of T. of the U., & California, R. of the U. of, Resilience Metrics, Engineering Reference Energy Plus, 2021.
[91] J. Gao, Y. Wang, P. Wargocki, Comparative analysis of modified PMV models and SET models to predict human thermal sensation in naturally ventilated buildings, Build. Environ. 92 (2015) 200–208, https://doi.org/10.1016/j.buildenv.2015.04.030.
[92] P.O. Fanger, Thermal Comfort: Analysis and Applications in Environmental Engineering, McGraw-Hill Book Company, 1970.
[93] 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, Build. Environ. 210 (December 2021) (2022), 108714, https://doi.org/10.1016/j.buildenv.2021.108714.
[94] A.R. Rempel, J. Danis, A.W. Rempel, M. Fowler, S. Mishra, Improving the passive survivability of residential buildings during extreme heat events in the Pacific Northwest, Appl. Energy 321 (May) (2022), 119323, https://doi.org/10.1016/j.apenergy.2022.119323.
[95] P. Ekamper, F. Van Poppel, C. Van Duin, K. Mandemakers, Heat waves and cold spells and their effect on mortality: an analysis of micro-data for The Netherlands in the nineteenth and twentieth centuries, Ann. Émogr. Hist. 48 (Issue 2) (2011), https://doi.org/10.3917/adh.120.0055.
[96] M. Baccini, A. Biggeri, G. Accetta, T. Kosatsky, K. Katsouyanni, A. Analitis, H. R. Anderson, L. Bisanti, D. D'Iippoliti, J. Danova, B. Forsberg, S. Medina, A. Paldy, D. Rabczenko, C. Schindler, P. Michelozzi, Heat effects on mortality in 15 European cities, Epidemiology 19 (5) (2008) 711–719, https://doi.org/10.1097/EDE.0b013e318176bfcd.
[97] J.F. Bobb, R.D. Peng, M.L. Bell, F. Dominici, Heat-related mortality and adaptation to heat in the United States, Environ. Health Perspect. 122 (8) (2014) 811–816, https://doi.org/10.1289/ehp.1307392.
[98] A. Gasparrini, Y. Guo, F. Sera, A.M. Vicedo-Cabrera, V. Huber, S. Tong, M. de Sousa Zanotti Stagliorio Coelho, P.H. Nascimento Saldiva, E. Lavigne, P. Matus Correa, N. Valdes Ortega, H. Kan, S. Osorio, J. Kyselý, A. Urban, J.J.K. Jaakkola, N.R.I. Ryti, M. Pascal, P.G. Goodman, B. Armstrong, Projections of temperature-related excess mortality under climate change scenarios, Lancet Planet. Health (2017) 360–367, https://doi.org/10.1016/S2542-5196(17)30156-0.
[99] A. Gasparrini, B. Armstrong, The impact of heat waves on mortality, Epidemiology 22 (1) (2011) 68–73, https://doi.org/10.1097/EDE.0b013e3181fdcd99.
[100] M. Pascal, ARROW @ TU Dublin an analysis of the mortality risks associated with heat and heat waves in Ireland , to assist in planning for climate change an analysis of the mortality risks associated with heat and heat waves in Ireland , to assist in planning for cl. https://doi.org/10.21427/D7R302, 2011.
[101] B. Fernandez Milan, F. Creutzig, Reducing urban heat wave risk in the 21st century, Curr. Opin. Environ. Sustain. 14 (2015) 221–231, https://doi.org/10.1016/j.cosust.2015.08.002.
[102] J. Taylor, P. Wilkinson, M. Davies, B. Armstrong, Z. Chalabi, A. Mavrogianni, P. Symonds, E. Oikonomou, S.I. Bohnenstengel, Mapping the effects of urban heat

island, housing, and age on excess heat-related mortality in London, Urban Clim. 14 (2015) 517–528, https://doi.org/10.1016/j.uclim.2015.08.001.
[103] R. Yao, Y. Li, C. Du, B. Li, A 'heart rate'-based model (PHSHR) for predicting personal heat stress in dynamic working environments, Build. Environ. 135 (January) (2018) 318–329, https://doi.org/10.1016/j.buildenv.2018.03.014.
[104] D.P. Eisenman, H. Wilhalme, C.H. Tseng, M. Chester, P. English, S. Pincetl, A. Fraser, S. Vangala, S.K. Dhaliwal, Heat Death Associations with the built environment, social vulnerability and their interactions with rising temperature, Health Place 41 (2016) 89–99, https://doi.org/10.1016/j.healthplace.2016.08.007.
[105] A. Moazami, S. Carlucci, V.M. Nik, S. Geving, Towards climate robust buildings: an innovative method for designing buildings with robust energy performance under climate change, Energy Build. 202 (2019), 109378, https://doi.org/10.1016/j.enbuild.2019.109378.
[106] A. Sengupta, J. Deleu, B. Lucidarme, M. Steeman, H. Breesch, Assessing Thermal Resilience to Overheating in an Office Building. *IAQ 2020: Indoor Environmental Quality Performance Approaches*, 2020.
[107] 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, Build. Environ. (2021), 108599, https://doi.org/10.1016/j.buildenv.2021.108599. September.
[108] 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, Build. Environ. 208 (September 2021) (2022), 108599, https://doi.org/10.1016/j.buildenv.2021.108599.
[109] S. Homaei, M. Hamdy, Thermal resilient buildings: how to be quantified? A novel benchmarking framework and labelling metric, Build. Environ. 201 (April) (2021), 108022, https://doi.org/10.1016/j.buildenv.2021.108022.
[110] M. Hendel, K. Azos-diaz, B. Tremeac, M. Hendel, K. Azos-diaz, B. Tremeac, B. Adaptation, H. Health, M. Hendel, K. Azos-diaz, B. Tremeac, Behavioral Adaptation to Heat-Related Health Risks in Cities to Cite This Version : Behavioral Adaptation to Heat-Related Health Risks in Cities, 2016.
[111] D. Robinson, F. Haldi, Model to predict overheating risk based on an electrical capacitor analogy, Energy Build. 40 (7) (2008) 1240–1245, https://doi.org/10.1016/j.enbuild.2007.11.003.
[112] R.S. Mcleod, M. Swainson, Chronic overheating in low carbon urban developments in a temperate climate, Renew. Sustain. Energy Rev. 74 (February) (2017) 201–220, https://doi.org/10.1016/j.rser.2016.09.106.
[113] R. Gupta, L. Barnfield, M. Gregg, Overheating in care settings: magnitude, causes, preparedness and remedies, Build. Res. Inf. 45 (1–2) (2017) 83–101, https://doi.org/10.1080/09613218.2016.1227923.
[114] M. Gustin, R.S. McLeod, K.J. Lomas, G. Petrou, A. Mavrogianni, A high-resolution indoor heat-health warning system for dwellings, Build. Environ. 168 (2020), 106519, https://doi.org/10.1016/j.buildenv.2019.106519.
[115] A. Ashtiani, P.A. Mirzaei, F. Haghighat, Indoor thermal condition in urban heat island: comparison of the artificial neural network and regression methods prediction, Energy Build. 76 (2014) 597–604, https://doi.org/10.1016/j.enbuild.2014.03.018.
[116] M. Kolokotroni, X. Ren, M. Davies, A. Mavrogianni, London's urban heat island: impact on current and future energy consumption in office buildings, Energy Build. 47 (2012) 302–311, https://doi.org/10.1016/j.enbuild.2011.12.019.
[117] M. Santamouris, Recent progress on urban overheating and heat island research. Integrated assessment of the energy, environmental, vulnerability and health impact. Synergies with the global climate change, Energy Build. (2019), 109482, https://doi.org/10.1016/j.enbuild.2019.109482.
[118] O. Duran, K.J. Lomas, Retrofitting post-war office buildings: interventions for energy efficiency, improved comfort, productivity and cost reduction, J. Build. Eng. 42 (April) (2021), 102746, https://doi.org/10.1016/j.jobe.2021.102746.
[119] A. O' Donovan, M.D. Murphy, P.D. O'Sullivan, Passive control strategies for cooling a non-residential nearly zero energy office: simulated comfort resilience now and in the future, Energy Build. 231 (2021), 110607, https://doi.org/10.1016/j.enbuild.2020.110607.
[120] P. O'Sullivan, A. O'Donovan, Ventilative Cooling Case Studies Energy in Buildings and Communities Programme, 2018.
[121] K. Goethals, H. Breesch, A. Janssens, Sensitivity analysis of predicted night cooling performance to internal convective heat transfer modelling, Energy Build. 43 (9) (2011) 2429–2441, https://doi.org/10.1016/j.enbuild.2011.05.033.
[122] House of Lords, Preparing for Extreme Risks: Building a Resilient Society, 2021. *HL Paper 110, December.HTM 03-01* (Issue October). (2013).
[123] A. Gatto, C. Drago. A taxonomy of energy resilience, *Energy Pol.*, *136 (December 2018) (2020) 111007*, https://doi.org/10.1016/j.enpol.2019.111007.
[124] M. Santamouris, D. Kolokotsa, Passive cooling dissipation techniques for buildings and other structures: the state of the art, Energy Build. 57 (2013) 74–94, https://doi.org/10.1016/j.enbuild.2012.11.002.
[125] D.K. Bhamare, M.K. Rathod, J. Banerjee, Passive cooling techniques for building and their applicability in different climatic zones—the state of art, Energy Build. 198 (2019) 467–490, https://doi.org/10.1016/j.enbuild.2019.06.023.
[126] E. Bacharoudis, M.G. Vrachopoulos, M.K. Koukou, D. Margaris, A.E. Filios, S. A. Mavrommatis, Study of the natural convection phenomena inside a wall solar chimney with one wall adiabatic and one wall under a heat flux, Appl. Therm. Eng. 27 (13) (2007) 2266–2275, https://doi.org/10.1016/j.applthermaleng.2007.01.021.
[127] H. Breesch, A. Bossaer, A. Janssens, Passive cooling in a low-energy office building, Sol. Energy 79 (6) (2005) 682–696, https://doi.org/10.1016/j.solener.2004.12.002.
[128] S.C. Camacho-Montano, M. Cook, A. Wagner, Avoiding overheating in existing school buildings through optimized passive measures, Build. Res. Inf. 48 (4) (2020) 349–363, https://doi.org/10.1080/09613218.2019.1663137.
[129] Y. Chen, Z. Tong, W. Wu, H. Samuelson, A. Malkawi, L. Norford, Achieving natural ventilation potential in practice: control schemes and levels of automation, Appl. Energy 235 (September 2018) (2019) 1141–1152, https://doi.org/10.1016/j.apenergy.2018.11.016.
[130] F. Flourentzou, J. Van Der Maas, C.A. Roulet, Natural ventilation for passive cooling: measurement of discharge coefficients, Energy Build. 27 (3) (1998) 283–292, https://doi.org/10.1016/s0378-7788(97)00043-1.
[131] C. Heracleous, A. Michael, A. Savvides, C. Hayles, Climate change resilience of school premises in Cyprus: an examination of retrofit approaches and their implications on thermal and energy performance, J. Build. Eng. 44 (2021), 103358, https://doi.org/10.1016/j.jobe.2021.103358.
[132] T. Schulze, D. Gürlich, U. Eicker, Performance assessment of controlled natural ventilation for air quality control and passive cooling in existing and new office type buildings, Energy Build. 172 (2018) 265–278, https://doi.org/10.1016/j.enbuild.2018.03.023.
[133] J. Stephen, L. Bourikas, D. Teli, A.S. Bahaj, R. Congreve, Internal thermal environment and futureproofing of a newly built, naturally ventilated UK school, IOP Conf. Ser. Earth Environ. Sci. 588 (3) (2020), https://doi.org/10.1088/1755-1315/588/3/032071.
[134] K. Voss, S. Herkel, J. Pfafferott, G. Löhnert, A. Wagner, Energy efficient office buildings with passive cooling - results and experiences from a research and demonstration programme, Sol. Energy 81 (3) (2007) 424–434, https://doi.org/10.1016/j.solener.2006.04.008.
[135] M. Zinzi, F. Pagliaro, S. Agnoli, F. Bisegna, D. Iatauro, On the built-environment quality in nearly zero-energy renovated schools: assessment and impact of passive strategies, Energies 14 (10) (2021), https://doi.org/10.3390/en14102799.
[136] N. Artmann, H. Manz, P. Heiselberg, Climatic potential for passive cooling of buildings by night-time ventilation in Europe, Appl. Energy 84 (2) (2007) 187–201, https://doi.org/10.1016/j.apenergy.2006.05.004.
[137] C. Heraclous, A. Michael, A. Savvides, C. Hayles, Climate change resilience of school premises in Cyprus: an examination of retrofit approaches and their implications on thermal and energy performance, J. Build. Eng. (2021), 103358, https://doi.org/10.1016/j.jobe.2021.103358.
[138] G. Chiesa, M. Simonetti, M. Grosso, A 3-field earth-heat-exchange system for a school building in Imola, Italy: monitoring results, Renew. Energy 62 (2014) 563–570, https://doi.org/10.1016/j.renene.2013.08.020.
[139] Y. Li, T. Long, X. Bai, L. Wang, W. Li, S. Liu, J. Lu, Y. Cheng, K. Ye, S. Huang, An experimental investigation on the passive ventilation and cooling performance of an integrated solar chimney and earth–air heat exchanger, Renew. Energy 175 (2021) 486–500, https://doi.org/10.1016/j.renene.2021.05.004.
[140] R. Misra, V. Bansal, G. Das Agarwal, J. Mathur, T. Aseri, Thermal performance investigation of hybrid earth air tunnel heat exchanger, Energy Build. 49 (2012) 531–535, https://doi.org/10.1016/j.enbuild.2012.02.049.
[141] J. Pfafferott, Evaluation of earth-to-air heat exchangers with a standardised method to calculate energy efficiency, Energy Build. 35 (10) (2003) 971–983, https://doi.org/10.1016/S0378-7788(03)00055-0.
[142] J.Ü.U. Pfafferott, S. Herkel, D.E. Kalz, A. Zeuschner, Comparison of low-energy office buildings in summer using different thermal comfort criteria, Energy Build. 39 (7) (2007) 750–757, https://doi.org/10.1016/j.enbuild.2007.02.005.
[143] R. Wagner, S. Beisel, A. Spieler, A. Gerber, K. Vajen, Measurement, Modeling and Simulation of an Earth-To-Air Heat Exchanger in Marburg (Germany). *4. ISES Europe Solar Congress*, Kopenhagen, Dänemark, 2000, 2000.
[144] J.R. Camargo, C.D. Ebinuma, J.L. Silveira, Experimental performance of a direct evaporative cooler operating during summer in a Brazilian city, Int. J. Refrig. 28 (7) (2005) 1124–1132, https://doi.org/10.1016/j.ijrefrig.2004.12.011.
[145] E. Ibrahim, L. Shao, S.B. Riffat, Performance of porous ceramic evaporators for building cooling application, Energy Build. 35 (9) (2003) 941–949, https://doi.org/10.1016/S0378-7788(03)00019-7.
[146] K. Panchabikesan, K. Vellaisamy, V. Ramalingam, Passive cooling potential in buildings under various climatic conditions in India, Renew. Sustain. Energy Rev. 78 (March 2016) (2017) 1236–1252, https://doi.org/10.1016/j.rser.2017.05.030.
[147] J.M. Wu, X. Huang, H. Zhang, Numerical investigation on the heat and mass transfer in a direct evaporative cooler, Appl. Therm. Eng. 29 (1) (2009) 195–201, https://doi.org/10.1016/j.applthermaleng.2008.02.018.
[148] A.P. Haghighi, S.H. Pakdel, A. Jafari, A study of a wind catcher assisted adsorption cooling channel for natural cooling of a 2-storey building, Energy 102 (2016) 118–138, https://doi.org/10.1016/j.energy.2016.02.033.
[149] J.K. Jain, D.A. Hindoliya, Energy saving potential of indirect evaporative cooler under Indian climates, Int. J. Low Carbon Technol. 11 (2) (2016) 193–198, https://doi.org/10.1093/ijlct/ctt076.
[150] G.P. Maheshwari, F. Al-Ragom, R.K. Suri, Energy-saving potential of an indirect evaporative cooler, Appl. Energy 69 (1) (2001) 69–76, https://doi.org/10.1016/S0306-2619(00)00066-0.
[151] S.N. Kharrufa, Y. Adil, Roof pond cooling of buildings in hot arid climates, Build. Environ. 43 (1) (2008) 82–89, https://doi.org/10.1016/j.buildenv.2006.11.034.
[152] A. Sharifi, Y. Yamagata, Roof ponds as passive heating and cooling systems: a systematic review, Appl. Energy 160 (2015) 336–357, https://doi.org/10.1016/j.apenergy.2015.09.061.
[153] M. Rabani, V. Kalantar, A.A. Dehghan, A.K. Faghih, Empirical investigation of the cooling performance of a new designed Trombe wall in combination with solar chimney and water spraying system, Energy Build. 102 (2015) 45–57, https://doi.org/10.1016/j.enbuild.2015.05.010.

[154] H.S. Bagiorgas, G. Mihalakakou, Experimental and theoretical investigation of a nocturnal radiator for space cooling, Renew. Energy 33 (6) (2008) 1220–1227, https://doi.org/10.1016/j.renene.2007.04.015.

[155] J. Khedari, J. Waewsak, S. Thepa, J. Hirunlabh, Field investigation of night radiation cooling under tropical climate, Renew. Energy 20 (2) (2000) 183–193, https://doi.org/10.1016/S0960-1481(99)00104-4.

[156] S. Vall, A. Castell, Radiative cooling as low-grade energy source: a literature review, Renew. Sustain. Energy Rev. 77 (April) (2017) 803–820, https://doi.org/10.1016/j.rser.2017.04.010.

[157] A. Tzempelikos, A.K. Athienitis, The impact of shading design and control on building cooling and lighting demand, Sol. Energy 81 (3) (2007) 369–382, https://doi.org/10.1016/j.solener.2006.06.015.

[158] R. Berry, S.J. Livesley, L. Aye, Tree canopy shade impacts on solar irradiance received by building walls and their surface temperature, Build. Environ. 69 (2013) 91–100, https://doi.org/10.1016/j.buildenv.2013.07.009.

[159] M.F. Shahidan, P.J. Jones, J. Gwilliam, E. Salleh, An evaluation of outdoor and building environment cooling achieved through combination modification of trees with ground materials, Build. Environ. 58 (2012) 245–257, https://doi.org/10.1016/j.buildenv.2012.07.012.

[160] S. Sadrzadehrafiei, K. Sopian, S. Mat, C. Lim, Application of advanced glazing to mid-rise office buildings in Malaysia, in: Proceedings of the 9th WSEAS International Conference on Environment, Ecosystems, and Development, 2011, pp. 197–201.

[161] N.L. Sbar, L. Podbelski, H.M. Yang, B. Pease, Electrochromic dynamic windows for office buildings, Int. J. Sustain. Built. Environ. 1 (1) (2012) 125–139, https://doi.org/10.1016/j.ijsbe.2012.09.001.

[162] U. Eicker, Cooling strategies, summer comfort and energy performance of a rehabilitated passive standard office building, Appl. Energy 87 (6) (2010) 2031–2039, https://doi.org/10.1016/j.apenergy.2009.11.015.

[163] X. Kong, S. Lu, Y. Li, J. Huang, S. Liu, Numerical study on the thermal performance of building wall and roof incorporating phase change material panel for passive cooling application, Energy Build. 81 (2014) 404–415, https://doi.org/10.1016/j.enbuild.2014.06.044.

[164] M. Kerres, S. Bedenlier, Systematic Reviews in Educational, 2020.

[165] H.W. Brink, M.G.L.C. Loomans, H.S.M. Kort, M.P. Mobach, Classrooms ' indoor environmental conditions affecting the academic achievement of students and teachers in higher education : a systematic literature review, 2021, pp. 405–425. https://doi.org/10.1111/ina.12745 (September 2020) (2021).

[166] A. Chong, Y. Gu, H. Jia, Energy & Buildings Calibrating building energy simulation models : a review of the basics to guide future work, Energy Build. 253 (2021), 111533, https://doi.org/10.1016/j.enbuild.2021.111533.

[167] C. Heracleous, A. Michael, Climate Change and Thermal Comfort in Educational Buildings of Southern Europe : the Case of Cyprus New Title : in *Energy*, Elsevier B.V, 2018.

[168] F. Flourentzou, Ventilative Cooling in Tertiary Buildings: A School Demo-Case and Parametric Analyses under Swiss Climate Conditions Central Europe, Springer, Cham, 2021.

[169] G. Chiesa, N. Huberman, D. Pearlmutter, Geo-climatic potential of direct evaporative cooling in the Mediterranean Region: a comparison of key performance indicators, Energy Build. (2019), https://doi.org/10.1016/j.buildenv.2019.01.059.

[170] G. Gómez, B. Frutos, C. Alonso, F. Martín-Consuegra, I. Oteiza, M.M. Castellote, J. Muñoz, S. Torre, J. Fermoso, T. Torres, M.A. Antón, T. Batista, N. Morais, Prediction of thermal comfort and energy behaviour through natural-based solutions implementation: a case study in badajoz, Spain, WIT Trans. Built Environ. 195 (2020) 17–27, https://doi.org/10.2495/ARC200021.

[171] A. Brambilla, A. Morganti, G. Lindahl, A. Riva, S. Capolongo, Complex projects assessment. The impact of built environment on Healthcare staff wellbeing, in: Computational Science and its Applications – ICCSA 2020, 2020, https://doi.org/10.1007/978-3-030-58814-4_24.

[172] S. Lamb, K.C.S. Kwok, A longitudinal investigation of work environment stressors on the performance and wellbeing of of fi ce workers, Appl. Ergon. 52 (2016) 104–111, https://doi.org/10.1016/j.apergo.2015.07.010.

[173] C. Shu, A. Gaur, L. Ji, A. Laouadi, M. Lacasse, H. Ge, The 16th Conference of the International Society of Indoor Air Quality & Climate (Indoor Air 2020) COEX , Seoul , Korea, 2020. July 20 - 24 , 2020.

[174] C Alan Short, G. Renganathan, K.J. Lomas, A medium-rise 1970s maternity hospital in the east of England : resilience and adaptation to climate change. https://doi.org/10.1177/0143624414567544, 2015.

[175] C.R. Iddon, T.C. Mills, R. Giridharan, K.J. Lomas, Ac ce pt cr t, Energy Build. (2014), https://doi.org/10.1016/j.enbuild.2014.09.053.

[176] C Alan Short, C.J. Noakes, C.A. Gilkeson, A. Fair, C.A. Short, C.J. Noakes, C. A. Gilkeson, A. Fair, Functional recovery of a resilient hospital type Functional recovery of a resilient hospital type, February, https://doi.org/10.1080/09613218.2014.926605, 2014, 2015, 37-41.

[177] A. Moazami, S. Carlucci, F. Causone, L. Pagliano, Energy retrofit of a day care center for current and future weather scenarios, Procedia Eng. 145 (1877) (2016) 1330–1337, https://doi.org/10.1016/j.proeng.2016.04.171.

[178] M. Zinzi, F. Pagliaro, S. Agnoli, F. Bisegna, D. Iatauro, ScienceDirect ScienceDirect Assessing the overheating risks in Italian existing school buildings renovated with nZEB targets a heat demand-outdoor Assessing the feasibility of using the, Energy Proc. 142 (2017) 2517–2524, https://doi.org/10.1016/j.egypro.2017.12.192.

[179] P. Taylor, P. De Wilde, W. Tian, The role of adaptive thermal comfort in the prediction of the thermal performance of a modern mixed-mode office building in the UK under climate change, J. Build. Perform. Simulat. (2010) 37–41, https://doi.org/10.1080/19401490903486114. October 2014.

[180] H. Gough, S. Faulknall-Mills, M.F. King, Z. Luo, Assessment of overheating risk in gynaecology scanning rooms during near-heatwave conditions: a case study of the royal berkshire hospital in the UK, Int. J. Environ. Res. Publ. Health 16 (18) (2019), https://doi.org/10.3390/ijerph16183347.

[181] A. Montazami, F. Nicol, Overheating in schools: comparing existing and new guidelines, Build. Res. Inf. 41 (3) (2013) 317–329, https://doi.org/10.1080/09613218.2013.770716.

[182] L. Moosavi, N. Mahyuddin, N. Ghafar, Atrium cooling performance in a low energy office building in the Tropics, a field study, Build. Environ. 94 (P1) (2015) 384–394, https://doi.org/10.1016/j.buildenv.2015.06.020.

[183] M. Zinzi, F. Pagliaro, S. Agnoli, F. Bisegna, D. Iatauro, Assessing the overheating risks in Italian existing school buildings renovated with nZEB targets, Energy Proc. 142 (February 2018) (2017) 2517–2524, https://doi.org/10.1016/j.egypro.2017.12.192.

[184] J. Bravo Dias, P.M.M. Soares, G. Carrilho da Graça, The shape of days to come: effects of climate change on low energy buildings, Build. Environ. 181 (April) (2020), https://doi.org/10.1016/j.buildenv.2020.107125.

[185] L. Pagliano, S. Carlucci, F. Causone, A. Moazami, G. Cattarin, Energy retrofit for a climate resilient child care centre, Energy Build. 127 (2016) 1117–1132, https://doi.org/10.1016/j.enbuild.2016.05.092.

[186] P.T. Bhaskoro, S.I.U.H. Gilani, M.S. Aris, Simulation of energy saving potential of a centralized HVAC system in an academic building using adaptive cooling technique, Energy Convers. Manag. 75 (2013) 617–628, https://doi.org/10.1016/j.enconman.2013.06.054.

[187] M. Sourbron, L. Helsen, Evaluation of adaptive thermal comfort models in moderate climates and their impact on energy use in office buildings, Energy Build. 43 (2–3) (2011) 423–432, https://doi.org/10.1016/j.enbuild.2010.10.005.

[188] L. Yang, W. Zheng, Y. Mao, J.C. Lam, Y. Zhai, Thermal adaptive models in built environment and its energy implications in Eastern China, Energy Proc. 75 (2015) 1413–1418, https://doi.org/10.1016/j.egypro.2015.07.237.

[189] International Energy Agency, I, The Future of Cooling Opportunities for Energy-Efficient Air Conditioning Together Secure Sustainable, 2018.