

A Critical Review of Overheating Risk Assessment Criteria in International and National Regulations—Gaps and Suggestions for Improvements

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Abstract: The escalating environmental threat of indoor overheating, exacerbated by global climate change, urbanisation, and population growth, poses a severe risk to public health worldwide, specifically to those regions which are exposed to extreme heat events, such as Australia. This study delves into the critical issue of overheating within residential buildings, examining the existing state of knowledge on overheating criteria and reviewing overheating guidelines embedded in (a) international standards and (b) national building codes. Each regulatory document is analysed based on its underlying thermal comfort model, metric, and indices. The advantages and limitations of each document are practically discussed and for each legislative document and standard, and the quantitative measures have been reviewed, analysed, and summarised. The findings illuminate a global reliance on simplistic indices, such as indoor air temperature and operative temperature, in the existing regulatory documents. However, other critical environmental parameters, such as relative humidity, indoor air velocity, and physiological parameters including metabolic heat production and clothing insulation, are often not included. The absence of mandatory regulations for overheating criteria in residential buildings in some countries, such as in Australian homes, prompts the call for a holistic approach based on a thermal index inclusive of relevant environmental and physiological parameters to quantify heat stress exposure based on human thermal regulation. Gaps and limitations within existing guidelines are identified, and recommendations are proposed to strengthen the regulatory framework for overheating risk assessment in residential buildings. The findings hold significance for policymakers, building energy assessors, architects, and public health professionals, providing direction for the improvement of existing, and development of new, guidelines that aim to enhance indoor thermal condition and population health while ensuring energy efficiency and sustainability in the building stock.

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1. Introduction

Overheating is a critical environmental hazard affecting billions of people globally and presenting a significant threat to public health [1]. Climate change, urbanisation, and population growth drive rising temperatures in many regions, exacerbating existing health disparities and increasing the risk of heat-related illnesses and deaths [2]. The direct and indirect impacts of overheating are complex, affecting various systems within the human body, from cardiovascular and respiratory function to mental health and cognitive performance (e.g., Refs. [3–6]). Impact studies indicate that extreme weather

events, such as heat waves and flooding, may occur more frequently due to anthropogenic climate change, drawing attention from policymakers and researchers worldwide [7].

In addition to global and regional climate processes, urban heat island (UHI) is another phenomenon that influences microclimates. Expansion of impervious land surface areas reduced green spaces, complex urban morphology, and anthropogenic heat emissions, and all conspire to intensify urban heat which, in turn, significantly exacerbates heat in indoor environments where we spend the majority of our daily lives [8]. The spill over of external heat into indoor spaces exacerbates overheating challenges, particularly in densely populated urban settings (e.g., Refs. [9–13]).

Extreme events can further amplify existing health disparities and socio-economic inequalities, with low-income communities facing greater exposure and susceptibility to heat-related illnesses and deaths [8]. It behooves us to apply a thorough understanding of the mechanisms underlying overheating impacts to the development of effective strategies to mitigate the increasing threat of extreme heat globally.

Despite the significant risks posed by overheating and heatwaves to public health, there is a current lack of clear and consistent guidelines and standards for ensuring thermal comfort and mitigating overheating risks in some countries around the world, i.e., in Australian residential buildings. Although some international standards and national building codes exist, their applicability to other countries may be limited due to the differences in climate conditions. Figure 1 illustrates the regional distribution of regulatory documents globally, predominantly implemented in North America, Europe, and East Asia (including, China, India, and Singapore). In addition to international standards, some countries, including France, Germany, the United Kingdom, Belgium, Sweden, Austria, Italy, Spain, and Greece, successfully integrated regulations for thermal comfort and overheating into their national building codes and standards [14–24].

Different countries and blocs maintain their own distinct standards, codes, and guidelines for thermal comfort and preventing overheating in residential buildings. For example, the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) developed ASHRAE Standard 55, offering guidelines for thermal comfort in indoor environments, which has been widely implemented in North America [25]. Meanwhile, the European Union's Energy Performance of Buildings Directive establishes minimum energy performance requirements for buildings, while maintaining minimum levels of indoor environmental quality (IEQ) in general, and indoor thermal comfort in particular [15]. In the United Kingdom, building regulations provide guidance on maximum allowable temperatures in dwellings during hot weather, along with requirements for adequate ventilation and shading [16].

It is also essential to consider the role of building simulation tools in the assessment of thermal comfort conditions. These tools enable detailed analysis of indoor environmental conditions by modelling heat transfer, ventilation, mean radiant temperature (MRT), and occupation behaviour under various scenarios. However, variations in simulation algorithms and assumptions can lead to discrepancies in results, highlighting the need for standardised methodologies to improve consistency and reliability across different tools [26]. It is also important to note that correct prediction of MRT by building simulation tools plays a significant role in predicting human thermal comfort and thermal regulation, which has been overlooked in the literature [27].

Australia is a vast country with variable climate which is classified into eight zones by the Australian Building Codes Board [28]. Despite Australia's unique climate, there is currently a lack of specific standards addressing overheating and thermal comfort in buildings. In the absence of a national overheating standard, analysis in Australia often relies on standards from other countries as indicated by [22]. Therefore, to develop a national overheating criterion, it will be necessary to consider the environmental conditions for each climate zone separately to be able to develop a nuanced, bio-climatically relevant approach to overheating. In this article, our objectives are to (a) review the current state of knowledge on overheating and thermal comfort criteria in

residential buildings, focusing on existing national building codes and international standards; (b) identify gaps and limitations in these guidelines; and (c) provide suggestions for improving the regulatory framework. The findings of this manuscript could be used to guide the development of new overheating regulatory documents for countries that have not employed any such as Australia, and those countries which are more sensitive to the increase in temperature, such as southern European countries, with a prospective vision for enhancing the health and well-being of residents while ensuring energy efficiency in buildings.



Figure 1. Regional distribution of regulatory documents around the world. The regulatory documents have mostly been implemented in North America, Europe, and East Asia. Source for the map: ArcGIS® software 10.7.1 (Esri (Environmental Systems Research Institute, Inc), in Redlands, California, USA) [29].

2. Review Methodology

This paper reviews overheating criteria and thermal comfort thresholds in (a) international standards and (b) national building codes. The scope of the manuscript has been narrowed down to the residential regulatory documents globally across all available climate zones. Each regulatory document is analysed based on its underlying thermal comfort model, metric, and indices. The advantages and limitations of each document are discussed in this manuscript.

The procedure employed for reviewing the literature was a thematic literature review approach to systematically review existing international standards and national building codes related to residential overheating. The review focused on identifying recurring themes, criteria, and gaps in how overheating is addressed in building regulations globally. Relevant literature was sourced from academic databases, including ScienceDirect, Web of Science, Scopus, and Google Scholar, using targeted keywords and Boolean operators to ensure a comprehensive search. After screening and selecting pertinent studies and documents, the findings were grouped into key themes, such as overheating thresholds, thermal comfort indices, and metrics. Each regulatory document was analysed to synthesise insights, highlight limitations and advantages, and identify areas for improvement in regulatory approaches.

2.1. Standards and Regulatory Documents

Regulatory documents that have been included in this review were listed as:

- a. International standards
 - I. ASHRAE 55 (2017), and ASHRAE 55 (2020)—Thermal Environmental Conditions for Human Occupancy [30,31]
 - II. CIBSE Guide A (2006), and CIBSE Guide A (2015)—Environmental Design [32]
 - III. CIBSE TM52—The limits of Thermal Comfort: Avoiding Overheating in European Buildings [18]
 - IV. CIBSE TM59 (2017)—Design Methodology for the Assessment of Building Services Engineers [33]
 - V. EN 15251 (2007)—Indoor environmental parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment. Lighting and acoustics [19]
 - VI. EN 16798 (2019) [34]
 - VII. ISO 7730 (2005)—Ergonomics of the thermal environment [35]
 - VIII. Passive House (2015) [36]
- b. National building codes
 - I. Belgium
 - II. France
 - III. Germany
 - IV. Netherlands
 - V. UK

2.2. Quantitative Measures

For each legislative document and standard the following quantitative measures have been reviewed, analysed, and summarised:

- a. Thermal comfort model (static thermal comfort, or adaptive thermal comfort model).
- b. Temporal domain (i.e., occupied hours; sleeping hours; and all hours).
- c. Spatial domain (i.e., living room; bedroom; and kitchen).
- d. Indices for quantifying thermal comfort (i.e., PMV ; T_{oi} ; and T_{ai}).
- e. Metrics for heat assessment (i.e., degree hours; hours; and percentage of hours outside the comfort range).
- f. Threshold limit (the maximum or minimum acceptable measure).
- g. Building operational category (i.e., naturally, mechanically ventilated building, or mixed mode operation building).

3. Findings and Discussions

This section illuminates the findings of the study, reviews the overheating assessment criteria, identifies the gaps, and critically discusses and examines the limitations of existing standards and building codes.

3.1. Thermal Comfort Parameters and Responses

To review and analyse the criteria of overheating, we need to first identify the definition of thermal comfort, thermal discomfort, and the difference between adaptive and static thermal comfort models.

According to ASHRAE-55 standard (2017) [30], thermal comfort refers to the mental state in which an individual expresses satisfaction with their environments' thermal conditions. There are six universally agreed parameters that influence thermal comfort, from which four are environmental parameters and two are so-called "personal parameters". Figure 2 shows the environmental and personal parameters that cause thermal discomfort.

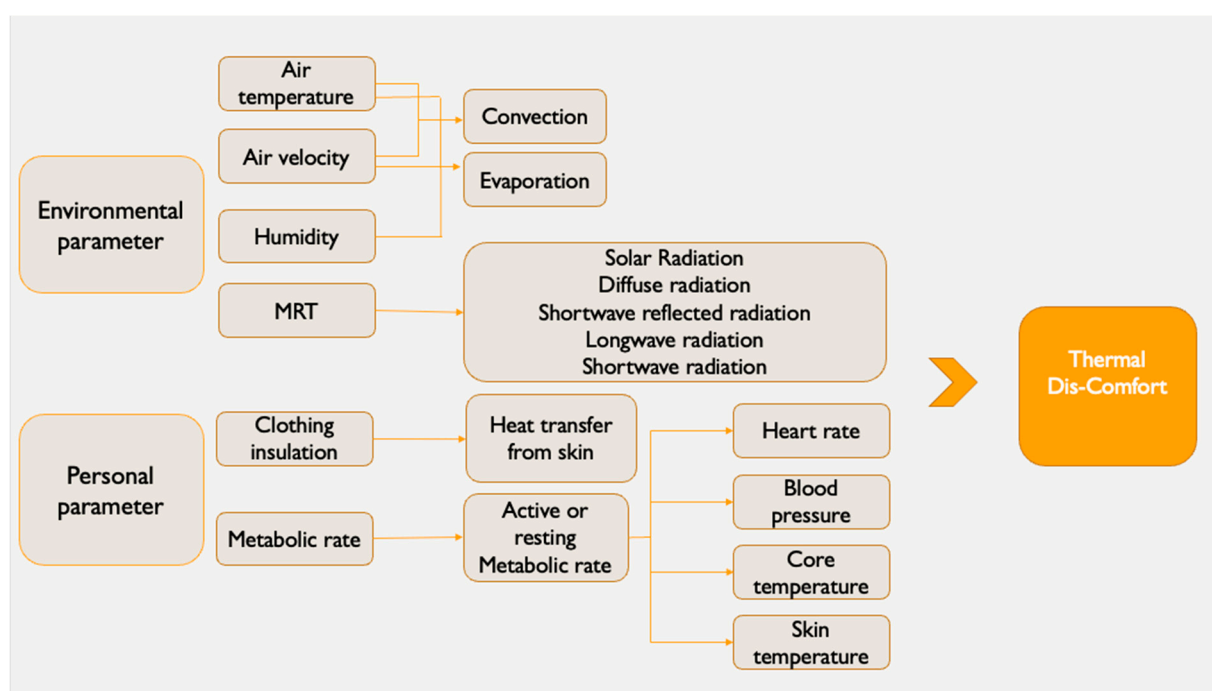


Figure 2. Environmental and personal parameters causing thermal discomfort.

Four environmental parameters, namely air temperature, humidity, air velocity, and mean radiant temperature (MRT), impact human thermal regulation by causing changes in the human body's heat exchanges with its environment via convective, conduction, radiative, and evaporative process. Mean radiant temperature is a key environmental parameter affecting radiative fluxes, exerting a significant impact on human thermal physiology in indoor environments, and even more so in outdoor settings where solar radiation is present. Radiative fluxes refer to the electromagnetic energy emitted by all matter having temperature above absolute zero [37]. It includes shortwave length components of direct and diffuse solar radiation and shortwave reflected radiation. Longwave-length radiation components include atmospheric infrared emission from greenhouse gases (particularly water vapour) and radiation emission from ground and built environmental surfaces [38,39].

Mean radiant temperature refers to the average temperature of all the surfaces surrounding a person, including the walls, sky, floor or ground, and other objects. High mean radiant temperatures due to intense solar radiation in outdoor environments, or hot surfaces in built environments, will lead to overheating and discomfort. Conversely, low mean radiant temperatures will exaggerate radiative heat loss from the body which, if sustained for long enough, lead to reduced skin temperature, shivering, and subjective cold discomfort. Therefore, accurate and effective measurement and management of all these elements in the bioclimatic radiative environment are crucial for ensuring thermal comfort and minimising the risk of thermal health problems, particularly in vulnerable populations such as the elderly and those with pre-existing medical conditions [40].

Human responses to the thermal environment can be categorised into three groups:

- (a) Physiological level responses operate under autonomic nervous system control and include vasomotor activity (dilation and constriction), sweating, and shivering [41].
- (b) Behavioural level responses are mediated by the central nervous system and include adjustments to the environment such as changing the rate of air movement indoors (V_i) by opening/closing windows, controlling fans, and directly adjusting room temperature with whatever conditioning technology presents. Another class of occupant behavioural response involves directly adjusting to the heat balance

- personal parameters, such as changing clothing insulation levels or changing the rate of metabolic heat production (e.g., resting after physical exertion) (e.g., Refs. [42,43]).
- (c) Psychological response refers to comfort expectations which derive from the cultural and climatological background.

Apart from these three categories of human response to the climatic environment is the building itself, including temperature swings in the building fabric. Figure 3 categorises the various types of thermal responses from the building occupant system.

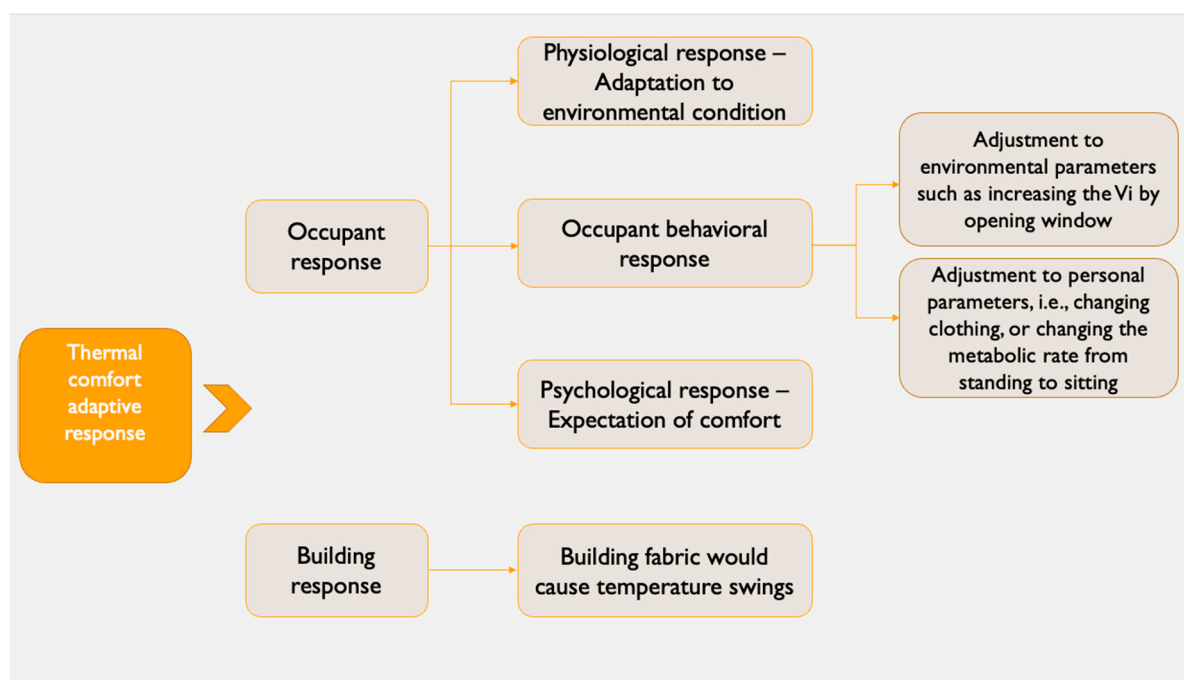


Figure 3. Adaptive response to thermal comfort from occupant and building.

3.2. Static Thermal Comfort Model

Static thermal comfort models underpin the conventional approach to indoor environmental design based on fixed, uniform temperature settings. The aim is to maintain a consistent temperature throughout a space to ensure that the majority of occupants are comfortable. The most widely used indices for predicting static thermal comfort in building design and environmental studies are known as the predicted mean vote (PMV) and predicted percentage dissatisfied (PPD), based on Fanger's 1970 heat balance "comfort equation" [44].

The PMV index expresses thermal comfort of a space in terms of the typical thermal sensation that an "average" person may experience in that space on the basis of the four thermal environmental and two personal thermal parameters enumerated earlier in Section 3.1. PMV is widely used to guide design and operational decisions about heating, ventilation, and air conditioning (HVAC) systems, but also building design, façade specifications, and floorplate layout.

The predicted percentage dissatisfied (PPD) index is the second part of the Fanger) static comfort model [45] and is itself derived from the PMV index. PMV refers to the average thermal sensation (expressed on a seven-point scale) of a large group of building occupants exposed to a given combination of indoor climatic and personal thermal parameters. That average is considered to be the mode of a normal (Gaussian) bell-shaped distribution of thermal sensation votes from the entire group along the seven-point sensation scale [46].

The central three categories of that subjective warmth scale (i.e., −1 slightly cool, 0 neutral, and +1 slightly warm) were assumed by Fanger to correspond with acceptable or

thermally satisfactory subjective states. PPD refers to the area of the Gaussian distribution 'tails' of thermal sensation votes falling beyond the thermally acceptable central three sensation categories (i.e., -3 cold, -2 cool, +2 warm, and +3 hot).

PMV/PPD static comfort assumes all occupants have similar preferences and responses to the given thermal conditions. In reality, however, individuals have very diverse sensitivities to temperature and other environmental stimuli. As a result, the PMV/PPD index may not accurately reflect the thermal comfort of many occupants in a given indoor environment [44]. Most standards recommend the static comfort models for air-conditioned buildings and the adaptive comfort models for non-air-conditioned or NV buildings.

3.3. Adaptive Thermal Comfort

Adaptive thermal comfort is a more recent approach that considers the dynamic nature of indoor environments, outdoor mean temperature, and individual occupant preferences. It recognises that people can tolerate a wider range of temperatures and that thermal comfort is influenced by a variety of adaptive responses and thermal background, such as adjustment to personal and environmental parameters initiated by occupants.

Therefore, the adaptive approach aims to provide a range of thermal conditions and allow occupants to adjust their clothing or behaviour accordingly, resulting in a more comfortable and energy-efficient indoor environment. Adaptive thermal comfort is mostly used for naturally ventilated buildings (NV). Equation (1) shows the concept for calculating adaptive thermal comfort.

$$T_{O_i} = (a \times T_{arm_{out}}) + b \quad (1)$$

where

T_{O_i} = Indoor comfort operative temperature (dependent variable);

$T_{arm_{out}}$ = Outdoor running mean air temperature (independent variable);

a = Gradient, proportional to the degree of adaptation to local climatic condition;

b = Y-intercept.

In ASHRAE-55 standard (2017) [30], a and b are identified as follows (Equation (2)):

$$T_{O_i} = 0.31 \times T_{arm_{out}} + 21.3 \text{ (if the air velocity } \leq 0.3 \text{ m/s).} \quad (2)$$

In EN15251 Cat II [17], CIBSE Guide A [32], and ISSO 74 Class C, a and b are identified as Equation (3).

$$T_{O_i} = 0.33 \times T_{arm_{out}} + 21.8 \text{ (if the air velocity } \leq 0.3 \text{ m/s)} \quad (3)$$

In Griffiths' Method [47], a and b are described as following (Equation (4)):

$$T_n = 0.35 \times T_{arm_{out}} + 13.5. \quad (4)$$

where

T_n = Neutral air temperature—indoor.

Modified Griffiths' Method [48,49] describes a and b as Equation (5).

$$T_{accept} = 0.26 \times T_{arm_{out}} + 15.5 \quad (5)$$

where

T_{accept} = Acceptable temperature.

De dear and Brager [50] developed a revision model for ASHRAE-55 (2020) 31for NV buildings, and illuminated a and b as follows (Equation (6)):

$$T_n = 0.31 \times T_{arm_{out}} + 17.8. \quad (6)$$

3.4. Analytical and Critical Comparison of International Standards

This section compares the metrics, indices, and threshold limits that have been implemented in the international standards, and critically reviews the advantage and limitations of each document.

3.4.1. EN 15251

Metric

EN 15251 [17] applies three metrics for quantifying the overheating or discomfort. These metrics are:

- (a) Percentage of occupied hours outside the range (%*OhOR*).
- (b) Degree hours (*Dh*).
- (c) Weighted *PPD*.

Percentage of Occupied Hours Outside the Range (%*OhOR*)

The %*OhOR* metric indicates the percentage of hours in which indoor operative temperature (T_{oi}) or the PMV falls outside the predefined comfort thresholds associated with the chosen comfort category. This metric is relevant for both static and adaptive comfort models.

To compute the %*OhOR*, a binary weighting factor is employed, where its value is set to zero during periods when the conditions remain within the comfort ranges, and it assumes a value of one when conditions deviate from these ranges (Equation (7)). This index provides a simple and direct representation of the frequency of discomfort, highlighting instances when occupants may experience discomfort due to environmental conditions. EN 15251 suggests acceptable deviation of 3–5% for both short-term and long-term periods, including daily, weekly, monthly, and yearly periods.

$$\%OhOR = \sum_{i=1}^N T_{oi} > T_{com} \quad (7)$$

where

N = number of occupied hours in a day when T_{oi} is above the comfort temperature,
 T_{oi} = indoor operative temperature,
 T_{com} = comfort temperature.

Degree Hours (*Dh*)

The degree hours (*Dh*) refers to the number of hours which fall above the acceptable threshold, multiplied into number of degrees above the threshold (Equation (8)). The maximum acceptable threshold of *Dh* is not identified for this metric. *Dh* is not normalised to the number of occupied hours.

$$Dh = \sum_{i=1}^N T_{oi} - T_{com} \quad (8)$$

Weighted *PPD* ($\sum PPD$)

Weighted *PPD* refers to occupied hours, when *PMV* exceeds the comfort threshold (above +0.5, or lower than −0.5). It quantifies the summation of hourly percentage of dissatisfaction (Equation (9)). However, no maximum threshold is identified.

$$\sum PPD = \sum_{i=1}^N -0.5 > PMV > 0.5 \quad (9)$$

where

N = number of occupied hours when *PMV* is above or lower comfort threshold.

Index

Indices applied in EN 15251 are indoor operative temperature (T_{oi}) and *PMV*. They could be applied in both adaptive and static thermal comfort models.

The limitations for EN 15251 criteria would be:

- (a) The %*OhOR* metric does not consider the intensity of exposure to heat.
- (b) The %*OhOR* metric applies the same threshold limitations for short-term (i.e., weekly), and long-term (yearly) exposure to discomfort.
- (c) The degree hours metric is not normalised to the occupied hours.
- (d) There is not a maximum threshold for the degree hour and weighted *PPD* metrics.
- (e) The index operative temperature does not consider air movement and relative humidity.

3.4.2. EN 16798

EN 16798 [18] suggests the same metric and indices used in EN 15251 for the thermal comfort measures; however, it revised the shortcoming of EN 15251 and suggests different acceptable percentage for short term and long-term exposure to heat. It proposes a 20–50% acceptable deviation on a weekly basis, 50% is the maximum acceptable criterion for the weekly basis. Accordingly, it suggests 12–25% for a monthly basis, and 3–6% for an annual basis during occupied hours.

3.4.3. ISO 7730

Metric

The metrics suggested in ISO 7730 [35] are:

- (a) Percentage of occupied hours outside the range (%*OhOR*).
- (b) Degree hours (*Dh*).
- (c) Weighted *PPD* ($\sum PPD$).
- (d) Average *PPD*.
- (e) Total *PPD*.

The difference between weighted *PPD* in ISO 7730 compared with EN 15251 is that in ISO 7730, percentage of discomfort happens when *PMV* is $\geq +0.5$ or ≤ -0.5 , whilst in EN15251, percentage of discomfort counts when *PMV* is bigger > than +0.5 or less than -0.5 . The average *PPD* metric presents the average accumulation of *PPD* during the occupied hours. The total *PPD* calculates the accumulation of all *PPDs* over the occupied hours.

Index

The indices suggested in ISO 7730 are operative temperature, and *PMV*.

Limitations of ISO 7730 are listed below:

- (a) There is not any threshold limit for all the defined metrics (%*OhOR*, *Dh*, weighted *PPD*, average *PPD*, and total *PPD*).
- (b) The index operative temperature does not consider air movement and relative humidity.

3.4.4. CIBSE Guide A (2006)

Metric

A single metric proposed in CIBSE Guide A (2006) [32] is percentage of occupied hours outside the range (%*OhOR*), which is defined only for the naturally ventilated buildings. It is calculated based on the summation of occupied hours above the threshold during the total number of occupied hours. The threshold limit is defined for up to 1% during the occupied hours over a year in bedrooms and living rooms in residential buildings.

Index

The index proposed in CIBSE Guide A (2006) is operative temperature.

Limitations of CIBSE Guide A are listed below:

- (a) The proposed index is operative temperature, which does not consider two environmental parameters, namely relative humidity and indoor air movement; and two personal parameters, known as metabolic rate and clothing value.
- (b) It does not include the intensity of exposure to heat.

3.4.5. CIBSE TM52

CIBSE TM52 [16] defines three criteria for the overheating risk assessment for only free-running buildings. Each dwelling that fails to meet any two of the three criteria is assessed as overheated.

CIBSE TM52 Criteria I

Metric

The metric proposed in CIBSE TM52 criteria I is percentage of exceedance hours (%Eh).

The %Eh is the percentage of occupied hours, when indoor operative temperature exceeds the threshold limit by 1 degree centigrade or above during the total number of occupied hours. This metric requires the calculation over the warm season (1st May to 30th September in Northern Hemisphere). The maximum limit is allowed for 3% during the occupied hours during the summertime.

CIBSE TM52 Criteria II

Metric

In criteria II, CIBSE TM52 focuses on overheating within one day and introduces daily degree exceedance hours (DEh). It quantifies the summation of exceedance hours multiplied to the intensity of heat. The intensity of heat is calculated as delta between the operative temperature and the maximum threshold limit. The maximum acceptable daily DEh is 6-degree exceedance hours in any one day to limit the overheating in extreme events such as during heatwaves.

CIBSE TM52 Criteria III

This criterion includes a maximum value in which the indoor operative temperature should not be exceeded by 4 degrees Celsius. This criterion does not consider the summation (intensity) of exposure to heat over the time.

Index

The index proposed in CIBSE TM52 for all three criteria is operative temperature. Limitations for CIBSE TM 52 are listed as follows:

- (a) The metric %Eh does not include intensity of exposure to heat.
- (b) The index, operative temperature does not include the two other environmental parameters (relative humidity, and indoor air movement), and two personal parameters (clothing value, and metabolic rate).

3.4.6. CIBSE TM59

Metric

The proposed metrics in CIBSE TM59 [33]:

- (a) For mechanically ventilated buildings, CIBSE TM59 applies a fixed set point, and forcing that operative temperature should not exceed of 26 °C for more than 3% during the occupied hours over a year in all zones (bedroom, kitchen, and living room).
- (b) Naturally ventilated buildings need to pass two criteria as follows:

- (1) All zones including bedrooms, living room, and kitchen need to follow criteria I in CIBSE TM52.
- (2) For the bedrooms, an additional metric named percentage of sleeping hours outside the range (*%ShOR*) is introduced. The *%ShOR* dictates that the operative temperature should not exceed 26 °C for more than 1% over a year during the sleeping hours (10:00 p.m.–7:00 a.m.) in the bedrooms.

Index

The index applied in CIBSE TM59 is operative temperature.

Limitation of CIBSE TM59:

- (a) The index proposed in TM59 is operative temperature, which does not consider relative humidity, indoor air speed, metabolic rate, and clothing insulation for the comfort calculation.
- (b) The intensity of exposure to heat is overlooked in the metrics of TM59.
- (c) The maximum threshold limitations are designed for the long-term overheating assessment and does not take into account the short-term overheating and extreme heat events, such as heatwaves.

3.4.7. CIBSE Guide A (2015)

Metric

The metrics applied in CIBSE Guide A (2015):

- (a) For the buildings with mixed mode ventilation (combination of mechanical and natural ventilation), CIBSE Guide A (2015) suggests percentage of occupied hours outside the range (*%OhOR*) metric. *%OhOR* shows the percentage of occupied hours above the comfort zone. The calculated *%OhOR* should not exceed 3% during the occupied hours over a year.
- (b) For naturally ventilated buildings CIBSE Guide A (2015), follows the three criteria proposed in CIBSE TM52.

Index

The indices used in CIBSE Guide A are operative temperature, and *PMV*.

Limitations for CIBSE Guide A (2015) are listed below:

- (a) The metric *%OhOR* does not consider the intensity of exposure to heat.
- (b) The indices applied are operative temperature and *PMV*, which do not include two environmental parameters (relative humidity and air speed) in the calculation of comfort.

3.4.8. Passive House

Metric

The metric introduced in Passive House [36] for passively cooled buildings (no active cooling such as air conditioning or HVAC systems) is the percentage of hours outside the range (*%hOR*) for occupied and unoccupied hours. It refers to the percentage of exceedance hours above 25 °C operative temperature. It requires that all zones not exceed 10% over a year.

Index

Index applied in Passive House standard is operative temperature.

Limitations of Passive House criteria:

- (a) The metric *%hOR* does not include the intensity of overheating.
- (b) The metric does not include the occupied hours.

- (c) The index applied is operative temperature, which does not count two environmental parameters of relative humidity and indoor air movement and two personal parameters of metabolic rate and clothing value in the comfort estimation.
- (d) It assesses the long-term risk of overheating over a year. Therefore, the short-term overheating assessment is overlooked.

3.4.9. ASHRAE-55 (2017) and ASHRAE-55 (2020)

Metrics

Metrics proposed in ASHRAE 55 (2017) and (2020) are listed below:

- (a) Exceedance hours (Eh).
- (b) Degree Exceedance hours (DEh).

Exceedance hours refer to accumulation of number of occupied hours when PMV or operative temperature falls beyond the thermal comfort zone threshold. The comfort zone could follow either static comfort zone boundaries or adaptive comfort zone boundaries.

The degree exceedance hours are calculated based on the number of exceedance occupied hours multiplied to the intensity of discomfort. For the static model, the intensity of discomfort is calculated as the accumulation of $PMVs$ above +0.5 and less than −0.5. For the adaptive model, degree of discomfort is calculated as the summation of operative temperatures above the upper limit of the comfort zone (for the overheating) and the summation of operative temperatures below the lower limit of comfort zone for the over cooling.

Index

The indices proposed in both ASRAE 55 (2017) and ASHRAE 55 (2020) are operative temperature and PMV .

Limitations of ASHRAE 55 (2027) and (2020):

- (a) The exceedance hours (Eh) metric does not calculate intensity of exposure to heat.
- (b) The maximum acceptable limit is not identified.

Table 1 summarises the metrics, indices, threshold limitations, building type, and the cooling operation systems in all the described regulatory documents described above.

Table 1. Analytical and critical comparison of international standards. Avg = average; %OhOR = percentage of occupied hours outside the range; T_{oi} = indoor operative temperature; %hOR = percentage of hours outside the range; %ShOR = percentage of sleeping hours outside the range; Dh = degree hours; Eh = exceedance hours; NV = natural ventilation; and mechanical ventilation = MV.

Standard	Metrics	Index	Threshold Limit	Thermal Comfort Model	Building Type	Building Operation System
EN 15251[19]	%OhOR; Dh; weighted PPD	PMV ; T_{oi}	Acceptable deviation of 3–5% of %OhOR for daily, weekly, monthly, and yearly periods during the occupied hours.	Static and adaptive model	All building types, with occupants' availability to adaptation response.	MV and NV
EN 16798 [34]	%OhOR; Dh; weighted PPD	PMV ; T_{oi}	Acceptable deviation of 20–50% of %OhOR (weekly); 12–25% (monthly); 3–6% (annually) deviation during occupied hours.	Static and adaptive model	All with occupant availability to adaptation response.	MV and NV
ISO 7730 [35]	%OhOR; Dh; weighted PPD; average PPD; total PPD	PMV	Not specified	Static and adaptive model	All with occupant availability to adaptation response.	MV and NV
ASHRAE 55[30,31])	Exceedance hours (Eh); degree exceedance hours (DEh)	PMV ; T_{oi}	Not specified	Static and adaptive model	All with occupant availability to adaptation response.	MV and NV

CIBSE Guide A (2006)[32]	%OhOR	T_{oi}	Max 1% deviation of %OhOR during occupied hours over a year in bedrooms and living room.	NA	Residential buildings	NV
CIBSE TM52 [18]	%Eh (Criteria I); DEh (Criteria II); T_{oi} (Criteria III).	T_{oi}	Criterion I: max 3% deviation of %Eh during occupied hours during a year. Criterion II: max 6 degree exceedance hours during a day. Criterion III: max 4 °C operative temperature right now right here.	NA	Residential buildings	NV
CIBCE Guide A (2015) [32]	%OhOR,	PMV, T_{oi}	Max 3% on %OhOR during the occupied hours for MV buildings; for NV buildings same as CIBSE TM52.	NA	Residential buildings	MV and NV
CIBCE TM59 [33]	%Eh %ShOR	T_{oi}	For MV buildings: Max T_{oi} of 26 °C for max 3% during the occupied hours over a year in all zones. For NV buildings: (a) living, kitchen, and bedroom follow CIBSE TM 52; and (b) bedrooms max T_{oi} of 26 °C for max 1% of total annual hours during the sleeping hours.	NA	Residential buildings	MV and NV
Passive house [36]	%hOR	T_{oi}	Max 10% of %hOR when T_{oi} is above 25 °C for all living areas.	NA	All	Passive cooling

3.5. Analytical and Critical Comparison of National Building Codes

The European Commission established a framework including the Energy Performance of Building Directive (EPBD) in 2012, aiming to reduce CO₂ emission and improve energy performance of the buildings by 2050. The member states of the European Commission have to implement the general regulations made by EPBD. This manuscript analysed and compared the thermal comfort and overheating assessment criteria embedded in the national building codes. For each available regulatory document, we extracted the employed standard, index, threshold limit, building type, and the building operation system (see Table 2). Only the available English version of national codes is included in this study.

Table 2. Analytical and critical comparison national building codes based on the Energy Performance of Building Directive (EPBD). NV = natural ventilation; Resi = residential building; T_{ai} = indoor air temperature; MRT_i = indoor mean radiant temperature; NS = not specified; NA = not applicable; IT = internal index (UK); IO = overheating index (Belgium); S_{oh} = solar transmittance index (Germany); and S_{zul} = sum of solar input parameters given in DIN 4108 (Germany).

National Building Code	Standard	Index	Threshold Limit	Thermal Comfort Parameters Included	Occupant's Adaptive Response	Building Type	Building Operation System
Belgium (Brussels)	Passive House	T_{oi}	Max 25 °C by 5% during the occupied hours over a year.	T_{ai} ; MRT_i	No	Resi	NV
Belgium (Wallonia and Flanders)	ISO 13790	IO	1000 Dh < I_{oh} < 6500 Dh	No	No	Resi	NV
Germany	DIN 4108	T_{oi}	Compliance through passing one of the criteria. Criteria I: $S_{oh} \leq S_{zul}$ (sum of solar input parameters given in DIN 4108). Criterion II: threshold temperature depends on climatic region (25 °C, 26 °C, and 27 °C), Dh < 1200 Dh during a year.	T_{ai} ; MRT_i	No	Resi	Passive cooling and active cooling
France	EN 15251	T_{oi}	Dh < 1250	T_{ai} ; MRT_i	Yes	Resi	NV
UK	SAP	IT	NA	T_{ai}	No	Resi	NV

Netherlands	NS	TOJULY; GTO; PMV	Criteria I: max limit value of 1 for TOJULY.	T _{ai} ; MRT _i	No	Resi	NV
			Criteria II: max threshold value of 450 for GTO in living area (when PMV exceed +0.5).				

3.5.1. France

France adopted the EN 15251 standard and implements the degree hours (Dh) metric and indoor operative temperature index to assess discomfort in new residential buildings during the summer months [12]. The threshold for the comfort zone is derived from the upper limit of adaptive comfort model used in EN 15251. The maximum acceptable exceedance operative temperature is 1250 Dh for the summertime. It could be translated to a 25-day period of 28 °C indoor operative temperature during the nighttime and 30 °C during the daytime. The weather file for the assessment should be similar to the weather data in 2003, when a heatwave occurred.

Critical review of the criteria:

- The criteria are applicable in all climate zones across the country (France has different climate zones, i.e., Oceanic and Mediterranean).
- The criteria are for the long-term assessment (during the summertime), therefore, extreme events such as heatwave days could be neglected.
- All hours including occupied, and non-occupied hours are included.
- The index applied is operative temperature, which excludes four other comfort parameters (i.e., relative humidity, indoor air movement, clothing insulation, and metabolic rate).

3.5.2. Belgium

Belgium is a country with three regions, namely Brussels, Flanders, and Wallonia. Each region implies its own regulation to meet the EPBD requirements. Brussels implements the thermal comfort criteria in residential buildings based on the Passive House standard. The operative temperature during the occupied hours should not exceed 25 °C for maximum of 5% during a year [15].

In Flanders and Wallonia, an overheating index (I_{oh}) is introduced which is derived from ISO 13790 and is calculated based on the heat balance equation taking into account the heat gain and heat loss of the building in degree hours (Dh). The acceptable range of I_{oh} is between 1000 Dh and 6500 Dh.

Critical review of these criteria includes:

- The indices To_i and I_{oh} do not include two environmental parameters (relative humidity, and indoor air speed) nor two personal parameters (clothing value and metabolic rate).
- It uses same threshold limitation for short-term and long-term exposure to heat stress.
- It counts all the occupied and non-occupied hours.
- It does not consider the adaptation responses from occupants.
- The intensity of exposure to heat is not counted.

3.5.3. Germany

In Germany, the overheating assessment method includes two criteria, and each building needs to meet at least one criterion to pass the assessment.

Criterion I

This criterion is based on solar heat gains in the most critical room. A solar transmittance index is introduced (S_{trans}) which is the function of window type, window size, room size, and shading systems.

Criterion II

Criterion II proposes the degree hours (Dh) metric. The maximum acceptable Dh is 1200 Dh over a year in the most critical room. The threshold operative temperature depends on the climate zone ranging between 25 and 27 °C.

Critical reviews of these criteria are listed below:

- (a) Criterion I is based on solar heat gain, therefore, the heat gain from occupants and devices, i.e., cooking heat, are not included.
- (b) Criterion I does not include the intensity of heat exposure.
- (c) In criterion I, the environmental and personal parameters of thermal comfort calculation are not included.
- (d) In criterion I, overheating assessment is time independent.
- (e) Both criteria do not consider the occupants' adaptation responses.
- (f) Both criteria are not normalised to occupied hours.

3.5.4. Netherland

In Netherland there are two criteria [12]:

Criteria I, introduce a dimensionless index only for the month of July, named overheating index July (IO_{July}). The index is calculated based on the number of external façades of the building and is derived from the average cooling requirement of the entire building. The maximum limit value for IO_{July} is 1.

Criterion II is based on weighted PPD when PMV exceed +0.5. The index is named GTO and has a maximum limitation of 450.

These criteria could be criticised as:

- (a) Both criteria are only applied in July. Therefore, other extreme events during other summer months are neglected.

Criteria I is based on heat balance equation and does not include thermal comfort parameters.

Criteria I is for all hours, including occupied and unoccupied hours.

Occupants' adaptation responses are not considered in both criteria.

3.5.5. United Kingdom

In the United Kingdom, the overheating evaluation is based on the standard assessment procedure (SAP) [21]. SAP introduces an index named internal threshold (IT) for overheating assessment during summer months (June, July, and August). IT is applied to estimate the likelihood of high indoor heat. In the calculation of IT, external air temperature, heat gains, heat losses, and building thermal mass are considered.

These criteria could be criticised as:

- (a) The criteria are specified for summer months only, therefore, other extreme events outside the summertime could be excluded.
- (b) The overheating assessment is for the long-term assessment (monthly), whilst the short-term events would be neglected.
- (c) The index is based on air temperature therefore other parameters impacting the thermal comfort are not included (relative humidity, air velocity, personal metabolic rate, and clothing value).
- (d) It calculates all hours including occupied hours and non-occupied hours.

Table 2 summarises the overheating assessment criteria in five national building codes.

The analysis of international standards reveals that most of the standards, the employed indices focusing primarily on the air temperature and operative temperature, neglect crucial environmental parameters (relative humidity and indoor air velocity) and personal factors (clothing value and metabolic rate) that significantly influence occupants' thermal sensation [51]. Furthermore, the regulatory documents often overlook occupants' adaptation responses. In naturally ventilated buildings, where occupants are more exposed to outdoor air temperature, the consideration of adaptive thermal comfort becomes pertinent [50]. The thermal comfort threshold and overheating criteria in the regulatory documents play a significant role in the energy consumption or savings in the buildings.

Following reviewing the international and national regulatory documents, we suggest following measures for the improvement or development of regulatory overheating criteria.

- (a) Introduce a comprehensive metric: Propose a metric which measures both intensity and duration of exposure to heat stress, such as the degree hours metric, examined by Sadeghi et al. (2021) [8]. During extreme events such as heat waves, the human body's thermal regulation responds not only to the intensity of heat, but also to the cumulative duration of exposure. Prolonged exposure to elevated temperatures can overwhelm the body's ability to dissipate heat, increasing the risk of heat-related illnesses. By integrating both factors, this metric provides a more holistic understanding of heat stress, enabling better assessment of overheating risks in residential buildings.
- (b) Thermal comfort index: apply an index that quantifies thermal sensation by encompassing four environmental parameters (indoor air temperature, mean radiant temperature, relative humidity, and indoor air velocity), along with two personal parameters (metabolic rate and clothing insulation).
- (c) Incorporate short-term and long-term assessment: implement a nuanced approach to consider both short-term evaluations (i.e., extreme heat events such as heatwaves), and long-term overheating assessment (i.e., over a year or over summertime).
- (d) Account for occupant adaptation: Include considerations for occupant adaptation responses, acknowledging that occupants may modify their behaviour based on the thermal conditions. For example, with regards to occupants' clothing value or metabolic rate, it could consider typical summer clothing value for calculations over summertime; or assume a metabolic rate of a standing relaxing person for the kitchen and sitting rooms predictions.
- (e) Climate zone differentiation: recognise the diverse climates across the country addressing the unique thermal challenges of each climate zone as classified by the national climate classification, i.e., National Construction Code (NCC) in Australia [23].

4. Conclusions

In this study, we explored and critically compared international standards and national building codes related to the assessment of thermal comfort and overheating risk in residential buildings. The findings reveal that most of the standards employ indices, particularly focusing on air and operative temperatures, yet often overlooking crucial environmental parameters and personal factors that significantly impact occupants' thermal experiences.

International standards such as ASHRAE-55, EN 15251, and ISO 7730 predominantly utilise metrics such as percentage of occupied hours outside the range (%*OhOR*), and weighted predicted percentage dissatisfied (*PPD*). While these metrics offer insights, they exhibit limitations, including a lack of consideration for the intensity of exposure to heat, uniform threshold limitations for short and long-term assessments, and neglect of adaptation responses from occupants.

The static thermal comfort models, exemplified by the predicted mean vote (PMV), offer a traditional yet limited approach by assuming uniform preferences among occupants. Conversely, the adaptive thermal comfort model recognises the dynamic nature of indoor environments, individual preferences, and adaptation responses, providing a more nuanced and energy-efficient framework especially suitable for naturally ventilated buildings [50].

Analysing national building codes, we explored criteria from France, Belgium, Germany, Netherlands, and the United Kingdom. Notably, these criteria vary in their approaches, introducing indices such as internal threshold (IT), overheating index (IO), and overheating metrics for specific months. However, common limitations persist, such as overlooking short-term events, neglecting occupants' adaptation responses, and focusing predominantly on the air temperature.

Considering the absence of mandatory regulations for overheating criteria in residential buildings in some countries across the world, i.e., Australia, we propose a comprehensive approach for developing new overheating regulatory documents specified to the local climate. Suggestions include introducing a metric to measure both intensity and duration of heat stress, employing a thermal comfort index encompassing environmental and personal parameters, differentiating between short-term and long-term assessments, accounting for occupant adaptation, and recognising the diverse climate zones across the country.

This study faced certain limitations that should be addressed in future research. Some national regulatory documents, such as those from Italy and Greece, were only available in local languages, and their English versions were inaccessible. As a result, the analysis relied on European legislation and documentation, limiting the inclusion of region-specific details from these countries. Future studies may look at possibilities for developing climate-adaptive regulations tailored to the needs of individual countries, which will be crucial to addressing the unique challenges posed by varying geographic and climatic conditions.

Addressing overheating risk in buildings requires a holistic and adaptive approach that considers the diverse factors influencing thermal comfort. Striking knowledge of human thermal physiology, human adaptation responses, building physics, and environmental climate especially in geographically varied countries such as Australia, is crucial for creating effective and sustainable regulations to ensure occupants' well-being and energy-efficient building practices. Our findings have implications for policymakers, building energy assessors, building designers, and public health professionals.

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Nomenclature

T_{oi}	Operative temperature—indoor (°C)
MRT	Mean radiant temperature—indoor (°C)
T_{ai}	Air temperature—indoor (°C)

T_{aout}	Air temperature—outdoor (°C)
PMV	Predicted mean vote (dimensionless)
PPD	Predicted percentage dissatisfied (%)
h	Hour (h)
Oh	Occupied hours (h)
Dh	Degree hours (°Ch)
$ Eh$	Exceedance hours (h)
Met	Metabolic rate (met)
Clo	Clothing value (clo)
V_i	Air speed—indoor (m/s)
W	Wind speed—outdoor (m/s)
$T_{arm out}$	Running mean air temperature—outdoor (°C)
T_n	Neutral air temperature (°C)
T_{accept}	Acceptable air temperature (°C)
T_{com}	Comfort temperature (°C)
$\%OhOR$	Percentage of occupied hours outside the range (%)
$\%hOR$	Percentage of hours outside the range (%)
$\%ShOR$	Percentage of sleeping hours outside the range (%)

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