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Simulation-based framework to evaluate resistivity of cooling strategies in buildings against overheating impact of climate change

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ABSTRACT

Over the last decades overheating in buildings has become a major concern. The situation is expected to worsen due to the current rate of climate change. Many efforts have been made to evaluate the future thermal performance of buildings and cooling technologies. In this paper, the term "climate change overheating resistivity" of cooling strategies is defined, and the calculation method is provided. A comprehensive simulation-based framework is then introduced, enabling the evaluation of a wide range of active and passive cooling strategies. The framework is based on the Indoor Overheating Degree (IOD), Ambient Warmness Degree (AWD), and Climate Change Overheating Resistivity (CCOR) as principal indicators allowing a multi-zonal approach in the quantification of indoor overheating risk and resistivity to climate change.

To test the proposed framework, two air-based cooling strategies including a Variable Refrigerant Flow (VRF) unit coupled with a Dedicated Outdoor Air System (DOAS) (C01) and a Variable Air Volume (VAV) system (C02) are compared in six different locations/climates. The case study is a shoe box model representing a double-zone office building. In general, the C01 shows higher *CCOR* values between 2.04 and 19.16 than the C02 in different locations. Therefore, the C01 shows superior resistivity to the overheating impact of climate change compared to C02. The maximum CCOR value of 37.46 is resulted for the C01 in Brussels, representing the most resistant case, whereas the minimum CCOR value of 9.24 is achieved for the C02 in Toronto, representing the least resistant case.

1. Introduction

During the last decade, the concept of resistivity of buildings and cooling strategies emerged in several studies [1]. The term resistivity appeared under different names including: Resistance, Resilience, Robustness, and other terms. For example, Attia et al. [1] defines cooling resistance as the building system's ability to maintain the initial design conditions during the disturbances such as heatwaves or power outages. This paper defines so-called "climate change overheating resistivity" as the ability of building cooling strategies to resist the increase of indoor overheating risk against the increase of outdoor thermal severity in a changing climate. In other words, the climate change overheating resistivity shows to what extend the indoor overheating risk will increase with the increase of outdoor thermal stress under future climate scenarios. This definition targets the ability of cooling strategies in buildings to maintain an acceptable thermal environment against the gradual worsening of weather conditions due to climate change, whereas the definition in Ref. [1] targets the ability of cooling strategies to suppress the short-term overheating incidents. There is a universal need to understand the notion of climate change overheating resistivity as a key factor in characterizing the future thermal performance of cooling strategies in buildings.

Despite the important role of opting for the implementation of climate change overheating resistive cooling strategies in buildings, it is being overlooked in the fight against climate change. Climate change overheating resistive cooling strategy improves the preparedness of the building for more intense and frequent overheating events in the future. The more the cooling strategy is resistant, the higher it is able to maintain a comfortable and healthy environment for the occupants in buildings. The concept of climate change overheating resistivity must be

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standardized through the regulation and policies to be strictly implemented in the building cooling requirements.

Several studies highlighted the importance of cooling strategies in mitigating the overheating impacts of climate change [2–4]. The cooling demand in buildings is predicted to encounter unprecedented growth with the continuation of global warming [5–7]. The increase in cooling demand will be further aggravated with the increase of internal gains related to growing occupancy densities [8]. The cooling strategies will become inexorable to remove sensible/latent heating loads, prevent heat gains to the indoor environment, or enhance personal comfort. Therefore, the cooling strategies are expected to play the main role in reducing the overheating risks in buildings and hence ensure comfortable environments in future climates.

The first question considered in evaluating the scientific literature is, *"what are the simulation-based studies that assessed the performance of cooling strategies in relation to climate change?"*. In response to the first question, some relevant studies are presented as follows. O'Donovan et al. [9] investigated ten passive cooling control strategies applied on a Nearly Zero Energy Building (NZEB). Each strategy uses different combinations of passive cooling systems such as day-time ventilation, nighttime ventilation, and dynamic solar shading. For different combinations of passive cooling systems, an increase in indoor operative temperature between 0.1°C and 0.3°C in Dublin (maritime climate) and between 1°C and 1.9°C in Budapest (continental climate) was resulted by 2050s. It was also mentioned that the passive cooling strategies (and their combination) are able to maintain 57–95% comfortable occupied hours. Chiesa & Zajch [10] investigated the sensitivity of Earth-to Air Heat Exchangers (EAHE) to climate change in nine different locations across Northern America. Using Local and Residual Cooling Degree Hour (CDH_{loc} and CDH_{res}) to calculate the virtual control of EAHE, they found a significant reduction in the cooling potential of the EAHE system for Representative Concentration Pathway (RCP) 4.5 and 8.5 scenarios by 2061–2090. Rey-Hernández et al. [11] studied the impact of climate change on the indoor operative temperature of a zero energy and carbon office building located in Valladolid, Spain. The cooling system consists of a chiller system backed up with an adsorption chiller connected to an Air Handling Unit (AHU). By using the CCWorldWeatherGen tool to produce future weather files, they found an increase in indoor air temperature of ~ 1°C between 2020 and 2050 and ~ 1.7°C between 2050 and 2080. Ibrahim & Pelsmakers [12] investigated the increase in indoor overheating risk in a PassivHaus retrofit case study using PassiveHaus Planning Package (PHPP) [13] metric. For the period between High Emission Scenarios (HiES) of 2050 and 2080, the study results show an increase in overheating frequency by 6% for roof insulation, 7% for wall insulation, 6% for reduced glazing size, 5% for nighttime ventilation, 5% for internal and external shading devices, and 3% for reduced glazing G-value.

There is a study by Hamdy et al. [14] that introduced the Overheating Escalation Factor (OEF) metric corresponding to the inverse of climate change overheating resistivity factor within this paper. The *OEF* shows the sensitivity of a building to increasing outdoor thermal severity. By morphing the historical data (1964/1965 and 2003), they generated future and worst future weather scenarios. By applying in total 4 weather scenarios, they found the *OEF* values between 0.1 and 0.989 in Dutch dwellings. It means that there are some dwellings (with only natural ventilation) that are very close to become overheated in the future.

The second question considered in evaluating the scientific literature is, *"do those studies allow for a universal and comprehensive evaluation of the resistivity of cooling strategies against the overheating impact of climate change?"*. In response to the second question, four criteria are set for a systematic analysis as follows.

- **Universality:** this criterion evaluates whether the study is conducted for a universal evaluation of cooling strategies. Most studies focus on a specific location and climate based on the national or regional standards for comfort models and definition of building characteristics.
- **Function-independency:** this criterion investigates whether the study is focused on a specific building typology and function mode. Function-dependent studies focus on specific residential or non-residential buildings. Therefore, they do not contain full guidance on how to define the operational properties, schedules, and comfort categories for different building types.
- **Comfort model-independency:** this criterion evaluates whether the study has provisions regarding the flexible selection of the static and adaptive comfort models. Such a provision enables the evaluation of both active and passive cooling strategies with different cooling modes (air conditioned, non-air conditioned, and mixed/hybrid modes).
- **Resistivity evaluation:** this criterion examines whether the study contains resistivity evaluation against overheating impact of climate change. The main factor for the resistivity evaluation is the use of specific metrics (e.g. *OEF*, *CCOR*, etc.) that relate the indoor and outdoor thermal environments while incorporating multiple historical and future weather scenarios. Such metrics show, via a single value, to what extend the thermal performance of the cooling strategies in buildings are affected due to the changes in outdoor thermal conditions over time.

The results of the literature analysis based on the four above-mentioned criteria are presented in Table 1.

Until now, there is a lack of comprehensive universal method to evaluate and compare the climate change overheating resistivity of cooling strategies. As part of the International Energy Agency (IEA) EBC Annex 80 – "Resilient cooling of buildings" project activities, this paper is developed to address the abovementioned knowledge gaps. The aim of this research is to broaden the comparative analysis among cooling strategies to global scales. The main research question is:

- How to evaluate the climate change overheating resistivity of cooling strategies worldwide?

The main research question can be divided into:

- Q1: How to characterize the climate data and building models in a consistent way to universally compare the cooling strategies?

Table 1
A list of studies in the literature concerning the thermal performance evaluation of buildings/cooling strategies under future climate scenarios.

Scientific article	Universality	Function-independency	Comfort model-independency	Resistivity evaluation
O'Donovan et al. [9]	×	×	×	×
Lomas & Ji [15]	×	×	×	×
Hanby & Smith [16]	×	×	✓	×
K.J. Lomas & Giridharan [17]	×	×	×	×
Gupta & Gregg [18]	×	×	×	×
Sajjadian et al. [19]	✓	×	×	×
Hamdy et al. [14]	×	×	✓	✓
Ibrahim & Pelsmakers [12]	×	×	×	×
Pagliano et al. [20]	×	×	✓	×
Chiesa & Zajch [10]	✓	×	×	×

- Q2: How to quantify and evaluate the climate change overheating resistivity of cooling strategies in buildings?
- Q3: How to test the evaluation framework?

This paper provides a generic simulation-based framework contributing to the body of knowledge in several ways. First, the framework is based on universally applicable standards enabling, with common boundary conditions, a universal comparison of cooling strategies in different climatic regions. Second, the framework is comprehensive; it allows for the comparison of a wide range of active and passive cooling strategies by providing systematic guidance on how to select the comfort models for the zones with different cooling modes (air conditioned, non-air conditioned, and mixed/hybrid mode). The framework is also not limited to any building typology and operation type; it encompasses residential and non-residential buildings, whether they are newly built or existing buildings. Third, the framework identifies and includes a multi-zonal and climate-change sensitive approach in the quantification of overheating risks in buildings. More importantly, a new fit-to-purpose metric called "Climate Change Overheating Resistivity (CCOR)" is introduced to quantify the resistivity of cooling strategies against overheating impacts of climate change. Finally, a Variable Refrigerant Flow (VRF) unit coupled with a Dedicated Outdoor Air Supply (DOAS) and a Variable Air Volume (VAV) system are compared in six reference cities to test the framework. Detailed information on their sizing is also presented.

The proposed framework can provide strong support for the building professionals to assess and compare different cooling strategies in the early design stage and retrofit of the new and existing buildings, respectively. Implementing the methodology may yield to thermal resiliency benefits in the buildings. Also, the research outcomes can inform the cooling industry regarding the resistivity of cooling strategies against climate change in different regions. It can instigate technical improvements towards more resistive cooling concepts. It also sheds light on the importance of resistivity requirements to be embedded in the regional and national building codes in defining thermal comfort requirements. The current paper is organized as follows. In Section 2, the methodology, including the framework is provided (Section 2.1) and the demonstration case (Section 2.2). Section 3 presents the results. Section 4 discusses the key findings, recommendations, strengths, limitations, and implications on the practice of the study and suggests potential future research. And, Section 5 concludes the paper.

2. Methodology

Fig. 1 shows the research methodology of the current paper. The methodology consists of two main parts. In the first part, the framework is introduced relying on the literature review, International standards, focus-group discussions, and follow-up discussions among the authors. In the second part, a demonstration case to test the proposed framework is provided.

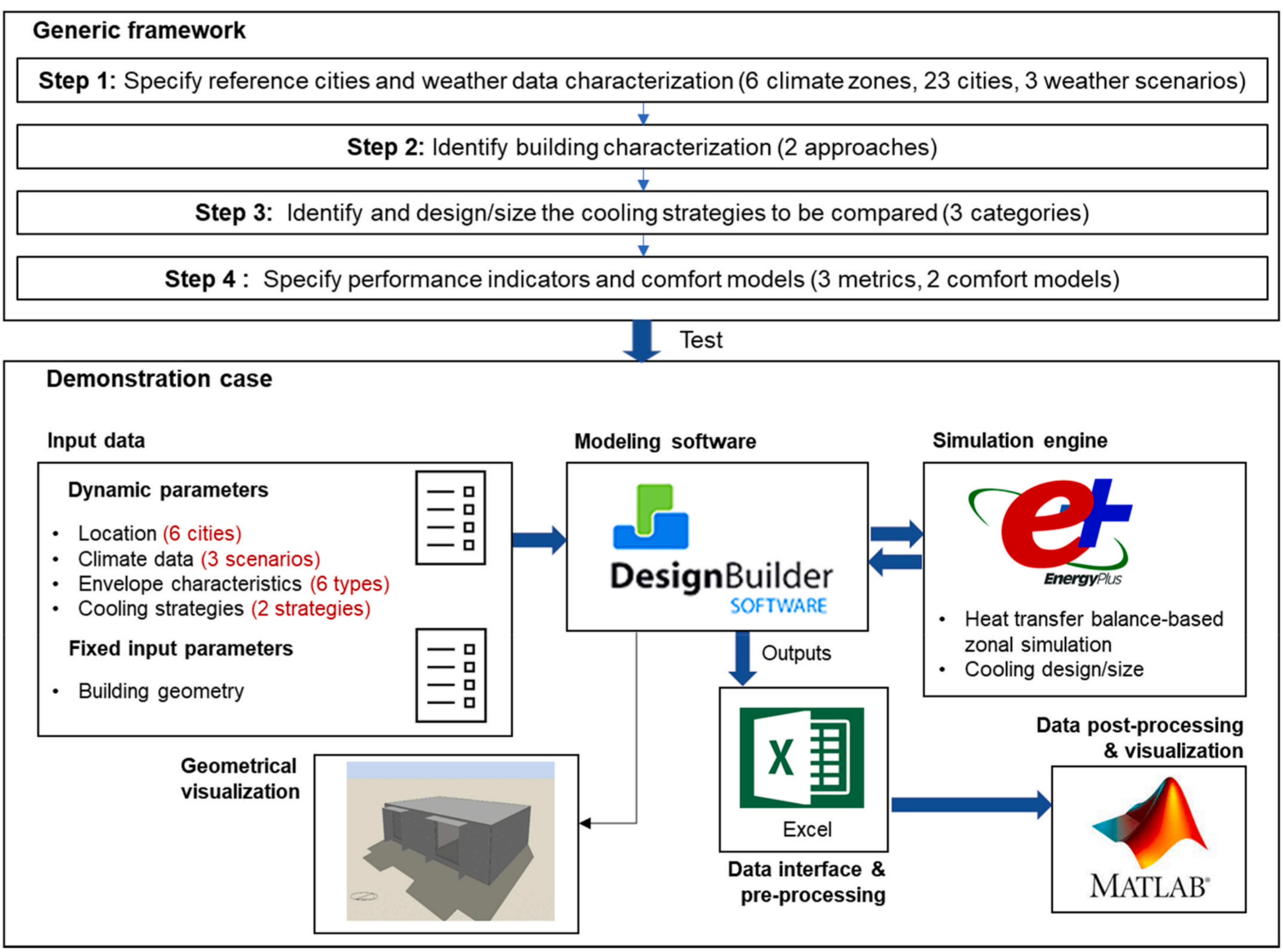

Fig. 1. Study conceptual framework (SCF).

2.1. Generic framework

Thermal discomfort in buildings can be divided into overheating discomfort and overcooling discomfort. Many researchers highlighted that with the continuation of global warming, overheating will become the increasing cause of thermal discomfort in buildings in most regions [21–25]. Therefore, the scope of the current framework is narrowed to the overheating discomfort and the evaluation of cooling strategies. In other words, the overcooling discomfort and heating system performance are excluded.

As shown in Fig. 2, the proposed framework consists of four main steps, 1) specify reference cities and weather data characterization (Section 2.1.1), 2) identify building characterization (Section 2.1.2), 3) identify and design/size the cooling strategies to be compared (Section 2.1.3), and 4) specify performance indicators and comfort models (Section 2.1.4). The framework allows a universal comparison of a wide range of active and passive cooling strategies. It encompasses almost the entire building typologies and function modes. The framework is also flexible to be used as a fast decision-support tool with recommending simple shoe box models as well as to more sophisticated analysis via reference building models. As mentioned earlier, the principal aim of the framework is to provide a standardized method (based on Internationally applicable standards) for a universal (different locations and climates) comparison of cooling strategies. However, for practical use, one can select a specific location and building and follow the suggested procedure to compare a set of applicable cooling strategies.

2.1.1. Step 1: specify reference cities and weather data characterization

Weather files are major prerequisites in any study related to climate change. The weather data requirements for the current framework is inspired by the work of (IEA) EBC Annex 80 - Weather Data Task Force. First, it necessitates the use of one contemporary (i.e. 2010s) and two future (i.e. 2050s and 2090s) weather scenarios. Future weather data projections are grouped according to the concentration and emission scenarios that are called Representative Concentrations Pathways (RCPs) to represent the 21st century. RCPs are based on energy, land use and cover, technological, socioeconomic, Green House Gas (GHG) emissions, and air pollutant assumptions [26]. With the current climate change mitigation efforts, the actual temperatures expected to be much higher than the projections in RCP2.6 (low emission scenario), RCP4.5 (medium-low emission scenario), and RCP6 (medium-high emission scenario) [27]. So, the framework requires future weather files based on RCP8.5 (high emission scenario). Current state-of-the-art approaches and tools to produce future global projections and weather files are widely discussed in Refs. [28–30].

Second, the framework recommends 23 cities (see Fig. 2) representing the climate zones 1 to 6 in ASHRAE 169.1 [31] classification. Multiple reference cities are assigned for each climate zone based on the population and the rate of growth.

Third, the framework allows both UHI effect included and excluded weather data. Including the UHI effect, especially in urban-related studies, quantifies the anthropogenic impacts on the evolution of outdoor thermal conditions [32]. Doing so contributes to more realistic weather data input for the simulations. However, due to limitations in obtaining such accurate weather data, the framework allows the use of weather files without UHI effects as an alternative.

2.1.2. Step 2: identify building characterization

The framework is applicable for evaluations in both new and existing buildings. The “existing buildings” are the buildings that are already in existence or constructed and authorized prior to the effective date of the current national or regional building regulations. Differently, the “new buildings” are the buildings that are already constructed or will be constructed after the effective date of the current national or regional building regulations. The framework provides two approaches for the selection of the building simulation models, the shoe box model (new buildings) and the reference building model (new and existing buildings).

The shoe box model is a basic and simplified model of a building that represents a building or its division as a rectangular box. The shoe box models can be made very quickly and therefore valuable to make early design decisions. In the case of shoe box models, the envelope characteristics must comply with ASHRAE 90.1 [33]. It is a widely accepted standard that specifies requirements for building envelope thermal properties for high-performance buildings (except for low-rise residential buildings) for each climate zone. The International standards ISO 18523- [34] and ISO 18253–2 [35] as well as ISO 17772–1 [36] are suggested to define schedules and condition of building, zone and space usage, including occupancy, operation of technical building systems, hot water usage, internal gains due to occupancy, lighting and equipment.

The reference building models are “*buildings characterized by and representative of their functionality and geographic location, including indoor and outdoor climate conditions*” (Annex III of the EPBD recast). The reference buildings can be created statistically (theoretical model) or by expert assumptions and previous studies (example model) or by selecting a real typical building [37]. Consequently, all the input parameters regarding the geometry, envelope properties, and operational conditions (schedule and condition of building, zone and space usage) can be derived by statistical analysis or expert assumptions or should reflect real typical conditions. Establishing reference building models provides a credible and robust model to evaluate the energy needs and retrofit measures [38] as well as thermal comfort and climate change adaptation measures. There are several studies that developed reference building models such as for educational buildings in Belgium [39], in Italy [40], in Ireland [41], in Australia [42], for office buildings in Korea [43], in England and Wales [44], for commercial buildings and residential buildings in the United States [33,45,46], and for residential buildings in thirteen European countries (Germany, Greece, Slovenia, Italy, France, Ireland, Belgium, Poland, Austria, Bulgaria, Sweden, Czech Republic, and Denmark) within the TABULA IEE-EU followed by EPISCOPE IEE-EU projects. In the case of reference building models, the users should create or select (e.g. from the above studies) representing a specific building typology and vintage (i.e., constructed during a specific new or old period) in the target reference city.

2.1.3. Step 3: identify and design/size the cooling strategies to be compared

Choosing a cooling strategy for buildings is challenging, especially when the designers are concerned with the impact of their choices on the resistivity against climate change. The framework lists a set of active and passive cooling strategies that are categorized by Ref. [4] as part of (IEA) EBC Annex 80 - Subtask B activities into four main categories (A, B, C, and D) based on their approaches in cooling the people or the indoor environment.

In category A, there are cooling strategies that reduce heat gains to the indoor environment and the occupants. It consists of solar shading and chromogenic glazing technologies, cool envelope materials, green roofs, roof ponds, green facades, ventilated roofs and facades, and thermal mass utilization. In category B, there are cooling strategies that remove sensible heat from indoor environments. It consists of absorption refrigeration (including desiccant cooling), ventilative cooling including Natural Ventilation (NV) and Mechanical Ventilation (MV), adiabatic/evaporative cooling, compression refrigeration, ground source cooling, sky radiative cooling, and high-temperature cooling (including radiant cooling). In category C, there are cooling strategies that enhance personal comfort apart from space cooling such as personal comfort systems. In category D, there are cooling strategies that remove latent heat from indoor environments such as high-performance dehumidification (including desiccant humidification). However, the framework cannot be used for category D due to the lack of relative humidity factor within the performance indicators (Step 4).

The cooling strategy (C_n) selected to be evaluated through the framework can be an individual or any combination of active and

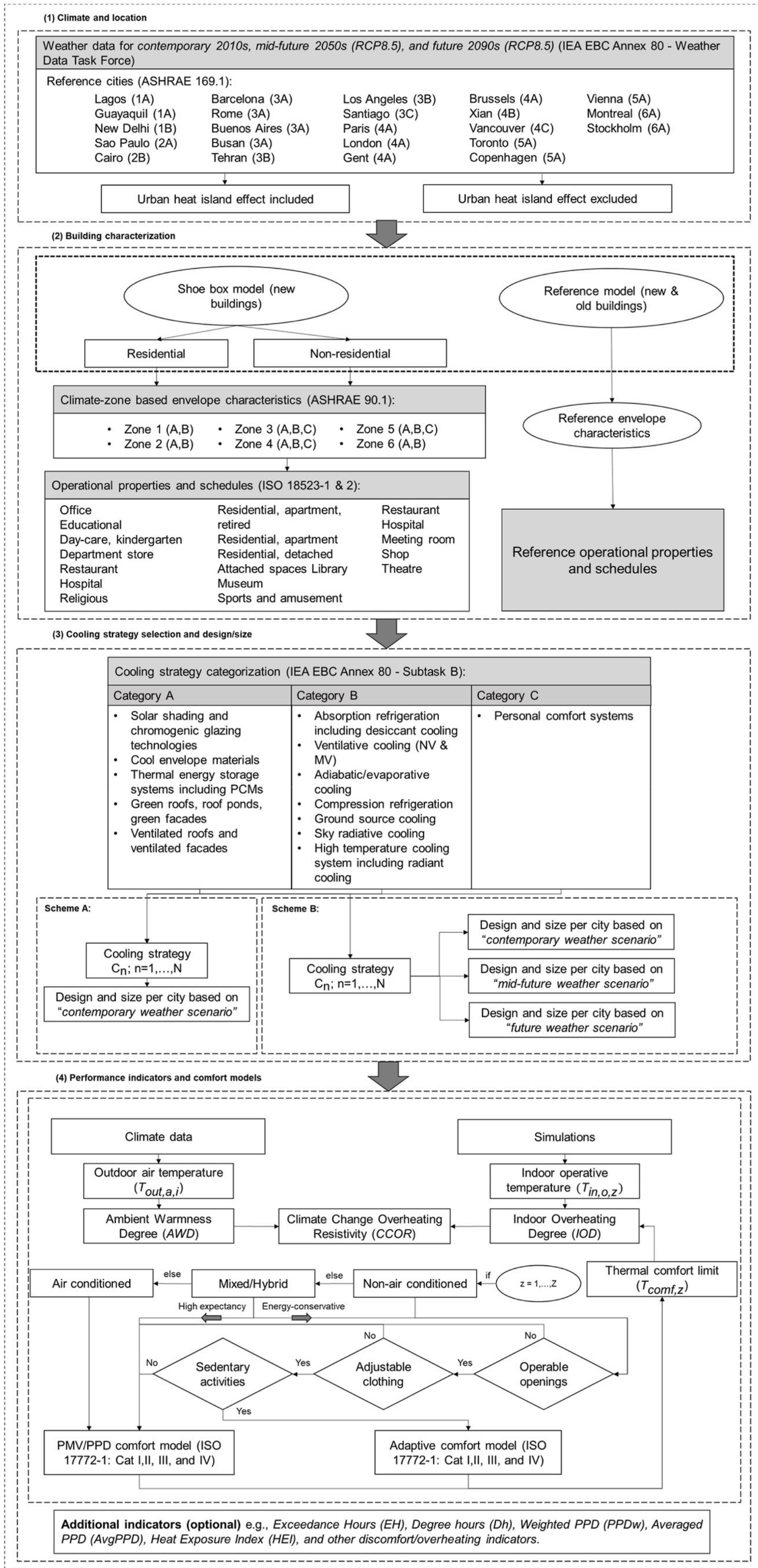

Fig. 2. The generic simulation-based framework to evaluate the climate change overheating resistivity of cooling strategies in buildings.

passive cooling strategies. The applicability of the selected cooling strategy in the target climates must be ensured while incorporating the different locations. Also, most active cooling systems have a life span of 15–25 years, depending on the type of the system and other contributing factors. Therefore, the framework allows for system adjustments through the long-term analysis period. It means that the cooling strategy characteristics can be changed in the mid-future and future scenarios.

Two schemes for cooling strategy adjustment is proposed within the framework. Scheme A: the C_n is designed or sized to provide an acceptable thermal environment in each reference city based on the *"contemporary weather scenario 2010s"* and is kept or replaced with the same for future scenarios, Scheme B: the C_n is adjusted at the end of its life span considering the changes in weather conditions, and thus is designed or sized based on future weather scenarios. In this case, it is possible to predict the thermal performance of the building if the cooling strategy design is not climate change-responsive (scheme A) or is climate change-responsive (scheme B).

Attaining the indoor thermal conditions always within the comfort limits can lead to oversizing the building cooling strategies. For the active strategies, the cooling strategy must be sized to summer design days. While for passive cooling strategies, the design should comply with the strict acceptable deviations criteria by Ref. [47]. It allows weekly 20%, monthly 12%, and yearly 3% deviations from the maximum comfort limits (Section 2.1.4.2) during the occupied hours. For mixed/hybrid mode cooling strategies, it is recommended that the building first operates via non-air conditioned cooling technology and use air conditioning to temper the weather extremes [48].

2.1.4. Step 4: specify performance indicators and comfort models

2.1.4.1. Performance indicators. There are several metrics introduced in the standards and scientific literature to quantify the time-integrated overheating in buildings. The time-integrated overheating indices describe, in a synthetic way, the extend of discomfort over time and predict the uncomfortable phenomena. Those indicators were extensively reviewed by Refs. [49,50]. Following the recommendations of [49], a climate change-sensitive overheating calculation method developed by Ref. [14] is selected that fits the scope of the current paper. Hamdy et al. [49] introduced a methodology based on two principal indicators, namely, Indoor Overheating Degree (IOD) (for the indoor environment) and Ambient Warmness Degree (AWD) (for the outdoor environment).

The *IOD* metric provides a multi-zonal approach in the quantification of intensity and frequency of overheating risks in buildings. Such a multi-zonal approach allows the implementation of zonal thermal comfort models (i.e., PMV/PPD and adaptive models) and requirements (i.e., comfort categories). Therefore, it is possible to assign variable comfort models with regard to the cooling mode and occupant adaptation opportunities in different zones of a building. It also tracks the zonal occupancy profiles and therefore excludes the effect of unoccupied zones in overheating calculations. The *IOD* $[^\circ C]$ is the summation of positive values of the difference between zonal indoor operative temperature $T_{in,o,z}$ and the zonal thermal comfort limit $T_{comf,z}$ (PMV/PPD or adaptive comfort limits) averaged over the sum of the total number of zonal occupied hours $N_{occ}(z)$ $[-]$,

$$IOD \equiv \frac{\sum_{z=1}^{Z}\sum_{i=1}^{N_{occ}(z)}\left[\left(T_{in,o,z,i}-T_{comf,z,i}\right)^{+}\times t_{i,z}\right]}{\sum_{z=1}^{Z}\sum_{i=1}^{N_{occ}(z)}t_{i,z}} \tag{2}$$

where t is the time step (1h), i is occupied hour counter $[-]$, z is building zone counter $[-]$, Z is total building zones $[-]$.

The *AWD* $[^\circ C]$ metric is used to quantify the severity of outdoor thermal conditions by averaging the Cooling Degree hours (*CDh*) calculated for a base temperature (T_b) of 18 °C [14] over the total number of building occupied hours,

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

where $T_{out,a,i}$ is the outdoor dry-bulb air temperature and N is the total number of building occupied hours. Only the positive values of $(T_{out,a,i}-T_b)^{+}$ are taken into account in the summation.

In this paper, the Climate Change Overheating Resistivity (CCORF) metric is introduced to couple the outdoor and indoor environments quantifying the climate change overheating resistivity of cooling strategies in buildings. The *CCOR* $[-]$ shows the rate of change in the *IOD* with an increasing *AWD* due to the impact of climate change. It can be calculated using the linear regression methods assuming linearity between the *IOD* and *AWD*,

$$\frac{1}{CCOR} = \frac{\sum_{Sc=1}^{Sc=M}\left(IOD_{Sc}-\overline{IOD}\right)\times\left(AWD_{Sc}-\overline{AWD}\right)}{\sum_{Sc=1}^{Sc=M}\left(AWD_{Sc}-\overline{AWD}\right)^{2}} \tag{4}$$

where *Sc* is the weather scenario counter, *M* is the total number of weather scenarios, and $\overline{IOD}$ and $\overline{AWD}$ are the average of total *IODs* and *AWDs*. $CCOR > 1$ means that the building is able to suppress the increasing outdoor thermal stress due to climate change, and $CCOR < 1$ means the building is unable to suppress increasing outdoor thermal stress due to climate change.

The framework is also open for the implementation of additional user-specific metrics such as Exceedance Hours (EH), Degree hours (Dh), Weighted PPD (PPDw) [47,51], Averaged PPD (AvgPPD) [52], Heat Exposure Index (HEI) [53], and other discomfort/overheating indicators.

2.1.4.2. Thermal comfort models. The evaluation of overheating risks in buildings requires the determination of thermal comfort criteria. Thermal comfort defined as *"that condition of mind which expresses satisfaction with the thermal environment"* [52] has two main approaches: PMV/PPD (static) and adaptive.

The PMV/PPD comfort model assumes the human body as a passive recipient of its immediate environment [54], thus defining static thermal criteria. It has been shown that the PMV/PPD comfort model works well in air-conditioned spaces [55–57]. The framework suggests the use of the Category-based PMV/PPD model of [36] for the air-conditioned zones (Table 2).

The adaptive comfort model, however, allows a chance for occupant adaptation (e.g. operable openings, activity and clothing adjustments) and provides variable thermal comfort limits based on outdoor running mean temperature T_{rmo} [36],

$$T_{rmo} = (1-\alpha).\left\{T_{ed-1}+\alpha T_{ed-2}+\alpha^{2}T_{ed-3+\dots}\right\} \tag{1}$$

where α is reference value between 0 and 1, T_{ed-i} is daily mean outdoor air temperature for $i-th$ previous day $[^\circ C]$. The adaptive comfort model presents a valuable alternative in an energy-constrained world and is recommended by most standards to non-air conditioned buildings [58,59]. Therefore, the framework suggests the use of the Category-based adaptive comfort model of [36] for non-air conditioned zones (Table 3). In the adaptive comfort model, the occupants should have access to operable openings (e.g. windows, vents, and doors etc.) and

Table 2
PMV/PPD comfort model ranges by ISO 17772–1.

Categories	PPD [%] & PMV [−]
I (high-quality environment)	$PPD\% < 6$, $-0.2 < PMV < +0.2$
II (medium-quality environment)	$PPD\% < 10$, $-0.5 < PMV < +0.5$
III (moderate-quality environment)	$PPD\% < 15$, $-0.7 < PMV < +0.7$
IV (low-quality environment)	$PPD\% < 25$, $-1.0 < PMV < +1.0$

Table 3
Adaptive comfort model ranges by ISO 17772–1.

Categories	Upper limit [°C]	Lower limit [°C]	T_{rmo} range [°C]
I (high-quality environment)	$0.33T_{rmo} + 18.8 + 2$	$0.33T_{rmo} + 18.8 - 3$	10–30
II (medium-quality environment)	$0.33T_{rmo} + 18.8 + 3$	$0.33T_{rmo} + 18.8 - 4$	10–30
III (moderate-quality environment)	$0.33T_{rmo} + 18.8 + 4$	$0.33T_{rmo} + 18.8 - 5$	10–30

mainly sedentary activities (∼ 1.2 *met*). They should also be able to adjust their clothing.

Different categories reflect the expected indoor environmental quality [50]. Category I is recommended for the high level of expectancy that is expected by very sensitive and fragile occupants such as the elderly, very young, and sick. Category II corresponds to the normal level of expectation and should be used for new buildings and renovations. Category III is the acceptable and moderate level of expectation and may be used for existing buildings. Category IV (only for the PMV/PPD model) defines the out of the range values that can be accepted for a limited part of the year.

So far, there is no sufficient Internationally applicable comfort model for mixed/hybrid cooling operation mode [48]. For mixed/hybrid cooling mode zone, the framework suggests the selection of either PMV/PPD model (high levels of expectancy or vulnerability of occupants) or the adaptive comfort model (energy-conservative purposes). The comfort Category (I, II, III, and IV) should be selected depending on building typology, occupant expectation, and climate context.

2.2. Demonstration case

To test the framework, in this section a demonstration case is provided to compare the climate change overheating resistivity of two cooling strategies, 1) Variable Refrigerant Flow (VRF) unit coupled with Dedicated Outdoor Air Supply (DOAS) system, and 2) Variable Air Volume (VAV) system. Those strategies applied on a double-zone office building under the operation of two cooling technologies in six different locations/climates.

2.2.1. Simulation program

In this paper, the DesignBuilder software based on EnergyPlus v8.9 simulation engine is used to conduct the simulations. EnergyPlus is developed by the U.S. Department Of Energy (U.S. DOE) as one of twenty major building energy simulation programs to run the simulations [60]. EnergyPlus contains an integrated heat and mass balance module and a building system module. Zone heating and cooling loads are calculated based on heat balance method recommended by Ref. [61]. The calculated loads are then passed to building HVAC module to calculate heating and cooling system, plant, and electric system response [62]. The HVAC simulation results via EnergyPlus have shown a close agreement with well-known simulation tools such as TRNSYS, ESP-r, and DOE-2.1E [63,64]. The simulations' results are then post-processed using a MATLAB script to calculate the *IOD*, *AWD*, and *CCOR*.

2.2.2. Weather data

To demonstrate the first step of the framework, six cities are selected including New Delhi, Cairo, Buenos Aires, Brussels, Toronto, and Stockholm covering zones 1 to 6 in ASHRAE 169.1 climatic classification [31]. Heating and Cooling Degree Days (HDD10°*C* and CDD18°*C*) averaged over 2016–2020 for the selected cities are summarized in Table 4.

Three weather scenarios are generated for each city. *Scenario 01* is the TMY [65] weather data constructed based on the recorded data in each weather station. It includes the solar radiation values for 1996–2015 and other parameters (i.e. air temperature, dew-point temperature, wind speed, wind direction, and precipitation properties) for 2000–2019. *Scenario 02* and Scenario *03* are future weather projections based on RCP8.5 defined by IPCC Fifth Assessment Report (AR5) [66]. To generate the future weather data, a representative subset (10 out of 35) of CMIP5 models are used for averaging the weather parameters [67]. All weather files are derived from Meteonorm v8 which is a combination of climate database, spatial interpolation tool and a stochastic weather generator, with global radiation data obtained from the Global Energy Balance Archive (GEBA) [28,29].

Table 4
Weather station location and climate characteristics of New Delhi, Cairo, Buenos Aires, Brussels, Toronto, and Stockholm (HDD10°*C* and CDD18°*C* averaged over 2016–2020).

City	Country	Coordinates (weather station)	Climate zone	HDD10°*C*	CDD18°*C*
New Delhi	India	28.6° N, 77.2° E	1B	24	3130
Cairo	Egypt	30.1° N, 31.3° E	2B	5	2327
Buenos Aires	Argentina	34.8° S, 58.5° W	3A	75	1034
Brussels	Belgium	50.9° N, 4.5° E	4A	780	258
Toronto	Canada	43.7° N, 79.4° W	5A	1630	494
Stockholm	Sweden	59.3° N, 18.1° E	6A	1501	171

2.2.3. Case study

The case study is assumed to be a double-zone office building formed by two adjacent identical zones (i.e., office room and administration room). Different comfort categories (i.e., comfort Category II and I) and operational conditions (i.e., occupancy density and heat loads by equipment) are considered for each zone. Each zone corresponds to the BESTEST 630 model [68]. It has east- and west- oriented windows (3 m × 2 m) with permanent solar shading devices (overhang and sidefins). The total building area is 96 m^2. The envelope characteristics are

Table 5
Building envelope characteristics for six cities (ASHRAE 90.1).

		Assembly maximum [W/m^2K]	Insulation Min. R-value [m^2K/W]
New Delhi	Roof	U-0.048	R-20 c.i.*
	Walls	U-0.089	R-13
	Floors	U-0.282	–
	Windows	U-0.45	–
Cairo	Roof	U-0.039	R-25 c.i.
	Walls	U-0.089	R-13
	Floors	U-0.033	R-30
	Windows	U-0.36	–
Buenos Aires	Roof	U-0.039	R-25 c.i.
	Walls	U-0.089	R-13
	Floors	U-0.033	R-30
	Windows	U-0.32	–
Brussels	Roof	U-0.029	R-35 c.i.
	Walls	U-0.058	R-13.0 + R-7.5 c.i.
	Floors	U-0.030	R-38.0
	Windows	U-0.32	–
Toronto	Roof	U-0.029	R-35 c.i.
	Walls	U-0.046	R-13.0 + R-12.5 c.i.
	Floors	U-0.030	R-38.0
	Windows	U-0.29	–
Stockholm	Roof	U-0.029	R-35 c.i.
	Walls	U-0.046	R-13.0 + R-12.5 c.i.
	Floors	U-0.024	R-38.0+ R-7.5 c.i.
	Windows	U-0.29	–

● Continuous insulation.

defined per city (climate zone) based on [33] and are summarized in Table 5. The case study is illustrated in Fig. 3.

The occupancy densities of 0.1 $person/m^2$ and 0.025 $person/\ m^2$ are set for the office room and the administration room. Heat gains by the lighting and appliances of 12 W/m^2 is considered for the office room. Heat gains by the lighting and appliances of 12 W/m^2 and 4 $W/\ m^2$ are assigned for the administration room. It is also assumed that the occupants have the generic winter 1 clo and summer 0.5 clo clothing, and metabolic rate of 1.2 met (sedentary activity). All the information regarding the lighting, equipment, and occupancy schedules can be found in Ref. [34].

2.2.4. Cooling strategies

2.2.4.1. VRF + DOAS system. The first cooling strategy (C01) includes the Variable Refrigerant Flow (VRF) air-conditioning unit coupled with a Dedicated Outdoor Air Supply (DOAS). The VRF system uses an electric expansion valve and a variable-speed compressor to vary the refrigerant flow rate to each terminal unit to meet the zonal thermal loads. There are two types of VRF systems: Heat Pump (HP) and Heat Recovery (HR). In VRF-HP, all zones must be either in heating or cooling mode. In VRF-HR, the system is able to operate in the heating and cooling modes simultaneously. This paper applies VRF-HR system by default performance curves in the EnergyPlus such as the polynomial performance curve (VRFCoolCapFTBoundary) for the cooling capacity ratio boundary curve from the manufacturer's data [69]. The VRF-HR is implemented in v8.6. EnergyPlus and validated by Ref. [70]. The default input values are mostly used for the VRF-HR system as described in Table 6 [62,70]. However, some input values are modified in this study, including the increase of maximum outdoor air temperature in cooling only mode to 50°C to avoid the system disruption in the hot climates of New Delhi and Cairo. The Coefficient Of Performance (COP) values of 3.23 and 3.2 are set for cooling and heating, respectively, as minimum efficiency requirements [33,62]. The VRF-HR unit is operated by load priority master thermostat control type. It means that the total zone load is used to vary the zonal operating mode as being either heating or cooling. A Constant Air Volume (CAV) Air Handling Unit (AHU) is coupled to the VRF-HR system as DOAS to handle the latent loads and provide ventilation rates as per [36,71]. The input values for DOAS system are also presented in Table 6.

2.2.4.2. VAV system. The second cooling strategy (C02) is Variable Air Volume (VAV) system that consists of an AHU and Air Distribution Units (ADUs). The supply air is heated or cooled with heating and cooling coils centrally in AHU and the thermal capacity is controlled by varying the supply air volume via the dampers installed in the zonal ADUs. At full cooling capacity, the damper is fully open and the fan operates at maximum speed to supply the maximum air flow rate. With decreasing the cooling demand, the damper closes until it reaches the zone minimum ventilation air requirements as per [36]. In this study, the default AHU is used for the VAV system which contains a variable speed fans. Such AHU supplies variable airflow at a constant temperature having additional precision in temperature control [72]. The VAV models in EnergyPlus have been validated by Ref. [73]. In this paper, the VAV system is modeled using mostly the default input values or the values derived from Refs. [62,74,75] as listed in Table 6.

For both C01 and C02, all thermal capacities and design flow rates are auto-sized to design days by EnergyPlus based on the reference cities' external design conditions and the building configuration. Assuming a non climate change-responsive design (scheme A), the cooling strategies are not re-sized for future climates. The C01 and C02 are schematically shown in Fig. 4. The two technologies are among widely available (TRL∼9) and applicable cooling technologies for the selected climate zones [4,62].

2.2.5. Zonal comfort criteria

Two air conditioned cooling strategies are selected for the case study. Therefore, the PMV/PPD comfort model is considered for both zones [36]. A Distinct comfort categories for the office room and the administration room are considered. The comfort Category II is set for the office room due to the normal level of expectation that should be used for the new buildings [76]. It corresponds to a fixed maximum indoor operative temperature limit of 26°C. The minimum ventilation rate requirement for Category II is 1.4 l/s.m^2. Assuming a high level of expectation for the occupants in the administration room, the comfort Category I is selected for this zone. It corresponds to a fixed maximum indoor operative temperature limit of 25.5°C. The minimum ventilation rate requirement for Category I is 2 l/s.m^2. The cooling and heating

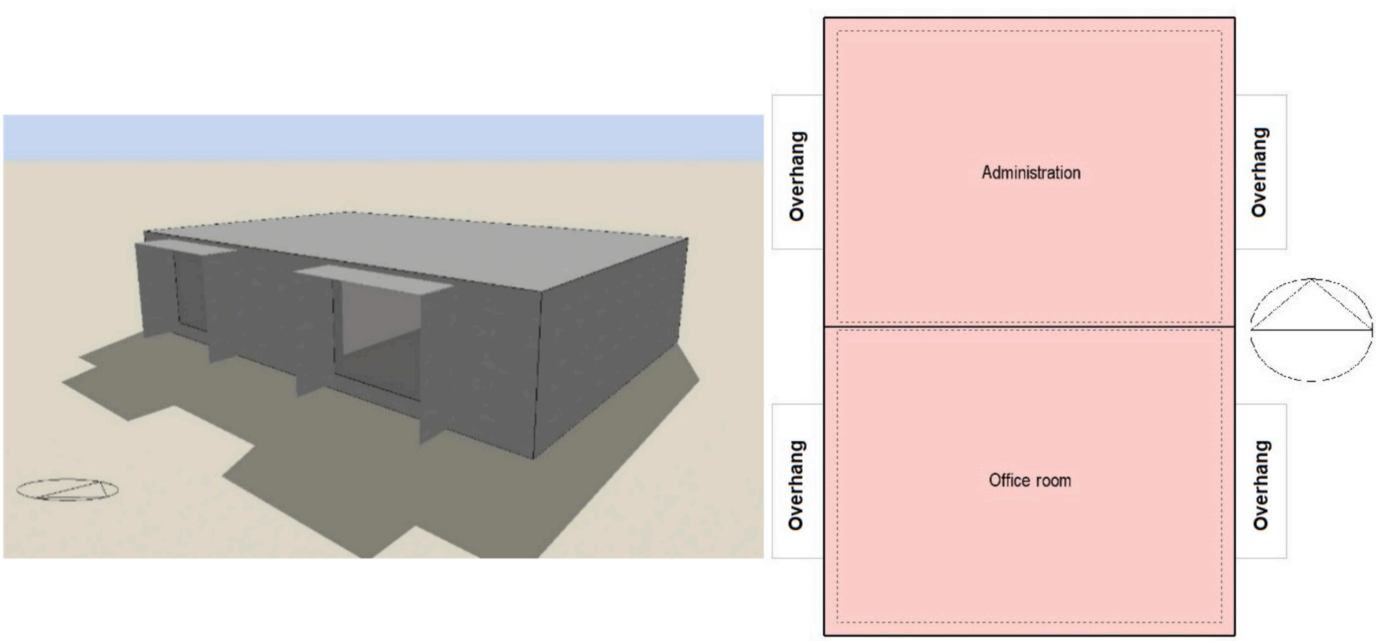

Fig. 3. The case study 3D view (left) and floor plan (right).

Table 6
The HVAC model inputs for C01 (VRF + DOAS) and C02 (VAV).

	C01 (VRF + DOAS)	C02 (VAV)
Set-points temperatures (occupied hours)	24.5°*C* for cooling/22°*C* for heating	24.5°*C* for cooling/22°*C* for heating
Set-back temperatures (unoccupied hours)	26.6°*C* for cooling/ 15.5°*C* for heating	26.6°*C* for cooling/15.5°*C* for heating
Minimum fresh air	1.4 l/s.m^2 (office room)/ 2 l/s.m^2 (Administration)	1.4 l/s.m^2 (office room)/2 l/ s.m^2 (Administration)
Fuel type	Electricity	Electricity (cooling)/Gas (heating)
Defrost strategy/ capacity	Resistive/Auto-sized	N/A
Condenser type	Air-cooled	Air-cooled
Heating	VRF outdoor unit	Gas furnace inside the packaged air conditioning unit
Cooling	VRF outdoor unit	Air-cooled chiller inside the packaged air conditioning unit
Total cooling capacity	Auto-sized to design days per city	Auto-sized to design days per city
Cooling COP	3.23	3.39
Total heating capacity	Auto-sized to design days per city	Auto-sized to design days per city
Heating COP	3.20	0.8 (gas burner efficiency)
Minimum outdoor temperature in cooling mode	−6°*C*	N/A
Maximum outdoor temperature in cooling mode	50°*C*	N/A
Minimum outdoor temperature in heating mode	−20°*C*	N/A
Maximum outdoor temperature in heating mode	40°*C*	N/A
Indoor unit supply air flow rates	Auto-sized to design days per city	Auto-sized to design days per city
Indoor fan efficiency/ type/pressure rise	0.7/constant volume/100 pa	N/A
Indoor cooling coil	VRF DX cooling coil	N/A
Indoor heating coil	VRF DX heating coil	N/A
AHU type	CAV	VAV
AHU supply air flow rates	Auto-sized to design days per city	Auto-sized to design days per city
AHU fan efficiency/ type/pressure rise	0.7/constant volume/600 pa	0.7/variable volume/600 pa
Supply air set-point manager	Preheat coil: Always 5°*C*	Air loop cooling: Always 14°*C*
AHU cooling coil	N/A	Water cooling coil
AHU heating coil	Electric heating coil	Water heating coil

set-point temperatures of 24.5°*C* and 22°*C* are set, respectively [36].

3. Results

Following the instructions given by the framework (see Fig. 2), this section is allocated to show the results of totally 36 simulation cases which are the combination of two cooling strategies (C01 and C02) and three weather scenarios (2010s, 2050s, and 2090s) in six locations (New Delhi, Cairo, Buenos Aires, Brussels, Toronto, and Stockholm). The simulations are run for annual period to cover the overheating incidents in winter and intermediate seasons as well. It should be mentioned that the heating system performance and cold discomfort is not in the scope of the current study.

3.1. Outdoor thermal conditions

The annual distribution of hourly outdoor air temperature for Scenario 01, Scenario 02, and Scenario 03 are illustrated in Fig. 5. The minimum, maximum, and average outdoor air temperature, Direct Normal Irradiance (DNI), Diffuse Horizontal Irradiance (DHI), *HDD10°C*, and *CDD18°C* over the annual period as well as *AWD* are summarized in Table 7. The increase in average and maximum outdoor air temperature is about 2.97–5.97°*C* and 3.5–6.5°*C* for the six reference cities by 2090s. In the cooling-dominated climates of New Delhi and Cairo, the AWD increases by 23% and 30% in the 2090s. It corresponds to CDD18°*C* variation of +42% and +62%, respectively, and HDD10°*C* tends to be zero in the future (i.e., 2050s and 2090s). New Delhi has the highest average and maximum outdoor air temperature of 29.15°*C* and 49.9°*C*, and has the highest AWD of 14.87°*C* in the 2090s. In the heating-dominated climates of Toronto and Brussels, both are expected to shift to cooling-dominated zones by increasing 248% and 224% in CDD18 °C and a decrease of 59% and 56% in HDD10°*C* by 2090s, respectively. In Toronto, higher maximum outdoor air temperature of around 2–4.1°*C* and higher CDD18°*C* of around 208–643 are resulted compared to Brussels. Therefore, Toronto shows higher AWD by 1.32°*C* in the 2010s, 2.7°*C* in the 2050s, and 3.89°*C* in the 2090s than in Brussels. Toronto has the highest increase in average outdoor air temperature by 5.97°*C*, maximum outdoor air temperature by 6.5°*C*, and AWD by 4.06°*C* in the 2090s. In Stockholm, although the CDD18°*C* increases by 313% in the 2090s, it still remains as a heating-dominated city with HDD10°*C* of 824 and CDD18°*C* of 413. Stockholm has the lowest average and maximum outdoor air temperature of 7.53°*C* and 30.20°*C* and therefore has the lowest AWD of 3.84°*C* in the 2010s.

3.2. Indoor operative temperature and exceedance hours (EH)

Fig. 6 shows the distribution of annual indoor operative temperature and Exceedance Hours (EH) (additional indicators) over the cooling set-point of 24.5°*C* in the office room and the administration room. The maximum indoor operative temperature fixed thresholds of 25.5°*C* of Category I (administration room) and 26°*C* of Category II (office room) are illustrated based on the static comfort model of ISO 17772–1. Table 8 summarizes the *IOD*, maximum indoor operative temperature, and *EH* for each scenario in six cities under the operation of C01 and C02.

In this study, the highest maximum indoor operative temperature of 34.98°*C* and the highest increase in maximum indoor operative temperature of 6.91°*C* are resulted for Toronto by 2090s. The highest *EH* of 625 and the highest increase in *EH* of 576 are also calculated for Toronto during the same period. It is due to the fact that, first, even though Toronto is classified as cool-humid climate (5A), more extreme up to 40.60°*C* and frequent hot weather conditions are expected by 2090s (similar to Buenos Aires) (see Table 7). Second, in line with the findings of [14,77], higher insulation levels in Toronto based on ASHRAE 90.1 requirements exacerbate the intensity and frequency of high indoor temperatures.

The ranges of the maximum indoor operative temperature difference between the office room and the administration room are 0.96–1.98°*C* for C01 and 0.63–2.07°*C* for C02. The ranges of the difference between the *EH* in the office room and the administration room are 16–143 for C01 and 19–131 for C02. The office room experiences higher maximum indoor operative temperatures and more overheating hours than the administration room. It is normal because of the higher internal gains by the office equipment and the higher number of occupants. However, the C01 shows more consistent zonal temperature control and therefore lower zonal temperature gradients [73]. The difference in the number of exceedance hours among the office room and administration room increases with global warming up to 346% (in Cairo). As a result, the office room is expected to have a relatively higher increase in the frequency of high indoor temperatures than the administration room due to climate change.

The C01 shows a lower maximum indoor operative temperature by 0.5–2.74°*C* in the office room (except for New Delhi) and 0.5–2.67°*C* in the administration room than C02. It shows that the C01 performs better

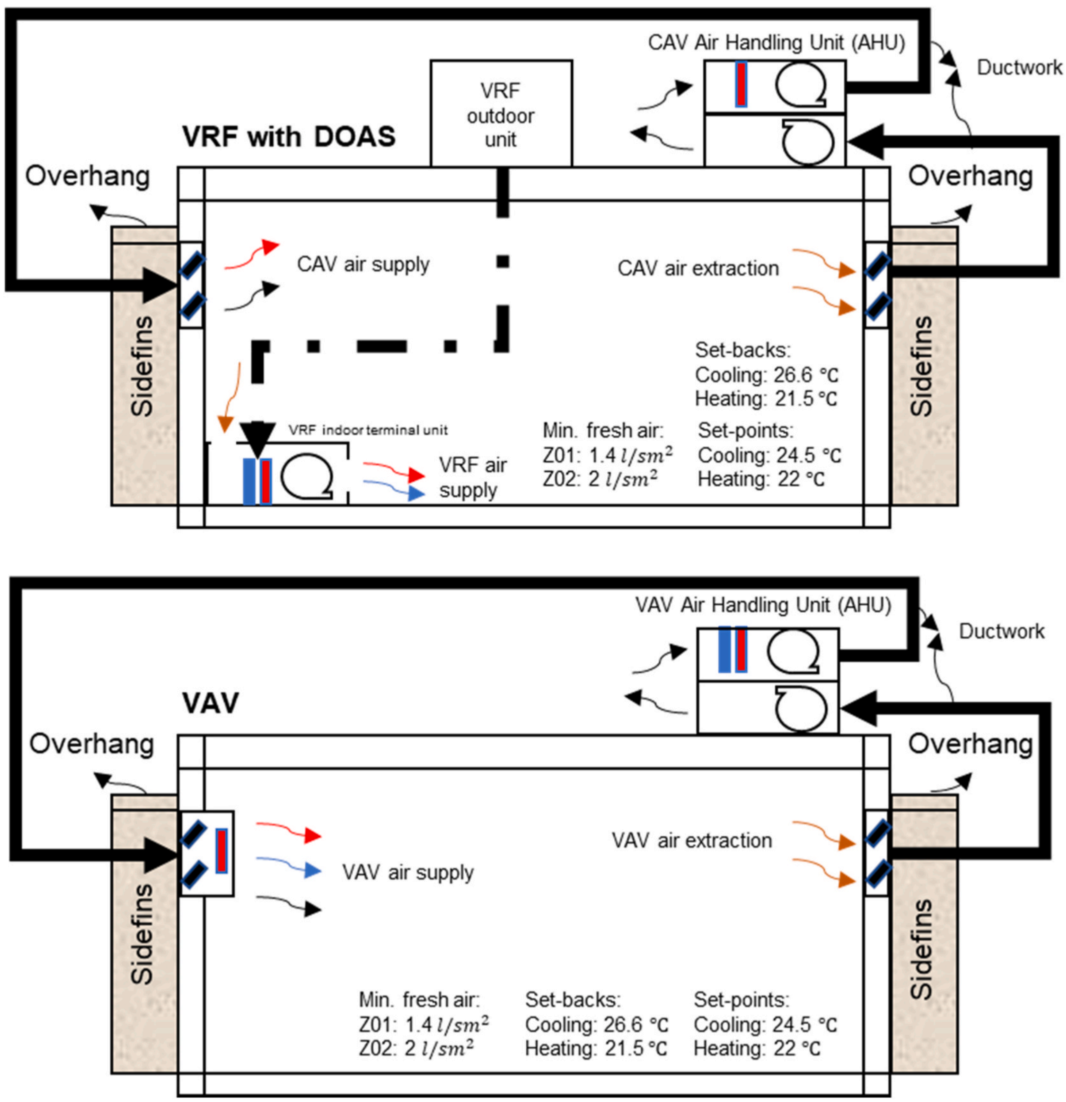

Fig. 4. Graphical representation of C01 (VRF with DOAS) (upper) and C02 (VAV) (lower).

in dampening the maximum indoor operative temperatures. The C01 results in higher *EH* between 1 and 56 (in office room) and 3–82 (in administration room) in relatively warmer climates of New Delhi, Cairo, and Buenos aires. However, the C02 shows lower *EH* between 2 and 57 (in office room) and 2–122 (in administration room) in Brussels, Toronto, and Stockholm. Both the above differences regarding the maximum indoor operative temperature and *EH* between the C01 and C02 increase with global warming. Overall, C01 performs better in reducing the maximum indoor operative temperatures in all climates and *EH* in Brussels, Toronto and Stockholm. At the same time, C02 has better performance in reducing the *EH* in New Delhi, Cairo, and Buenos Aires.

3.3. Overheating risk and climate change overheating resistivity

This section presents the results of the Indoor Overheating Risk (IOD) and Climate Change Overheating Resistivity (CCOR) of the selected cooling strategies. The *IOD* represents the intensity and frequency of overheating in buildings considering zonal comfort criteria. The *CCOR* quantifies the increase in the *IOD* corresponding to an increase in the *AWD*. Fig. 7 shows the linear regression models representing *IOD* as *AWD*. It shows a direct correlation between *IOD* and *AWD*; that is, when the *AWD* increases, overheating risk increases as well. The climate scenarios, namely 2010s, 2050s, and 2090s are represented by their *AWD* in each city.

Fig. 7 shows that the overheating conditions are becoming more intense and frequent with the increase of *AWD*. Since the C01 and C02 are sized to design days based on the *"Contemporary weather scenario 2010s"*, very low *IOD* values between 0.005 and 0.012 are calculated for this scenario.

In this study, the highest value of *IOD* 0.46°*C* is calculated for Toronto by 2090s associated with the maximum indoor operative temperature of 34.98°*C* and the *EH* of 589 under the operation of C02. It means that the current building configuration (i.e., the envelope complying with ASHRAE 90.1 standard and C02 as the cooling strategy) in Toronto is expected to have the highest risk of overheating in the future. In all cases, with the continuation of global warming the difference of *IOD* between C01 and C02 increases, especially in Brussels, Toronto, and Buenos Aires where higher differences up to 0.182 are observed. It shows that C02 is more affected by climate change than C01.

The *CCOR* values vary between 9.24 and 37.46 depending on the city and cooling strategy. However, it is >1 for all cases. It shows that the cooling strategies (C01 and C02) selected and sized for the current weather conditions will be able to maintain an acceptable thermal environment and suppress global warming [14]. It is normal since the case study is equipped with active cooling systems, making it more

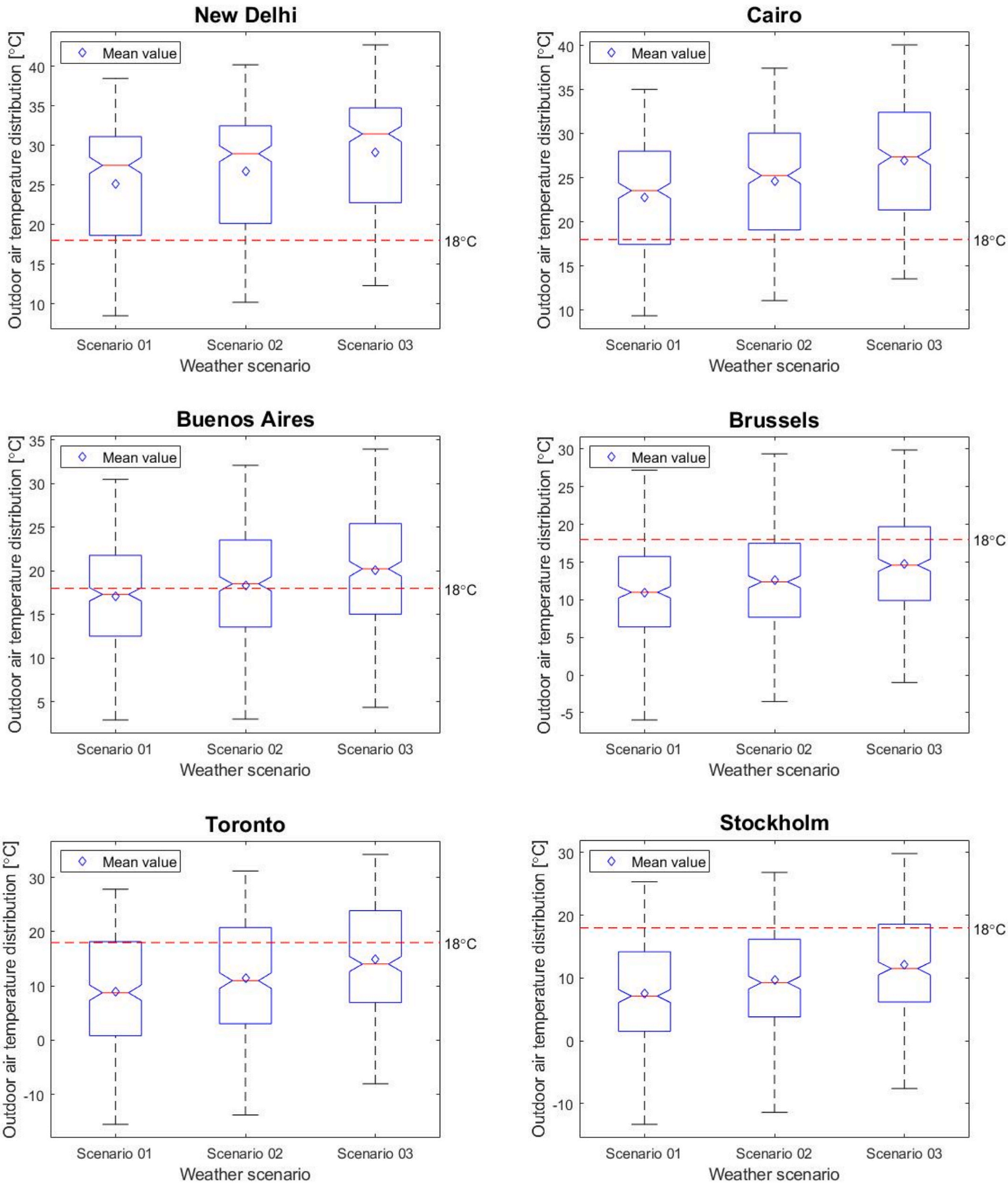

Fig. 5. Distribution of annual outdoor air temperature for Scenario 01 (2010s), Scenario 02 (2050s), and Scenario 03 (2090s).

resistant to climate change impacts but with different levels of success. The case study with C02 in Toronto has the lowest *CCOR* of 9.24 representing the case that affected most by climate change. On the other hand, the case study with C01 in Brussels has the highest *CCOR* of 37.46 and therefore is the most resistant case in this paper. In the analysis, the C01 always has higher *CCOR* values than C02, showing its superior resistance toward climate change. Especially in relatively cold climates of Brussels, Toronto, and Stockholm, the differences between the *CCOR* values among C01 and C02 are 19.16, 6.04, and 14.41, respectively. It was shown that most design variants such as internal heat gain, building

Table 7
Summary of average, minimum, and maximum outdoor air temperature, Direct Normal Irradiance (DNI), Diffuse Horizontal Irradiance (DHI), HDD10°C, CDD18°C, and AWD for three scenarios in all cities.

		Scenario 01	Scenario 02	Scenario 03
New Delhi	$T_{out.ave}$ [°C]	25.11	26.65	29.15
	$T_{out.max}$ [°C]	44.90	46.80	49.9
	$T_{out.min}$ [°C]	3.70	5.30	7.50
	DNI [W/m^2]	166.93	147.47	142.28
	DHI [W/m^2]	99.08	100.75	102.71
	AWD [°C]	12.12	13.05	14.87
	HDD10°C	2.51	0	0
	CDD18°C	2911	3355	4149
Cairo	$T_{out.ave}$ [°C]	22.80	24.63	26.99
	$T_{out.max}$ [°C]	41.80	44	46.9
	$T_{out.min}$ [°C]	5.60	7.40	9.30
	DNI [W/m^2]	185.36	176.62	179.95
	DHI [W/m^2]	94.24	96.88	95.69
	AWD [°C]	9.39	10.59	12.16
	HDD10°C	1	0	0
	CDD18°C	2052	2581	3325
Buenos Aires	$T_{out.ave}$ [°C]	17.11	18.33	20.08
	$T_{out.max}$ [°C]	37.50	39.10	41
	$T_{out.min}$ [°C]	−2.70	−1.70	−0.50
	DNI [W/m^2]	198.75	189.61	187.88
	DHI [W/m^2]	77.53	80.43	82.12
	AWD [°C]	6.49	7.40	8.42
	HDD10°C	135	109	55
	CDD18°C	777	1048	1446
Brussels	$T_{out.ave}$ [°C]	10.93	12.58	14.70
	$T_{out.max}$ [°C]	32.10	33.90	36.50
	$T_{out.min}$ [°C]	−7	−5.70	−3.40
	DNI [W/m^2]	101.95	115.44	117.58
	DHI [W/m^2]	65.94	65.03	66.47
	AWD [°C]	3.64	4.59	5.13
	HDD10°C	804	572	325
	CDD18°C	134	264	467
Toronto	$T_{out.ave}$ [°C]	8.99	11.40	14.96
	$T_{out.max}$ [°C]	34.10	36.60	40.60
	$T_{out.min}$ [°C]	−18.90	−16.40	−11.10
	DNI [W/m^2]	138.58	143.01	141.83
	DHI [W/m^2]	71.80	72.68	73.30
	AWD [°C]	4.96	7.29	9.02
	HDD10°C	1794	1405	782
	CDD18°C	342	663	1110
Stockholm	$T_{out.ave}$ [°C]	7.53	9.63	12.20
	$T_{out.max}$ [°C]	30.20	32.10	34.60
	$T_{out.min}$ [°C]	−15.70	−13.30	−10.60
	DNI [W/m^2]	130.22	133.42	138.46
	DHI [W/m^2]	53.30	54	52.31
	AWD [°C]	3.84	4.53	5.96
	HDD10°C	1742	1280	824
	CDD18°C	100	189	413

archetype, construction period, orientation, solar shading option are not key aspects to describe the resistivity to climate change [14]. However, the study shows that the selection of the active cooling system has a sound effect in determining the comfort conditions in buildings in the future. The relative potential to adapt to climate change metric *P* is quantified via the difference between the *IOD* resulted by C01 and C02 in the 2090s $(IOD_{C01,2090s} - IOD_{C02,2090s})^+$ over the Max $[IOD_{C01,2090s}, IOD_{C02,2090s}]$ [14]. By calculating the *P,* the C02 shows to have 13%, 29%, 8%, 51%, 39%, and 49% more potential to adapt compared to C01 in New Delhi, Cairo, Buenos Aires, Brussels, Toronto, and Stockholm, respectively.

4. Discussion

4.1. Findings and recommendations

More intense and frequent overheating events are expected with the continuation of global warming. Comparative building performance simulations seek to evaluate different strategies or measures in buildings concerning climate change with identical boundary conditions. Therefore, a generic simulation-based framework is developed that allows performing a relative comparison of individual or multiple cooling technologies in the frame of the (IEA) EBC Annex 80 – "Resilient cooling of buildings" project. The framework considers all function types (i.e., residential and non-residential), comfort categories (i.e., I, II, III, and IV), and cooling strategies (i.e., conditioned air, non-conditioned air, and mixed/hybrid mode). And, the selection of weather data and comfort criteria are based on unique approaches for climate change overheating resistivity evaluations in buildings.

Through the efforts to assign the building models in the framework, it was found that while in the North America especially in the United States, the creation of benchmark building models has consistently evolved [78–80], it is a recently emerging concept in other regions [39, 40,43,81]. For example, after introducing the Energy Performance of Building Directive (EPBD) in Europe in 2003 which was implemented after in 2008, the projects such as the TABULA and the EPISCOPE started to create a central and structured depository of building stocks. However, there is still a substantial knowledge gap in the reliable benchmark models for different building typologies, vintages, and functions. Therefore, the framework is open to the implementation of the shoe box models for basic early design decisions and reference models for more sophisticated analyses.

The framework uses *IOD*, *AWD*, and *CCOR* as principal indicators to calculate the indoor overheating risk, the severity of the outdoor thermal environment, and climate change overheating resistivity of cooling strategies in buildings. The *IOD* metric allows a multi-zonal approach representing the real situations in buildings including zones with variable thermal comfort models (i.e., PMV/PPD and adaptive models) and requirements (e.g., comfort categories) tracing the occupied hours in each zone of the building (Section 2.1.4.2). Therefore, the framework is flexible and allows for personalization to evaluate cooling strategies under real and artificial conditions at zone levels. The *AWD* is a useful metric to quantify the severity of outdoor thermal conditions. However, it does not take into account the effect of solar radiation. As a result, it underestimates the severity of the outdoor thermal environment during the days with high solar radiation and low air temperatures.

The proposed methodology is tested by comparing C01 (VRF unit with DOAS) and C02 (VAV system) cooling strategies on a double-zone (i.e., office room and administration room) shoe box model in New Delhi, Cairo, Buenos Aires, Brussels, Toronto, and Stockholm (Section 2.2). Both systems are able to suppress the outdoor warming conditions by the end of this century. The C01 showed reduced maximum indoor operative temperature as well as *EH* compared to C02 leading to lower overheating risks (Table 8) and higher climate change overheating resistivity (Fig. 7). It shows that the C02 system is more prone to outdoor temperature increase and thus has less potential to overcome the climate change impacts. Although the VAV system cooling capacity can be increased by an increase in the amount of inlet air or by decreasing the inlet air temperature, it can lead to droughts and cold discomfort due to excessively high air velocities associated with low air temperatures [82]. The superior performance of C01 over C02 is more evident in Brussels, Toronto, and Stockholm. However, it should be mentioned that in this paper, a maximum temperature of 50°C is set as the temperature above the VRF system does not operate. Such assumption ensures the operation of the VRF system throughout the year in the selected reference cities

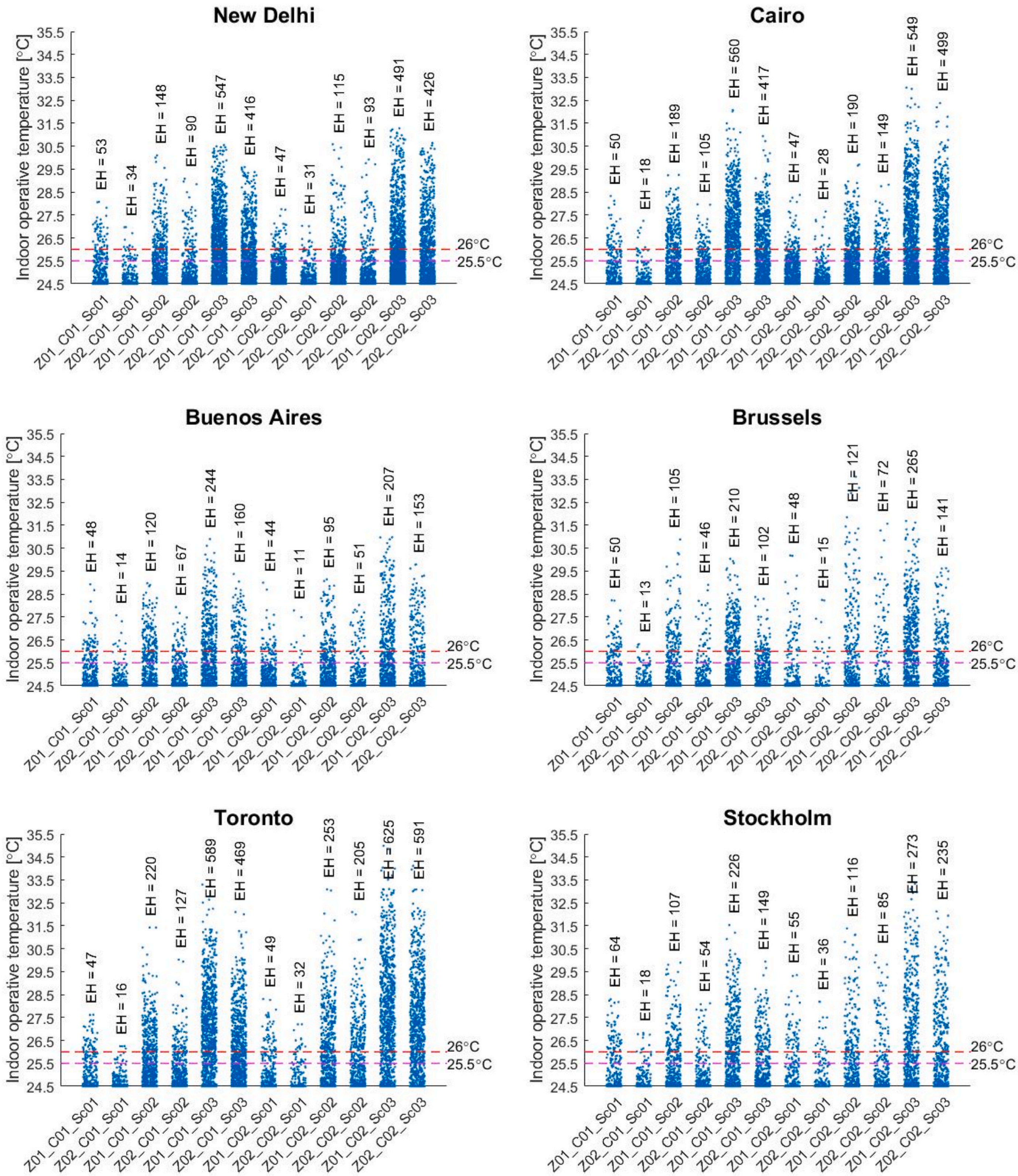

Fig. 6. Annual distribution of indoor operative temperature over cooling set-point of 24.5°*C* in office room and administration room for C01 and C02 during the occupied hours. The maximum indoor operative temperature threshold of 25.5°*C* is assigned for comfort Category I (administration room) and 26°*C* for Category II (office room). Exceedance Hours (EH) are shown for each zone per cooling strategy per scenario.

considering the weather data used in this study. Also, a previous study by Ref. [73] showed the energy-saving potential of the VRF system between 14 and 39% over the VAV system in all climatic zones across the U.S. Consequently, the VRF unit with DOAS seems to offer better performance in comparison to the VAV system in both energy-saving and thermal comfort aspects.

To summarize the significant recommendations, the list below is provided:

Table 8
Summary of IOD, exceedance hours, and maximum indoor operative temperature during occupied hours in the office room and the administration room.

			C01		C02	
			Office room (Z01)	Administration room (Z02)	Office room (Z01)	Administration room (Z02)
New Delhi	Scenario 01	IOD [°*C*]	0.0075		0.0058	
		EH [−] ($T_{i,max}$) [°*C*]	47 (28.07)	31 (26.97)	53 (27.75)	34 (27.02)
	Scenario 02	IOD [°*C*]	0.0362		0.0361	
		EH [−] ($T_{i,max}$) [°*C*]	115 (30.09)	93 (29.07)	148 (30.58)	90 (29.91)
	Scenario 03	IOD [°*C*]	0.1891		0.2162	
		EH [−] ($T_{i,max}$) [°*C*]	491 (30.54)	426 (29.58)	547 (31.27)	416 (30.64)
Cairo	Scenario 01	IOD [°*C*]	0.0066		0.0075	
		EH [−] ($T_{i,max}$) [°*C*]	50 (28.32)	18 (27.24)	47 (28.37)	28 (27.65)
	Scenario 02	IOD [°*C*]	0.0357		0.0447	
		EH [−] ($T_{i,max}$) [°*C*]	189 (29.24)	105 (27.96)	190 (29.69)	149 (28.81)
	Scenario 03	IOD [°*C*]	0.2087		0.2946	
		EH [−] ($T_{i,max}$) [°*C*]	560 (32.07)	417 (30.93)	549 (33.05)	499 (32.37)
Buenos Aires	Scenario 01	IOD [°*C*]	0.0063		0.0050	
		EH [−] ($T_{i,max}$) [°*C*]	44 (28.92)	11 (27.57)	48 (28.99)	14 (27.78)
	Scenario 02	IOD [°*C*]	0.0235		0.0229	
		EH [−] ($T_{i,max}$) [°*C*]	95 (28.97)	51 (27.93)	120 (29.13)	67 (28.02)
	Scenario 03	IOD [°*C*]	0.0792		0.0862	
		EH [−] ($T_{i,max}$) [°*C*]	207 (30.89)	153 (29.37)	244 (30.97)	160 (29.78)
Brussels	Scenario 01	IOD [°*C*]	0.0055		0.0107	
		EH [−] ($T_{i,max}$) [°*C*]	48 (28.22)	15 (26.31)	50 (30.18)	13 (28.24)
	Scenario 02	IOD [°*C*]	0.0261		0.0544	
		EH [−] ($T_{i,max}$) [°*C*]	121 (30.87)	72 (28.89)	105 (33.61)	46 (31.56)
	Scenario 03	IOD [°*C*]	0.0461		0.0935	
		EH [−] ($T_{i,max}$) [°*C*]	265 (30.03)	141 (28.37)	210 (31.68)	102 (29.61)
Toronto	Scenario 01	IOD [°*C*]	0.0046		0.0081	
		EH [−] ($T_{i,max}$) [°*C*]	49 (27.62)	32 (26.25)	47 (28.30)	16 (27.20)
	Scenario 02	IOD [°*C*]	0.0558		0.1087	
		EH [−] ($T_{i,max}$) [°*C*]	253 (31.42)	205 (30.02)	220 (33.08)	127 (32.09)
	Scenario 03	IOD [°*C*]	0.2810		0.4636	
		EH [−] ($T_{i,max}$) [°*C*]	625 (33.29)	591 (32.09)	589 (34.98)	469 (34.11)
Stockholm	Scenario 01	IOD [°*C*]	0.0088		0.0122	
		EH [−] ($T_{i,max}$) [°*C*]	55 (28.29)	36 (26.82)	64 (29.34)	18 (28.19)
	Scenario 02	IOD [°*C*]	0.0259		0.0461	
		EH [−] ($T_{i,max}$) [°*C*]	116 (29.88)	85 (28.11)	107 (31.38)	54 (30.21)
	Scenario 03	IOD [°*C*]	0.0819		0.1602	
		EH [−] ($T_{i,max}$) [°*C*]	273 (31.53)	235 (29.93)	226 (33.33)	149 (32.12)

- It is recommended to use the proposed framework to assess the indoor overheating risks in buildings and conduct comparative studies on the climate change overheating resistivity of different cooling strategies in buildings.
- It is also recommended to implement *IOD*, *AWD*, and *CCOR* as three principal indicators in climate change sensitive overheating evaluations. Designers and decision-makers can use these indicators for a multi-zonal comparison of building designs and their cooling strategies in the context of climate change.
- It is recommended to include additional weather files with intermediate periods (e.g., 2030s, 2040s, 2060s, etc.), which contributes to the CCOR's accuracy as the inverse slope of the linear regression line between the *IOD* and the *AWD*.
- It is recommended to further explore the potential of the VRF unit coupled with the DOAS as a promising strategy in enhancing the resistivity of buildings against overheating impacts of climate change.

4.2. Strength and limitations

There is an ongoing concern regarding the overheating risks that will be encountered more in future climates. There is no common guidance so far for evaluating the climate change overheating resistivity of cooling strategies to overcome the potential overheating issues in buildings. For this aim, the paper develops a comprehensive framework that can be followed step by step to compare the climate change overheating resistivity of a wide range of cooling strategies in buildings. The first strength of the study relies on the strong intellectual support via long-lasting brainstorming sessions by the members of (IEA) EBC Annex 80 – "Resilient cooling of buildings" project. The study provides a well-established framework based on universally applicable standards and state-of-the-art methods. This paper also provides the basis to compare different cooling strategies worldwide. The study's strength also relates to the implementation of a multi-zonal and climate change sensitive approach in the quantification of overheating risk as well as quantification of climate change overheating resistivity of cooling strategies. The proposed framework is also tested by comparing the C01 (VRF with DOAS) and C02 (VAV) cooling strategies in six reference cities. Despite the numerous previous studies on both above systems [83–87], there is no comparative study on their impact on the climate change overheating resistivity with detailed information on the system design and sizing.

However, the study has some limitations. First, this paper considers a shoe box model as the case study due to the restrictions in obtaining region-specific reference models. Second, the focus was on the thermal

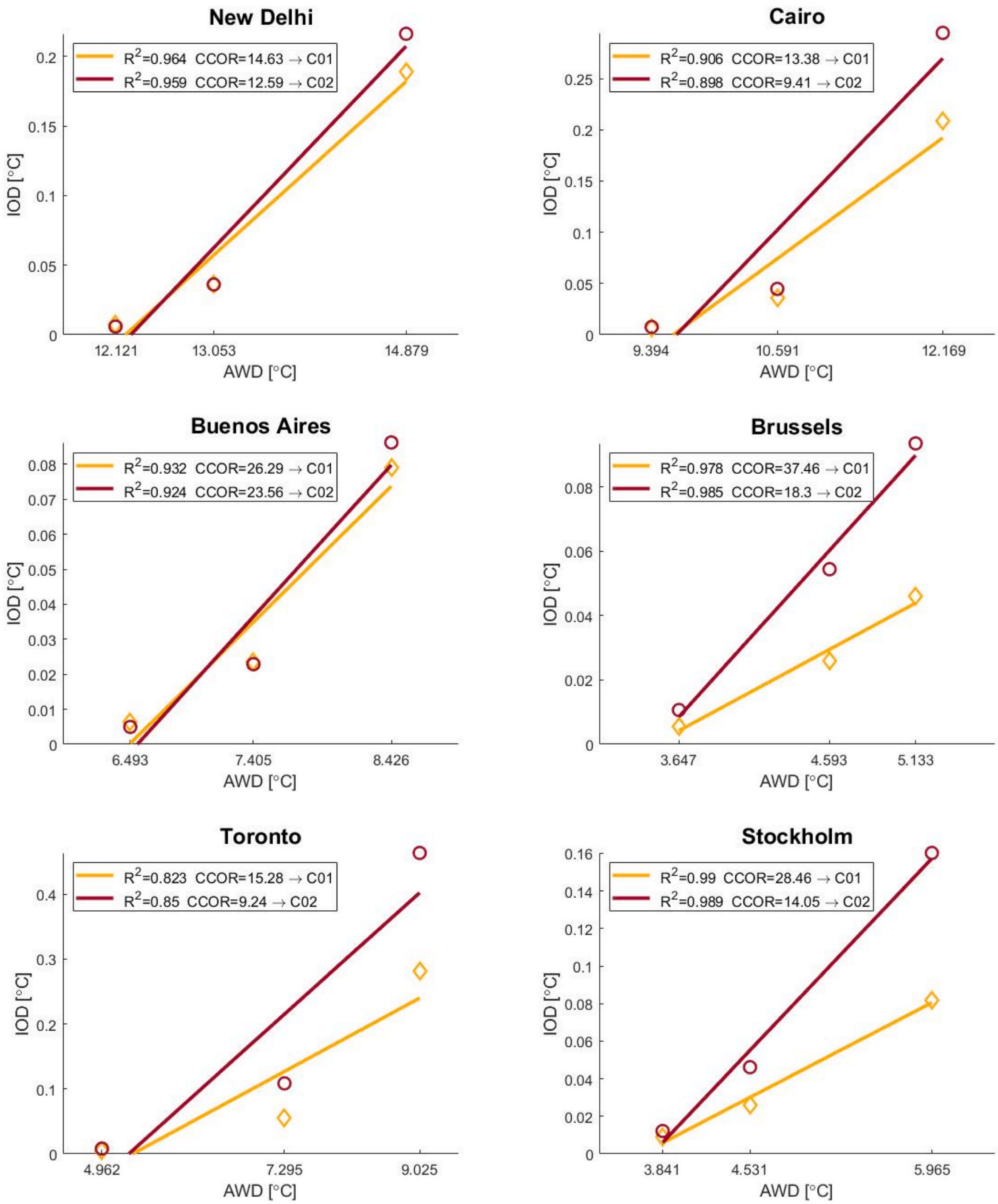

Fig. 7. IOD versus AWD. The slope of the regression line inverse shows the CCOR per city per cooling strategy.

comfort aspect, neglecting the energy performance of the selected cooling strategies. Third, spatial, cultural, and occupant behavioural differences are not considered in the selected cities to accurately define simulation parameters such as clothing factor, metabolic rate, control strategies, etc. Fourth, the weather data applied in the current study are generated using an autoregressive model very similar to the morphing technique [88]. It means that the same weather events are assumed to occur in the future in the same way as they do under the current climate, with the only difference being a linear shift in temperature throughout the year. Fourth, the effect of heat stress is not only dependent on air temperature or operative temperature. Considerations for relative humidity and other comfort parameters such as clothing factor, metabolic rate, and air velocity are also important in determining thermal comfort. Those parameters are neglected within the evaluation framework of the current study. Therefore, more accurate studies are suggested to overcome the limitations of this paper.

4.3. *Implication on practice and future research*

One of the implications of the current work is to interpret and include the proposed framework and recommendations in future revisions of national, regional, or local building regulations. Most regulations, such as the EPBD in Europe, do not provide a straightforward method to assess the indoor overheating risk and have no considerations for climate change. Consequently, the indoor overheating risks arising from global warming are undermined in building designs. Also, the study establishes the foundation for the experts of the field such as the members of (IEA) EBC Annex 80 – "Resilient cooling of buildings" project to compare the resilient cooling strategies in different climate zones worldwide. The results will be communicated publicly to disseminate knowledge and raise community awareness to adapt the buildings to worsening outdoor conditions.

As some areas of the framework yet remain undemonstrated, some potential research recommendations are provided. First, future research is recommended to incorporate other reference cities specified in the framework using more accurate and reliable weather files. Second, even though the use of multi-zonal shoe box models provides preliminary but valuable insights into the performance of cooling strategies in a simple and fast way, the future research is recommended to apply real residential and non-residential reference building models developed for local, provincial or national building stocks for more realistic evaluations. Third, through the demonstration case in this paper, only the performance of two active cooling systems are compared. Therefore, future research is recommended to use the framework for the evaluation of other active cooling strategies and passive cooling strategies (see Section 2.1.3) as well as their combinations. Forth, future studies are suggested to implement additional discomfort/overheating indices besides the primary ones (i.e., *IOD*, *AWD*, and *CCOR*) to complement the overheating assessments.

In addition to the research recommendations on undemonstrated parts of the framework, future research is recommended to improve the performance indices suggested by the framework (i.e., *IOD* and *AWD*). The new metric for the indoor environment and occupant comfort should include more comfort parameters such as relative humidity, metabolic rate, clothing factor, and air velocity to better reflect the occupant's thermal sensation. At the same time, the new metric for the outdoor environment should include more outdoor thermal parameters such as solar radiation, relative humidity, etc. Future research is also encouraged to define a well-defined post-processing procedure to establish sensitivity and optimization analysis. It further extends the functionality of the current framework to optimize the cooling strategies for the buildings in different typologies and climates.

5. Conclusion

In this paper, a generic simulation-based framework is developed to evaluate the climate change overheating resistivity of cooling strategies in varying climates. Following the framework yields consistent results contributing to comparative studies among cooling strategies. The framework requires four key decisions: 1) specify weather data characterization (Section 2.1.1), 2) identify building characterization (Section 2.1.2), 3) identify and design/size the cooling strategies to be compared (Section 2.1.3), and 4) specify performance indicators and comfort models (Section 2.1.4). 23 cities are suggested as reference cities worldwide based on the rate of growth and population covering zones 1 to 6 in ASHRAE 169.1 classification. The framework considers all function types (i.e., residential and non-residential), comfort categories (i.e., I, II, III, and IV), cooling strategies (i.e., conditioned air, non-conditioned air, and mixed/hybrid mode). Three metrics are implemented namely, Indoor Overheating Degree (IOD), Ambient Warmness Degree (AWD), and Climate Change Overheating Resistivity (CCOR) allowing for a multi-zonal approach in the quantification of intensity and frequency of overheating during the zonal occupied hours.

Subsequently, the framework is tested by comparing sufficiently-sized VRF unit with DOAS and VAV cooling strategies in New Delhi, Cairo, Buenos Aires, Brussels, Toronto, and Stockholm. It was concluded that the VRF unit with DOAS results in reduced maximum indoor operative temperature and Exceedance Hours (EH) compared to VAV system. More importantly, the results showed that the building equipped with the former are more resistant to overheating impact of climate. It should be mentioned that the demonstration case is aimed to show that the framework is working well in conducting a universal comparison among cooling strategies. The validation of the results achieved in this study is required by using the framework in real multi-zonal reference buildings by using more reliable and accurate future climate data.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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